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Edited by Hassan M. Behery

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Dedicated to
My wife Mervet
My daughter Hala
My son Mohamed

For their enduring help and continuous assistance.
Without them this work may not have been completed
as it is today. H.M.B.

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Preface

The phenomena of fabric hand is one of the most significant characteristics in determining fabric marketing, and providing the fabric scope of end-uses, performance, and appearance.

For several decades, the study of fabric hand has attracted interest of research and development in engineering groups, textiles and fiber scientists, statisticians, fabric designer industrialists, and dyers and finishers. Many groups and committees were formed to elucidate the fundamental aspects of fabric hand, either by subjective assessments or by a more quantitative approach of objective measurements relating to the physical and mechanical properties of the fabric.

Subjective assessments of fabric hand by human judges rely on psychophysical approaches or psychological techniques. Psychophysical approaches use consumer judges, because sensory evaluation of fabric hand by consumers gives information about their perceptions and preferences of fabrics for specific end uses.

Since the 1930s, Peirce has pioneered the laboratory attempts to characterize the hand of fabrics. Initially, this was difficult by the fact that no single definition of hand existed at the time. Since then, there have been many efforts to specify what defines fabric hand.

In surmountable publications have been introduced by various groups of researchers in journals, conference proceedings, meetings, and workshops. Much new equipment has been designed and put into service for the objective assessment of fabric hand. Such activities were developed in the four corners of the globe. However, it is worth noting that Japan and Australia, not only took the lead in this activity, but contributed most in both the subjective and objective assessments of fabric hand.

This book is primarily a textbook, based on the wealth of information and experience of numerous researchers and scientists who devoted the majority of their time and effort towards the advancement of knowledge in the field of fabric hand for both subjective and objective hand assessments. The book is intended for textile students in universities and colleges. It will also be of immense assistance and help in providing knowledge and know-how to fabric designers and industrialists who are looking for a specific product for a particular end-use. The book discusses the effect of physical and mechanical properties on fabric hand, starting with the fiber level, to yarn and fabric level, including the effect of the wet processing (dying and finishing). The development of equipment and instruments for objective hand measurement is also presented in the book.

The application of the advanced statistical methods are given with practical examples and illustrations. Most important, the comparison of the assessment of fabric hand between different cultures, gender and languages, and the need for common terms and definitions are outlined and presented. Finally, the effect of refurbishment on fabric hand is discussed.

The reader is also provided extensive appendices covering The Standardization and Analysis of Hand Evaluation presented by the HESC – (Hand Evaluation and Standardization Committee), The Textile Machinery Society of Japan. And, also the SiroFAST – fabric assurance by simple testing which was developed in Australia by the SCIRO Division of Wool Technology.

H.M.B.

1

Introduction

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1.1 Historical

Consumers instinctively use fabric hand to describe and assess fabric quality and its suitability for a specific end use. Fabric hand could be evaluated by mechanical and electronic devices and by human judges using psychophysical or psychological techniques. Judgments of fabric hand provide understanding of underlying fabric properties. In the measurement of fabric hand, psychological approaches use consumer judges, because sensory evaluation of fabric hand by consumers gives information about their perceptions and preferences for fabrics for specific end uses. In early studies by Schwartz[1] and Brand,[2] fabric hand was defined as a subjective property evaluated by consumers.

The need for developing means to evaluate fabric hand objectively has been recognized over many years. Several instruments have been designed, redesigned and developed for the measurement of fabric mechanical properties and have evolved through the pioneering work of Peirce[3] in 1930, which quantified the relationship between measurable fabric properties and hand.

Nowadays, several instrumentations are available and testing measurements and techniques are actually in use in the textile industry, as well as in research and development work. These are presented and discussed in Chapters 2 and 3.

1.2 Definition and concept of fabric hand

Fabric hand has been defined[4] as '… the subjective assessment of a textile obtained from the sense of touch. It is concerned with the subjective judgment of roughness, smoothness, harshness, pliability, thickness, etc.'. Judgments of fabric hand are used as a basis for evaluation quality, and thus for determining fabric value, both within the textile, clothing, and related industries and by the ultimate consumer. Studies of fabric hand may be of major commercial significance if, for example, they assist in explaining hand assessment or provide a means of its estimation based on objective measurement. It is necessary to examine the subjective assessment of hand before examining its relationship to fabric mechanical and surface properties.

1.2.1 Review of the literature for definition of fabric hand

Peirce[3] described hand as being the judgment of the buyer, which depends on time, place, season, fashion, and personal predilections. Therefore, the intention to replace expert human assessors by numerical data from physical testing would be worthless. What human fingers sense, on the other hand, depends upon the physical properties of the cloth, so that data from physical measurements can provide a basis upon which to exercise judgment.

In a series of technical investigations of textile finishing treatments, Schwartz[1] defined hand of a fabric as a property judged as a function of the feel of the material, and explained that the sensation of stiffness or limpness, hardness or softness, and roughness or smoothness constitutes hand. He reported the desirability of physical testing which may analyze and reflect the sensations felt and which can assign numerical values to the measurements of these parameters.

Patterson[5] studied the causes of changes of hand in woolen fabrics. He defined fabric hand as a certain quality expressed by an individual reaction through the sense of touch upon examining a fabric or one or more fabrics of the same quality. He explained that a woolen fabric may be described as having a good hand, which may be further classified as soft, slick, sharp, woolly, smooth, or silky; if the hand is poor, it may be described as harsh, greasy, gummy, sticky, boardy or dry. However, he concluded that the question of hand of fabrics has been complicated because of the inability to evaluate this property of a fabric by any definite or standard method.

Hoffman and Beste,[6] in their study of fiber properties related to fabric hand, reported that fabric hand means the impressions that arise when fabrics are touched, squeezed, rubbed, or otherwise handled. The handling of a fabric may convey visual impressions as well as tactile ones; therefore, it seems proper to include luster and covering power in the properties considered.

Thorndike and Varley[7] studied the frictional property of fabrics as related to hand, and defined hand briefly as a person's estimation when feeling the cloth between fingers and thumb. Their discussion is based on the assumption that the static and/or dynamic coefficient of friction between the cloth surface and the thumb or fingers is one of the factors which influence the subjective judgment of fabric hand, although flexibility, thickness, and other properties of the material may also be involved when making such an assessment of cloth quality.

Mechanical properties related to the hand of heavy fabrics were investigated by Kita Zawa and Susami.[8] They introduced the term 'synthesized hand'. They discussed whether hand is a psychological phenomenon and whether, if hand is defined as a perceptible pattern obtained by the tactile sense of fingers, transmitted by the nervous system and assessed by the brain, explanation of the sensory pattern in a direct and objective way without clarifying the mechanisms of the sensory organs, nervous system and brain will be impossible. If so, expressing the sensory values of a fabric obtained by different assessors by use of a statistical technique becomes inappropriate. The very difference in the results of hand assessment by different assessors is an important factor in defining hand. Each assessor forms his or her own idea about the pattern of a given fabric; however, regarding such elementary sensory properties as stiffness, thickness and warmth, it is possible that communication between assessors may constitute a common idea, such as 'wool hand' or 'silky touch'. This common and qualitative idea formed by an assessor about the multiplicity of resembling samples is defined as 'synthesized hand'. A series of basic mechanical properties are assumed to govern the synthesized hand of a fabric. Then, it is possible to develop a correlation between the synthesized hand and the pattern of the mechanical properties of standard samples, provided that this standard pattern can be established.

Lundgren's[9] concept of fabric hand is that hand is considered as the summation of the 'weighed' contributions of stimuli evoked by a fabric on the major sensory centers presumably present in the human hand. Such centers can be uniquely sensitive to such physical properties as roughness, stiffness, bulk and thermal characteristics. He also stated that the term 'hand' is used to describe the tactile and muscular (kinesthetic) sensations produced by a fabric.

In a study of hand and drape of fabrics, Owen[10] defined that by hand are meant all the sensations that are felt by the fingers when the cloth is handled. He suggested the following eight physical properties as the important factors involved in hand: stiffness, smoothness, weight, thickness, compressibility, liveliness, ease of skewing or shearing, and cold feel.

Matsuo *et al.*[11] defined hand, in general terms, as what a person sensorily assesses from the mechanical properties of a fabric. In other words, human hands assess the mechanical properties of fabrics in place of sensory assessors. They classified hand terminology by defining and using new terms such as 'whole hand', 'characterized hand' and 'evaluated hand'. According to their definitions, the 'whole hand' of a fabric is what is sensorily transformed from all the mechanical properties of the fabric. And when 'whole hand' is judged in values, it is transferred to what they called 'evaluated hand'. This depends on both functional and synthetic factors. Evaluated hand may also be influenced by fashion, climate, social state, personal taste, etc. When the 'whole hand' of a fabric is compared with that of a standard fabric, attention has to be given to the differences in 'whole hand' between the two fabrics.

Therefore, the hand of the fabric which is compared with the standard must be characterized by descriptive adjectives and is classified as 'characterized hand'. The authors listed five mechanical properties – stretching, shearing, bending, compression, and surface friction – as principal parameters to define 'basic hand' as the sensibility corresponding to each of the five mechanical properties. To each property there corresponds a sensibility which people detect sensorily regardless of the extent of the sensibility. Therefore, the 'whole hand' corresponds to the assemblage of the basic mechanical properties.

Tactile properties of non-woven fabrics were investigated by Mendoza and Harrington.[12] They introduced the term 'total softness', which can be defined as a function of a composite of such physical properties as drape, hand, bulk, mass, resilience, and surface smoothness. They explained that as every human being possesses a subconscious, as well as a conscious, appeal to preferences when handling fabrics, these preferences cannot be objectively isolated, and thus total softness cannot be interpreted absolutely as a united physical response. Softness, therefore, is a relative human appeal or desirability upon handling fabrics.

Kobayashi[13] regarded hand of a fabric as a tactile evaluation judged from physical stimuli of fabric mechanical properties in his analysis of fabric hand by application of information theory. However, he further suggested that visual factors should also be taken into consideration to evaluate fabric hand on a broader scale.

From the survey of the literature on the definitions of fabric hand, it can be concluded that definitions differ considerably according to the interests of researchers. Among them, those given by Kita Zawa and Susami[8] and Matsuo *et al.*[11] seem to be the most promising in the sense that hand of a fabric can be analyzed into its mechanical property components and thus expressed by exact numerical values from objective measurements of constituent physical characteristics.

1.3 Fabric hand attributes and quality descriptors

Mahar *et al.*[14] introduced the term 'fabric hand attributes' to describe fabric characteristics such as stiffness, softness, smoothness, warmth, coolness, crispness, smooth drape, etc. Several attempts have been reported[3,11,15–19] to derive a set of hand attributes for textile materials. Despite observations that experimenters sometimes try to simplify the situation objectively and thus can fuse its subjectivity,[20] a number of authors have isolated relationships between mechanical properties and hand (for example, see references 11, 15, 18, and 19).

More information about the quality of a fabric may be conveyed by considering the separate fabric characteristics or attributes that, taken together, constitute the complex notion of hand, rather than by considering the overall concept of hand.

1.3.1 Evaluation of fabric hand

The Hand Evaluation and Standardization Committee (HESC) of Japan's Textile Machinery Society has published standards (Appendix A) incorporating samples of appropriate fabrics for overall fabric hand, or Total Hand Value (THV), for men's winter suitings[16,17]. The Committee has also published similar types of standards for fabric hand attributes or Primary Hand Value (PHV), considered important in the fabric hand evaluation of both men's winter and summer suiting fabrics and ladies' thin dress materials.[16,17] The PHVs nominated by the HESC for men's winter suitings are Koshi, Numeri, and Fukurami. Similarly, the PHVs for men's summer suitings are Koshi, Shari, Hari, and Fukurami (Appendix A).

The work of the HESC in establishing and subsequently publishing standards for overall fabric hand (THV) and fabric quality attributes (PHVs) has resulted in much improved communication of the aesthetic qualities of fabrics, both within and between the Japanese textile and clothing industries. These standards for fabric hand and quality attributes, with their associated descriptions and terminology, will also be used on an international scale to initiate a similar improvement in communication on fabric aesthetics. However, the speed, and ultimately the scale, of international acceptance of Japanese fabric hand standards will be hindered by the deficiencies inherent in language translation. This will be discussed and presented in Chapter 5.

1.3.2 Instrumentation

To evaluate fabric hand objectively, the need to use instrumentation was imperative in order to measure physical and mechanical properties of the fabric. Calculations of objective hand value were then made by various interpretations of the different properties measured. The different methods by which objective hand value are calculated are discussed in Chapter 5.

1.4 Development of fabric hand evaluation

Chapter 3 discusses the developments in measurement and evaluation of fabric hand. A survey of the different earlier method is discussed together with the latest developments and a newly patented system.

1.5 Elements relating to fabric hand

The basic elements that can fundamentally affect fabric hand are as follows:

- Fiber characteristics: fineness, length, friction property, resilience, compressibility
- Yarn type: staple fiber, continuous filament, textured, count and twist, etc.

- Fabric construction: woven, knit, non-woven, weight, thickness, surface, roughness, etc.
- Method and type of dyeing and finishing processes.

These elements are discussed in Chapters 6 to 10.

1.6 Application of statistical methods in assessing fabric hand

Due to the nature of variations and elements involved in assessing fabric hand, particularly subjective hand value and the objective assessments, statistical methods and approaches have been adopted widely in the field. Chapter 4 presents all the statistical methods used in assessing fabric hand.

1.7 Comparison of fabric hand assessments in different cultures

Comparative studies of the different ways of assessing fabric hand as a result of differing cultures and other human factors are necessary for the following reasons:

- The effects of culture, customs and tradition vary from one country to another.
- The ability of different languages to describe the feel and the hand of the fabric with similar terms or single words has made it difficult to communicate this fabric property, which is an essential feature in global trade and business.
- Men and women differ in their assessment of fabric hand; this has been studied in the USA and Korea.
- The effect of evaluating objective as well as subjective hand values using different methods was proven to give different results and conclusions.

Special attention has been given to the two major methods applied in the industry nowadays, namely the Kawabata (KES) system (Japan) and the FAST system developed by the AWTOMEC (Australia).

Some other methods based on an engineering approach have been compared with the Kawabata (KES) system. Also, subjective hand evaluations by judging panels from different countries have been directed towards fabric produced commercially from different countries: the USA, Japan, Australia, and Korea. The results have shown more agreements than disagreements to warrant negative effects on the outcome of the judgment.

1.8 Effect of performance and refurbishing on fabric hand

A critical property of fabric in its end use is its performance and how it withstands washing and/or dry cleaning to maintain its hand. Results of studies addressing this important phenomenon are presented in Chapter 11.

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Part I

Understanding and evaluating fabric hand

2

Concepts and understanding of fabric hand

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2.1 Introduction

In spite of its acknowledged importance, hand (or handle) remains, in most sectors of the industry, an inherently subjective characteristic of fabric and, as such, is affected by the whims and perceptions of the handler. Hand is used in the evaluation of fibre, yarn, fabric and garments as well as finishing technology. It remains one of the key components of the perceived quality of fabrics and garments and, as such, is the source of commercial dispute, claim and counter-claim. Over several decades, hand, which has been elusive and a matter of fierce debate within the industry, has come under close scrutiny. In recent years, something approaching consensus has been reached in some sectors of the textile industry, not only on the nature of the sensations that make up hand, but also on the terminology that must be used to describe them and the techniques that can be used in their assessment.

This chapter will outline the approaches that have been used to assess/measure/determine hand and the methods that have been adopted to standardise subjective assessments of hand. It will also describe two of the techniques that have been developed to objectively measure this elusive fabric characteristic.

2.2 Subjective evaluation of fabric hand

Considerable effort has been directed towards achieving an understanding of the nature of the tactile sensations making up hand and to determine the source of decisions made concerning hand.[1] There is a general recognition that subjective hand is a complex sensation consisting of a summation 'of the weighted contributions of stimuli evoked by the fabric on the major sensory centres' of the hand.[2]

The considerable research activity has been directed into a number of major areas:

- Understanding the concept(s) involved and terminology used. These studies have involved evaluations by panels and individual experts, supported by sophisticated statistical techniques.
- Analysis of the hand terms used and their relative contribution to the overall subjective assessment.
- Studies of the psychology and physiology of hand including the use of microprobes to measure nerve activity derived from handling fabric.
- Work to relate the sensory perceptions to measurable properties of the fabric.

Many studies have been conducted to identify the component parts of hand.[3–7] Two types of hand descriptor are normally used: single and bipolar. Examples are shown in Table 2.1. A rating can be obtained within any such descriptor using a single judge or a panel. However, to communicate the rating or to use this rating in a commercial context requires reference to meaningful standards against which any fabric can be assessed. The ASTM Committee on Sensory Evaluation developed terms that are used to describe hand (ASTM D123). The AATCC has also developed a standard protocol for hand evaluation (AATCC Evaluation Procedure 5).

Table 2.1 Hand descriptors

Single descriptor[13]	Bipolar descriptor[15]
Stiffness	Limp–crisp
Smoothnes	Scratchy–silky
Fullness	Fine–coarse
Liveliness	Light–heavy
Crispness	Smooth–rough
Scroopy	Thick–thin
Flexible and Soft	Firm–sleezy
Soft	Hard–soft
	Flexible–stiff

Fabric hand and its component parts are normally judged by comparison with something else, such as an agreed sample, a control or a standard, in order to form a better–worse decision. In a commercial environment, the ‘control’ may lie within the memory of the customer. The use of simple rankings and paired comparisons are the most widely used techniques to assess subjective hand, as there are several statistical methodologies that can be applied to analyse such judgements. These range from the Spearman Rank Analysis of rankings/ratings through analyses for paired comparisons, Multiple Factor Analysis to Spectrum Descriptive Analysis. The last two techniques are widely used in subjective and panel testing in all sectors of the food and cosmetics industry.

As early as 1926, Binns[8] reported the use of ranking techniques to compare fabrics and to compare the ranking of different panels of judges from different socio-economic groups. Various forms of factor analysis have been used in a large number of studies to identify key components of the judgement of overall hand in a range of fabric types. Using this technique, Howorth[4,5] observed that 86% of all decisions made by judges were made on the basis of nine descriptors: smoothness, softness, firmness, coarseness, thickness, weight, warmth, harshness and stiffness. The results of this work suggested that three 'dimensions' or factors could be used to explain the judgements made. The correlation between these factors and the descriptors was determined, with smoothness being the major characteristic dominating Factor A. Factors B and C were not so easily described but were tentatively identified with stiffness and thickness. Later analysis of Howorth's data determined that a better description was obtained using four factors: smoothness, stiffness, bulk, and thermal character. These have also been described in bipolar terms (roughness–smoothness, etc.).

Lundgren[2] described the analysis of hand in terms of the four descriptors above using ideas derived from Information and Decision Theories. In a series of articles in the *Bulletin of the Research Institute for Polymers and Textiles (Japan)*, Kobayashi[7,9] also described the use of discriminant analysis and information theory for the evaluation of terms used in hand and for distinguishing different 'types' of hand (silk-like, wool-like, etc.). On the basis of earlier Japanese work, the authors used a different set of hand terms from those derived in Europe. The four hand terms used, translated into English, were smoothness, softness, fullness and liveliness, which the authors were able to relate to specific fabric characteristics.

Principal component analysis was used to re-analyse the data from trials conducted to compare the hand assessment of international groups of judges.[10] Although the statistical technique did not allow identification of the five factors observed, it was found that different groups of judges placed different weightings on the various factors.

Prior to the late 1960s, none of the outcomes of these analyses had been adopted by the textile community in any systematic way to describe hand and there was no significant use of the outcomes in commerce. An important attempt to standardise the concepts and terminology used to describe and evaluate fabric hand was initiated in 1972 by the Textile Machinery Society of Japan. A full account of this activity is found in a number of review articles.[11,12] This initiative was part of a larger programme in Japan to develop an objective evaluation system for commercial use in the fabric and garment manufacturing industries in Japan. A committee (the Hand Evaluation and Standardisation Committee – HESC – under the chairmanship of Professor S. Kawabata) was formed to bring order into the evaluation, measurement and use of hand terms in trading and research.[13] This committee achieved remarkable progress, including, as it did, participants from industry and research, processing mills and universities. The terms of reference of this committee were derived from the observation that, although the textile industry in Japan had achieved much in terms of the application of modern manufacturing techniques to improve quality and speed of processing, there remained little agreement on the criteria on which hand, the key characteristic determining quality, could be judged. There was also recognition that the ongoing attempts to objectively measure hand characteristics that had been conducted since the 1920s were hindered by the lack of standardisation of description and assessment of subjective hand.

The first target of the research was the analysis of the technique by which Japanese experts made judgements on fabric hand. The work focused on the wool sector, particularly fabric finishing, reflecting the special importance of hand in the high-quality tailoring sector in Japan. This activity was aided in Japan by the concentration of the wool fabric and apparel manufacturing industries at that time, its progressive outlook and its strong commitment to R&D through its links with universities.

In spite of the acknowledged complexity of subjective hand, the approach used by the HESC was deceptively simple and consistent with earlier attempts to describe hand in terms of its component parts. In Japan, the terms used to describe hand had some professional recognition and there was some common understanding of the features of hand between experts. Kawabata and Niwa also recorded that 'visual appearance' was also an important factor in the expert judgement of hand.[11]

By observing around 12 experts, mostly from the wool weaving and finishing industries, it was noted that these experts rated the fabric for certain initial characteristics and then undertook a complex summation of these characteristics into an overall hand value. This observation was entirely consistent with the conclusions drawn by earlier researchers. Consensus was reached on the subjective fabric characteristics that were regarded as 'essential or important for the garment material required for a particular end use'.[11] The HESC called these characteristics 'Primary Hand Values – PHVs'. Importantly, it was agreed that it was 'not possible to replace each of these characteristics by a combination of other hand expressions'.[11] Finally, it was agreed that these primary hand values could be quantified in terms of their 'intensity'.

Not surprisingly, for some fabric types, the descriptors were quite similar to those developed in earlier studies in Europe (described above) and those developed by Matsuo, also working in Japan. However, the HESC studies demonstrated that the nature of subjectively assessed Primary Hand Values depended on the end-use of the fabric. In the initial publications of this work, only the primary hand values for men's summer and winter suiting were described. Later publications clarified the hand descriptors for a wider range of fabric types and end-uses.

Again, consistent with the judgements of former workers, it was observed that, after judging primary hand, experts formed an evaluation of the overall hand (or 'Total Hand Value – THV') based on a complex mental summation of these primary values in a two-stage process. It was observed that the manner in which PHVs contributed to the overall hand also depended on end-use.

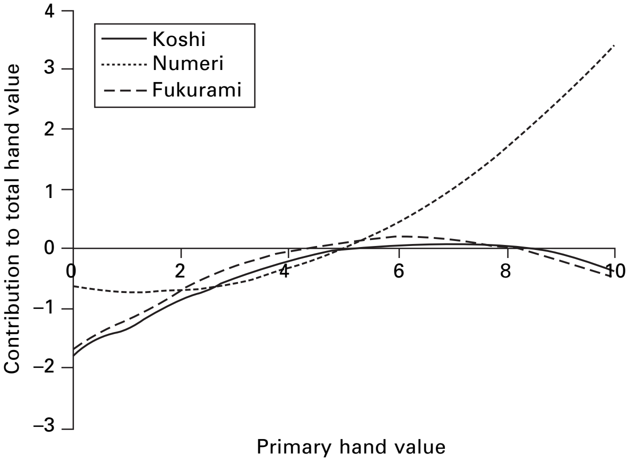
An important distinction was made between primary and total hand values. Each primary hand described the expert assessment of a specific characteristic. It was anticipated that primary hand values would be independent of the cultural and fashion preferences for overall hand and be a much more reliable standard for the subjective assessment of hand.

Having agreed on the concept of a two-step approach to hand evaluation, the HESC developed a series of standards to illustrate the subjective characteristics described by the primary hands (on a 0–10 scale). This involved the subjective evaluation by the 17 experts of around 500 winterweight men's suiting fabrics for each of the agreed primary hand values. Initially each expert graded the fabrics into three groups for each primary hand and then subdivided each group again into three subgroups. A set of potential standards was chosen from each of the grades. These tentative standards were again examined to confirm the grade. Once these standards had been agreed and confirmed, individual fabrics on which the ranking by the experts showed substantial agreement and which were close to unit values in the rating were chosen to establish the original definitive standard samples. These standards were chosen so that the scatter of the ratings was within 0.3 units. These standards were published as a series of reference 'documents'. A similar exercise was carried out for summer suitings, standards for which were also published. Later, 'books' of standard fabric were also published to describe the terms *Kishimi, Shinayakasa* and *Sofutosa,* which are relevant to ladies' wear fabrics.

During the assessment the experts also subjectively rated the total hand value on a 0–5 point scale (0 = unusable). Kawabata noted that it was necessary to exclude some judges in this latter process 'because of their extreme deviation of their ratings from the average'.[11] The effective number of experts was reduced to eight for this second process.

At the same time as this exercise was in progress, the mechanical, surface and physical properties of the fabrics were being measured. The outcomes of this exercise will be described in the next section of this chapter. The objectively measured PHVs and THVs also played an important role in the final selection of the standard fabric samples. The comparison of objective and subjective ratings of fabrics also determined their suitability for use as standards.

Obviously the major driver for this exercise leading to the publication of the standards was the need to improve technical and commercial communication about fabric hand. The HESC considered that the use of the PHVs and THV would be adequate to describe the hand of a fabric for commercial trading. It was considered that, even if the concept of good hand changed with time, culture or fashion, the change would be incorporated by redetermining the relative contributions of the PHVs. The contribution of the PHVs to the THV of winter suiting is seen in Fig. 2.1. It is clear that there are optimum levels for *Koshi* and *Fukurami* but that fabrics with the highest *Numeri* have a preferred hand.



2.1 Relationship between PHV and THV.

Various attempts have been made to determine the relevance of the Japanese studies to other textile markets. The translation of the Japanese PHV terms into English has been the subject of independent studies[14] and alternative English words to those originally used by the HESC have been developed. The differences are relatively small and probably subject to variation even within and between the various English-speaking countries.

The study by the HESC[13] was certainly not the last word on developing a model to describe fabric hand. An extensive study of 'Tactile Sensory Assessment' was published in 1980[15] using polyester and cotton fabrics. Rather than randomly selected fabrics, the authors chose 16 woven samples to represent the poles of stiffness–flexibility, smoothness–roughness and thick–thin. These fabrics were rated on a 99-point scale by each of 59 judges against nine pairs of polar adjectives and the data were transformed to normal deviates (so that the middle scores had a lower weighting) to create 'transformed sensory response values'. An ANOVA analysis related the four main criteria (listed above – plus fibre type) against the adjectival pairs. The work indicated that stiff and flexible fabrics were distinguished by all polar pairings, even those nominally not related to stiffness. For roughness, eight of the nine polar descriptors had significant F values. Moreover, the analysis revealed significant interaction between the chosen properties in the descriptions given. This work confirmed the observation of the HESC of the importance of interactions between subjective descriptors of fabric hand even where attempts are made to select samples on the basis of independent characteristics. The authors also drew attention to the particular impact of *stiffness* on sensory perception of this sample set, perhaps acknowledging the importance placed on this characteristic by Pierce.[16]

In contrast, a study was conducted in Australia using six bipolar fabric descriptors on a set of 110 wool and wool-rich suiting, jacketing, and trouser fabrics. It was found that smoothness–roughness ($r = 0.82$), extensibility–inextensibility and firmness–suppleness were the three most important attributes for Australian judges in assessing overall fabric hand. Studies of handle using the HESC set of fabrics were also carried out in the USA, China and other countries.

In spite of all the work in this area, the uptake of any standardised form of subjective hand assessment outside Japan has been limited. The major reason lies in the errors inherent in the process itself. Postle evaluated the repeatability and reproducibility of subjective assessments of a range of judging panels in an international hand survey using fabrics that formed part of the HESC data set. The minimum resolution of an individual judge on a scale of 0–5 was 1.6 for winter suiting and 3.1 for summer fabrics.[17] Extending the assessment outside national panels further increased the error. Such errors are high but can be reduced by the use of more than one judge. Unfortunately the use of hand assessment panels is not consistent with the day-to-day requirement for subjective assessment in industry and the requirements of a standardised system.

Cultural differences in the concepts of hand and emphasis have further impeded the adoption of a standardised system for international trade. Such errors, inherently recognised in Japan by the HESC, compounded by inconsistencies from a single judge, have been the driver for the development of objective measurement systems – notably the Kawabata Evaluation System for Fabrics (KES-F).

However, notwithstanding the cultural difference in the weighting of the various components of hand that are used to make decisions on overall hand, some form of consensus seems to be have been derived in the many studies of hand, namely:

- That overall hand is made up of component parts
- That the component parts can be determined in a semi-quantitative way against standards.

The following list represents a loose consensus of the relatively independent terms:

- Stiff–supple
- Rough–smooth
- Full–thin (lean)
- Warm–cool (cold)
- Lively–limp
- Stretchy–nonstretchy (inextensible)

Anomalies remain particularly around the use of word ‘softness’. The usage of the term can differ considerably as evidenced by the relatively large number of antonyms or bipolar opposites that are used with this descriptor.

2.3 Objective evaluation of fabric hand

The objective measurement of fabric hand has been a ‘holy grail’ of research workers in this area since the pioneering work of Peirce in the 1920s.[16,18] As outlined above, it is widely recognised that subjective techniques are unable to meet the requirements of a very diverse marketplace or to overcome the loss of expertise in assessing fabrics caused by the retirement of experienced employees.

The link between measurable fabric properties and subjective fabric characteristics such as hand has been known for many years. The issues facing developers of fabric objective measurement (FOM) technology to measure hand have always been:

- To identify which measurable properties are related to hand
- To determine under what conditions such measurements should be made
- To describe quantitatively how these properties are related to hand.

Peirce identified fabric bending properties as a key component of hand, or more correctly of fabric stiffness, and developed a number of tests to measure fabric rigidity in bending. Since this time alternative tests for fabric bending properties have been developed[18] along with the recognition that hand is much more complex than can be predicted from bending measurements alone.

An ideal objective measurement technology would measure only those properties necessary to specify hand and control quality. It is claimed that this is now possible as a result of the development of instruments sufficiently sensitive to measure fabric properties at the low stress levels consistent with the measurement of hand and techniques for the handling of the large amount of data generated.[19]

Writing in 1958, Howorth and Oliver commented[4] on the large number of papers that had been written in the USA alone on the topic of hand and methods for its objective measurement. This work continued through the 1960s to the 1990s as more sophisticated techniques were brought to bear and simplifications of the complexity of hand measurement were developed.

The ASTM D123 identifies the physical properties of fabrics related to hand descriptors (Table 2.2).

Table 2.2 Properties correlating with hand[a]

Bipolar attribute	Related mechanical properties
Stiff–pliable	Bending
Soft–hard	Compressibility
Stretchy–nonstretchy	Extensibility
Springy–limp	Resilience
Compact–open	Density
Rough–smooth	Surface contour
Harsh–slippery	Surface friction
Warm–cool	Thermal character

[a] ASTM Standard D123-83a.

Kim and Vaughn[20] measured 20 physical and/or mechanical properties on a range of cotton, polyester and blend fabrics and found 14 of these exhibited good correlations with subjective ranking of the hand.

Similar studies were undertaken in Japan by Matsuo and co-workers[21] who related 'the basic mechanical properties' of fabrics to their hand descriptors using the Weber–Fechner Law, which was developed to describe the relationship between a stimulus and the response. This approach used the concept of the *differential limen*, a term used in psychology to describe the smallest change in a fabric property that will result in a perceptual change for the judge. The total response is given by the collection of the responses for the different properties. The key to this approach lies in the ability to determine the *differential limen* and to appropriately sum the several responses.

In his aforementioned series of articles,[9] Kobayashi determined the physical properties of fabrics that correlated with *fuai* (hand). Using principal component analysis, the authors conclude that liveliness related to flexural rigidity and crease resistance, rigidity to crease resistance, and coarseness to fabric surface properties. This study illustrates one of the problems caused by the interrelations of measured fabric properties. Crease resistance of fabrics is a function of the stiffness of a fabric and its stress relaxation characteristics. Both these properties are in turn determined by fibre properties and fabric structural characteristics. In this instance, the observed correlation between liveliness and crease resistance is indicative of their dependence on more fundamental fibre and/or fabric properties. There are grounds to question the universality of the use of crease resistance as a measure of subjective liveliness.

Since the initial work of Peirce, a large number of individual instruments have been developed to measure a number of properties under the low stress conditions consistent with the measurement of hand. In many of the studies above, simple instrumentation, which had been developed to measure a property rather than measure that property under conditions relevant to hand, was used. The development of the KES-F system sought to overcome this deficiency.

In this chapter only two sets of instruments will be discussed: the KES-F and the SiroFAST systems for Fabric Objective Measurement. In succeeding chapters, the range of alternative approaches developed to objectively measure hand will be outlined.

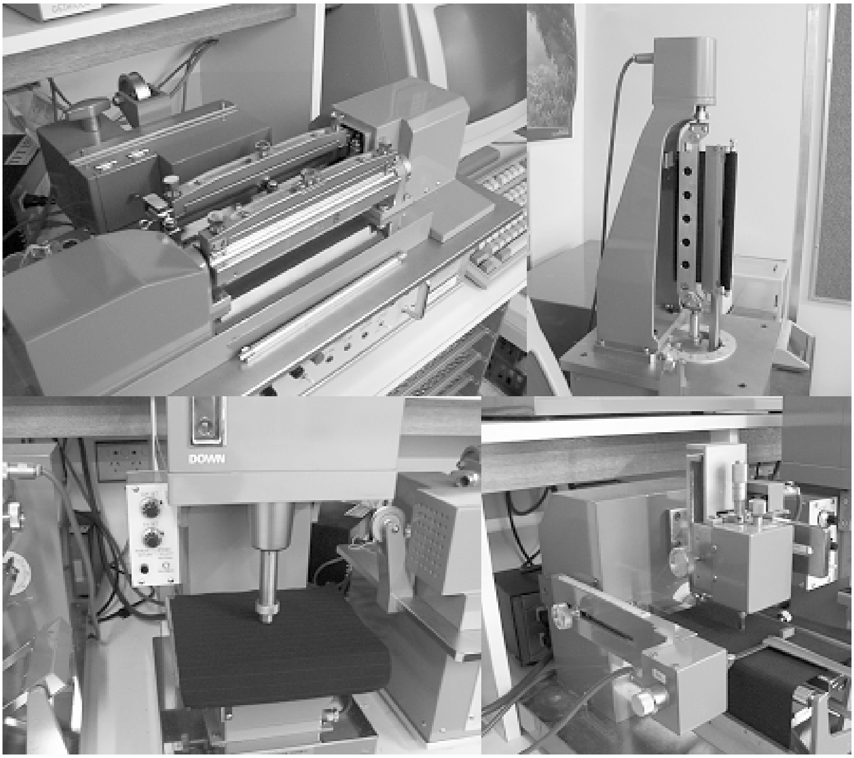
2.3.1 The Kawabata Evaluation System for Fabrics (KES-F)

The instruments that make up the KES-F system were developed from extensive work in Japan to ascertain the nature of the key fabric properties that affected hand, the appropriate mode of deformation to measure these properties, and the conditions under which the properties must be measured. The system, manufactured by Kato Tech. Co. of Kyoto, measures physical, mechanical and surface properties of fabrics using four separate instruments, two of which are used in each of two modes of deformation.

Detailed descriptions of the principles and outputs of these instruments appear in a large number of publications.[22,23] However, the instruments (Fig. 2.2) may be briefly described as follows:

- *KES-F1 Shear/Tensile Tester*
  This instrument measures the load–extension characteristics of a fabric (50 mm ¥ 200 mm gauge width) sample to a load of 500 gf/cm (490 N/m). In its second mode of operation it measures the stress–strain characteristics of the same sample in cyclic shear deformation between a shear strain of +8 deg and –8 deg.
- *KES-F2 Bending Tester*
  This instrument measures the couple–curvature characteristics of a 200 ¥ 10 mm sample in cyclic bending deformation between a curvature of 2.5 cm^{-1} and $-2.5\ \text{cm}^{-1}$.
- *KES-F3 Compression Tester*
  This instrument measures the pressure–thickness characteristics of fabric up to a pressure of 50 gf/cm^2 (4.9 kPa).
- *KES-F4 Surface Tester*
  This instrument measures the frictional force generated when the fabric is moved under a metallic friction head. In its second mode of operation, it measures the vertical movement of a probe under a 10 gf load as it moves over the surface of the fabric.

The first machines were released in 1972. Later models, called the KES-FB series, were released in 1978 and were designed to reduce the time required for specimen preparation and testing. By 1984, the system had been adopted in Japan and, to a lesser extent, worldwide. Development of more



2.2 KES-FB instruments.

automated models of the instruments (called the KESFB-AUTO-A System), which includes automated sample loading procedures and thereby further reduces operator working time, were completed in 1997. Pictures and specifications of these instruments can be found on the Kato Tech. website (www.kesfkato.co.jp/english/).

All instruments have analogue outputs so that a very large number of parameters can be determined from the curves that are generated in the test. Computer interfaces to handle the data and to rapidly compute the key properties were developed by a number of R&D organisations and universities including CSIRO and the German Wool Research Institute (DWI). A commercial interface, which permits computer analysis of the analogue output of the instruments, is also available from Kato Tech. Co.

The 27 measurements (reduced to 16 by averaging warp and fill) used for the objective determination of hand are shown in Table 2.3. The exception is, somewhat surprisingly, the extensibility (Em) of the fabric, which, while measured by the KESF-1B and considered to be useful for assessment of the tailoring performance of fabric, is not used to calculate Total Hand Value. This reflects an important feature of the subjective evaluation of hand by

Table 2.3 KES-F measurements recommended by the HESC[13]

Instrument	Description	Symbol[a]	Measurement
KES-F1 Shear/Tensile Tester	Work to extend	WT	Warp and weft
	Tensile resilience	RT	Warp and weft
	Linearity of extension curve	LT	Warp and weft
	Extension at 500 gf/cm	Em	Warp and weft
	Shear rigidity	G	Warp and weft
	Shear hysteresis (measured at 0.5 deg)	2HG	Warp and weft
	Shear hysteresis (measured at 5 deg)	2HG5	Warp and weft
KES-F2 Bending Tester	Bending rigidity	B	Warp and weft
	Hysteresis in bending	2HB	Warp and weft
KES-F3 Compression Tester	Work of compression	WC	
	Compressional resilience	RC	
	Linearity in compression	LC	
	Thickness at 0.5 gf/cm^2	To	
	Thickness at 50 gf/cm^2	Tm	
KES-F4 Surface Tester	Coefficient of friction	MIU	Warp and weft
	Mean deviation in the frictional force	MMD	Warp and weft
	Geometric roughness	SMD	Warp and weft
Physical properties	Weight per unit area	WT	

[a] LT = 2 ¥ WT/(500Em).
RT = 100 ¥ WT¢/WT where WT¢is the energy released in recovery (determined from area under recovery curve).
LC = 2 ¥ WC/[50 (To – Tm)].
RC = 100 ¥ WC¢/WC where WC¢is the energy released in recovery (determined from area under recovery curve).

Japanese experts, who, unlike their Australian counterparts, for example, placed little significance on the extensibility of the fabric as a key characteristic of hand.

The project to determine the relationship between measured fabric properties and subjective hand was undertaken in parallel with the HESC activities to standardise subjective hand. Around 200 fabrics (selected to avoid overlap) were subjectively re-evaluated using the newly developed standards for primary hand, and their properties were measured using the KES-F instrumentations. The subjectively determined PHVs were correlated with the fabric properties using a block regression analysis.

Before inclusion in the regression equation, each mechanical property was 'normalised' using the mean and standard deviation derived from the total data set. This allowed for the difference of the relative impact of different properties on the various components of hand. In the second edition of the HESC manual, the logarithms of many of the measured properties were used in the regression equations instead of the values directly. Kawabata and Niwa reported that the prediction increased with an increasing number of blocks (of properties) but that the accuracy saturated after three or four blocks. Notwithstanding this observation, all properties are used in the published regression equations, although it is made clear that most of the latter properties add virtually nothing to the prediction.

Normalised value of property $P_i = (X_i - A_i)/\mathsf{s}_i$ (2.1)

where X_i is the value of the property (or its logarithm), A_i is the mean value of that property (or its logarithm) over the data set, s_i is the standard deviation of that property (or its logarithm), and, i represents the 16 measured properties.

Primary Hand Value $H_i = C_0 + \text{Â}(C_i \text{ ¥ } P_i)$ (2.2)

for all 16 measured properties

Normalised value of PHV $Y_i = (H_i - M_i)/S_i$ (2.3)

Normalised value of PHV squared $Z_i = (H_i^2 - N_i)/T_i$ (2.4)

where H_i is the primary hand value
M_i is the mean value of the PHV
S_i is the standard deviation of the PHV
N_i is the mean value of the PHV squared
T_i is the standard deviation of the PHV squared

Total Hand Value THV $= K_0 + [K_1Y_1 + K_2Z_1] + \ldots$ (2.5)

for all PHV values
where K_0, K_1 and K_2 . . . are constants.

Around 100 separate fabrics were used to determine the accuracy of the prediction equations. The correlation coefficients for predicted and subjectively determined primary hand ranged from 0.93 for the *Koshi* of men's winter suiting (RMS error = 0.90) to 0.392 for *Fukurami* of summer men's suits (RMS error = 1.33).

The equations relating subjective Total Hand Value (THV) to the subjective primary hand values were applied to the objectively determined PHV to derive an objective THV. The correlations between objective and subjective THV were 0.90 for men's winter suits and 0.849 for men's summer suits; RMS errors were 0.33 and 0.35 respectively.

Recognising the difficulty of condensing and visualising the many values associated with the measured properties and calculated hand values, the HESC proposed the graphical representation of the data based on a ‘snake diagram’, shown in Fig. 2.3. The scale used in the construction of this snake also reflected the ‘normalisation’ process used for the properties based on the mean and standard deviation of that property within the data set.

There has been little controversy over the modes of deformation used and the methods of measuring shear, tensile, bending and compression properties used in the KES-F system. Some concern has been voiced over the surface measurements (KES-F4B) and the use of the metal fingerprint. The measurements made in this module (MIU, MMD and SMD), which contribute strongly to objective evaluation of *Numeri* (smoothness), have been less well accepted.

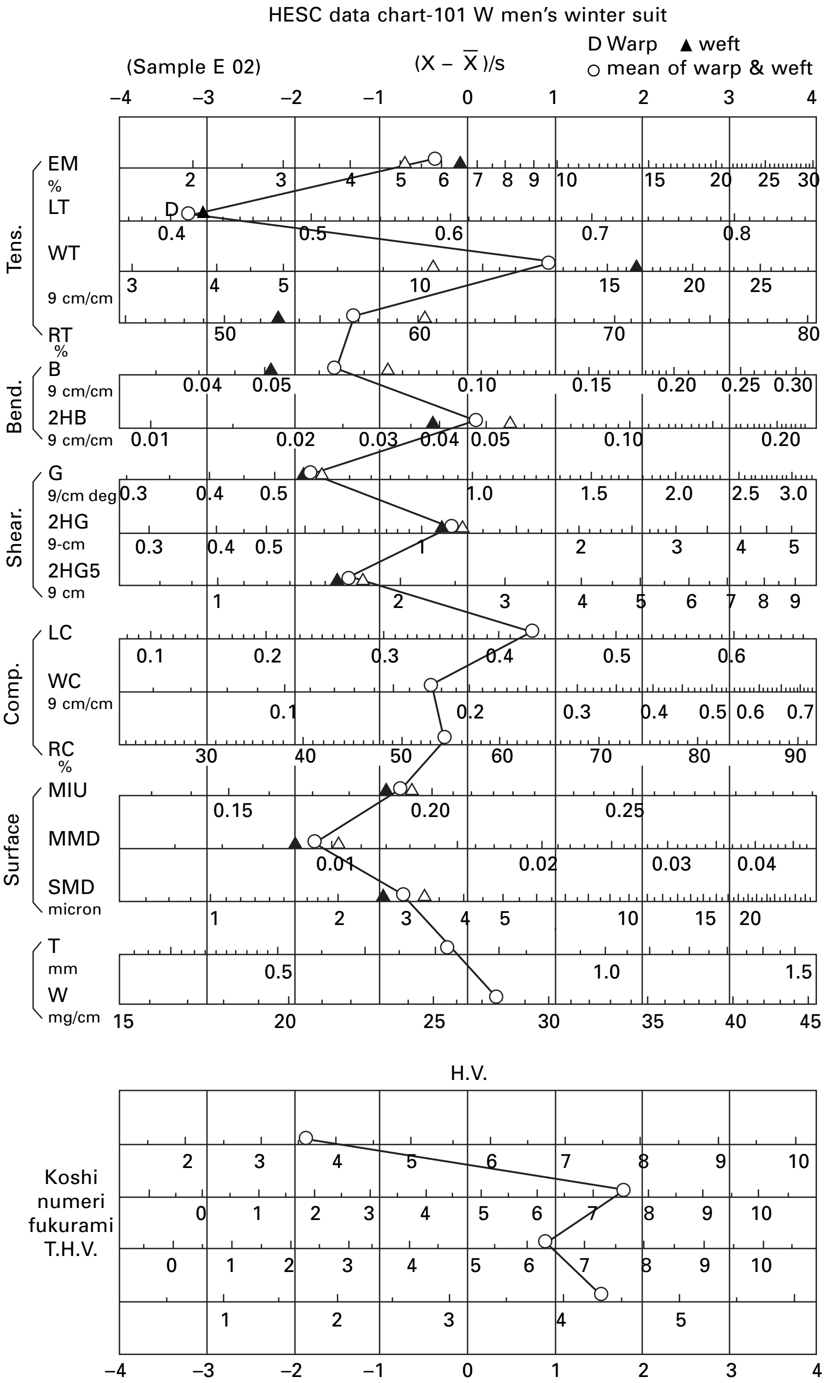
The statistical methodology used by Kawabata (block regression analysis) has also been the subject of some debate and alternative statistical techniques have been proposed. These will be discussed later in this chapter. None of the alternative statistical treatments have been adopted commercially.

Two interlaboratory trials of the precision and accuracy of the KES-F system have been published.[24–26] The results obtained are summarised in Table 2.4.

In the final analysis, in spite of the extensive work done to relate mechanical properties measured in the KES-F instruments to subjective hand using a variety of statistical techniques to massage the raw data, the objective measurement of overall hand or even elements of hand has not been widely adopted commercially. Commercial practice, where objective measurements are required, remains the identification and measurement of a small number of key properties that correlate well with the required hand change (such as stiffness and softness, etc.). Although expensive and sophisticated, the KES-F instruments remain eminently suitable for this role, measuring both deformation and recovery properties of fabrics with a high degree of precision. This allows comparison of those properties of fabrics most related to the observed differences in hand.

AWTOMEC – the Australian application of KES-F data

Australia was one of the first countries outside Japan to evaluate the use of KES-F instruments and the model developed by the HESC. This reflected the importance of wool in the high-quality men’s tailoring sector at which the Japanese efforts had been directed. The Australian Wool Textile Objective Measurement Executive Committee (AWTOMEC), comprising representatives from the Australian Wool Corporation, the University of NSW, CSIRO Divisions of Textile Industry and Textile Physics as well as from the fabric and garment manufacturing industries and the Department of Defence, was



2.3 HESC fingerprint (from the HESC manual[13]).

Table 2.4 Reproducibility of measurements on KES-F instruments[26]

Property	Measurement	Critical differences[a]	
		Within laboratories	Between laboratories
Tensile	Extensibility	0.69	1.29
	Work to extend	1.06	2.38
	Linearity in extension	0.042	0.181
	Resilience in extension	3.56	10.95
Shear	Shear rigidity	0.060	0.171
	Shear hysteresis (0.5°)	0.135	0.392
	Shear hysteresis (5.0°)	0.193	0.536
Bending	Bending rigidity	0.005	0.018
	Bending hysteresis	0.004	0.117
Compression	Thickness (0.5 gf/cm^2)	0.044	0.114
	Thickness (50 gf/cm^2)	0.034	0.063
	Work to compress	0.023	0.033
	Linearity in compression	0.035	0.059
	Resilience in compression	2.7	10
Surface	Frictional coefficient	0.010	0.038
	Variation in friction	0.006	0.016
	Surface contour	0.78	2.35

[a] Based on three replicates.

formed in 1984. The group, financed by the Australian Wool Corporation, had three major objectives:[27]

- 'To evaluate the introduction of objective measurement in menswear, worsted fabrics and garment manufacturing sectors'
- 'To review the Japanese system of test data presentations and modify it as appropriate to Australian requirements'
- 'To establish an Australian database for worsted menswear fabrics'.

The first objective involved a comprehensive testing programme of pure wool and blend fabrics. It was aimed at determining the extent to which the KES-F system could be used in the Australian industry to specify fabric and garment quality. The second objective was to address the major concern over the complexity and extensive amount of data derived from the original HESC model and resulted in the reporting of an alternative set of data for fabrics (Table 2.5).

There were two sources of concern in the HESC recommendations for use of measurements derived from the KES-F instruments:

- The use of hysteresis measurements
- The relevance and methodology used for surface measurements.

Table 2.5 Measurements recommended by AWTOMEC

Properties	HESC recommendation (cgs units) Warp, weft, average	AWTOMEC SI units)[a]
Tensile	LT, WT, RT, Em	Em, [b]RT (warp, weft only)
Bending	B, 2HB	B, RB (warp, weft only)
Shear	G, 2HG, 2HG5	G, RS, 2HG5 (average only)
Compression	To, LC, WC, RC	To, C, RC
Surface	MIU, MMD, SMD	SMD (warp, weft only)
Dimensional stability		RS, HE (warp, weft only)
Derived		Formability (warp, weft only)

[a]RB(*m* – 1) = 0.5 ¥ 2HB/B
RS (deg) = 0.5 ¥ 2HG/G
C (%) = 100 ¥ (To – Tm)/Tm where Tm is the thickness at 50 gf/cm^2
RS (%) = Relaxation shrinkage % (derived from AWC test method no. 10)
HE (%) = Hygral expansion (dry–wet) %
Formability = B ¥ El/49.035 where El is the extensibility at 49.035 N/m (50 gf/cm).
[b]Em (HESC) is used only in the determination of tailoring performance.

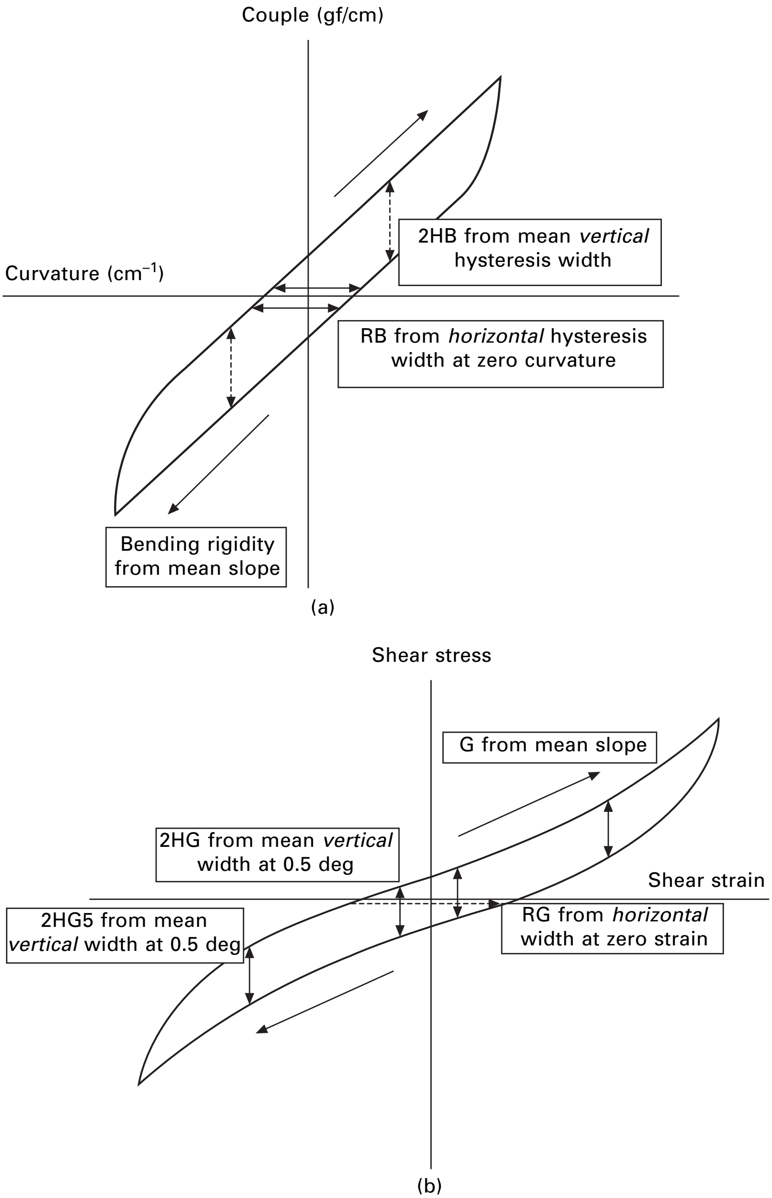
Concern over the use of hysteresis measurements by the HESC equations centred around the specific interpretation of 2HB, 2HG and 2HG5 rather than any disagreement on the need for measurement of hysteresis and recovery in some form. These measurements of hysteresis in bending and shear recommended by the HESC correlated extremely well within the fabric data set with the modulus-related properties B (bending rigidity) and G (shear rigidity). There was concern that two such well-correlated measurements added little to the understanding of the separate contributions of modulus and hysteresis in deformation. From the other potential measures of hysteresis in deformation in bending and shear, AWTOMEC elected to use the properties *Residual Curvature* (in bending) and *Residual Strain* (in shear). These measurements are shown in Fig. 2.4(a) and (b) respectively.

For a perfect curve, the following equations apply:

RB = 0.5 ¥ 2HB/B

RG = 0.5 ¥ 2HG/G

AWTOMEC adopted these calculations rather than the direct measurement of the residual curvature and strain. Direct measurement of RB can be affected by distortions of the bending curve at very low curvatures caused by the clamping mechanism on the KES-F2 bending meter. Moreover, both direct measurements were susceptible to electrical and mechanical noise in the instruments. Notwithstanding this difference, the committee decided to continue to report 2HG5 because of the importance placed on this parameter by Japanese garment manufacturers.



(a)

(b)

2.4 (a) Bending and (b) shear curves.

The concern over the surface properties measured by the KES-F system centred around the reproducibility of the measurements, given their importance in the prediction of *Numeri* (smoothness). There were some misgivings about the interpretation of results from the metal fingerprint for friction measurements.

However, there was less concern about the contour measurement – SMD, which is measured and reported in the AWTOMEC chart.

AWTOMEC also approved the reporting of *formability*, a term derived from Swedish work[28] on the relationship between fabric properties and performance in garment manufacture. Formability is a measure of the extent to which fabrics can be compressed in-plane before buckling and thus can be used to predict seam pucker.

Formability = BR ¥ El/49.035

where BR is bending rigidity (KES-F2 instrument) and El is the extensibility, directly measured at 50 gf/cm width (KES-F1 instrument). Alternative measurements and definitions of formability have since been proposed.[29–30]

The details of the testing procedures and the reporting of results were collated in the AWTOMEC manual. AWTOMEC also developed an alternative form of the fabric fingerprint (Fig. 2.5). This fingerprint uses linear scales to give a simpler form of data presentation. An important decision of the committee was to exclude calculation of primary and total hand values 'in order to concentrate initially on hand interpretation directly via the fabric mechanical and surface properties'.[27]

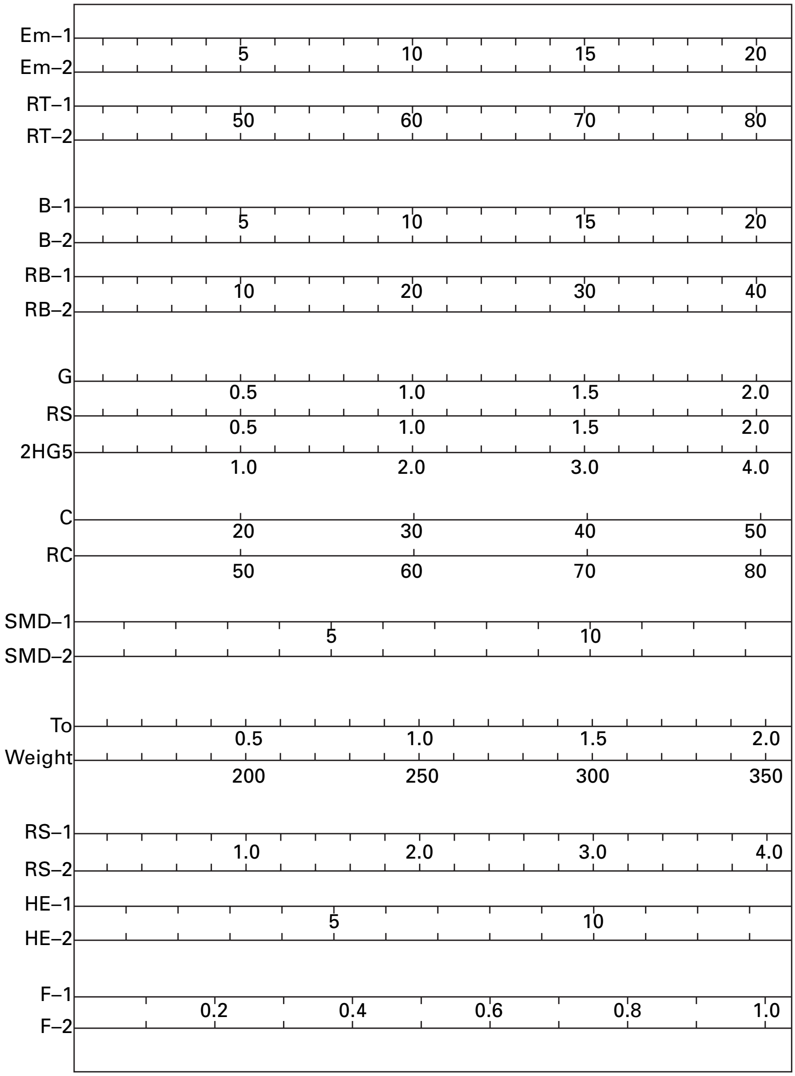
AWTOMEC continued its activities until 1991. In that time, the committee adopted a set of six bipolar hand descriptors that were thought to be more relevant to the Australian industry for the description of hand. A trial was conducted to determine the key mechanical properties involved in each hand characteristic (Table 2.6).

Before it completed its work in 1991, AWTOMEC also conducted a major fabric/garment tailoring trial, developed a video on the use of the KES-F system, circulated a series of case studies in the use of fabric objective measurement (mainly on the relationship between fabric/structure/finishing and subsequent properties) and held a seminar on the topic.

Alternative approaches to interpretation of KES-F data

Earlier in this section, reference was made to the concern expressed over the statistical techniques used to develop predictive hand equations from the fabric properties measured by the KES-F instruments. It is acknowledged that the 16 properties recommended by Kawabata contain a degree of overlap.

British workers[32] re-analysed the data on men's winter suiting published by Kawabata and suggested that alternative, independent variables could be used to describe the fabric and obtain the necessary correlation with subjective hand. The variables chosen (using the notation of the HESC) were W/B, SMD/T, T/B, SMD/W, SMD*B, W*T and their combinations with MIU. The regression equation



2.5 AWTOMEC chart.

$$\text{Hand} = 4.27(\text{W/B}) + 0.786(\text{T/B}) - 79(\text{SMD/T}) - 0.24(\text{MIU/T}) - 2.423$$

was found to correlate with overall subjective hand at a level similar to that given by the HESC equations. Moreover, this approach required only the measurement of surface properties (KES-F4), fabric weight, bending rigidity (KES-F2) and thickness (KES-F3). A number of alternative test instruments are available for the last two properties.

Table 2.6 Relationship between fabric properties and AWTOMEC bipolar descriptors[31]

Descriptor	Related properties[a]	Overall prediction[b]
Extensible – Inextensible	Tensile (0.87), Compression, Shear	0.92
Springy – Limp	Shear (0.80), Surface, Tensile	0.90
Firm – Supple	Shear (0.79), Surface, Tensile	0.90
Full – Lean	Surface (0.74), Shear, Compression	0.88
Smooth – Rough	Surface (0.68), Shear, Compression	0.88
Warm – Smooth	Weight (0.69), Compression, Shear	0.92
Overall handle	Surface (0,64), Compression, Shear	0.88

[a] Numbers in parentheses give the correlation coefficient between the handle characteristic and the most important group of properties.
[b] Overall prediction includes all properties measured.

In an alternative interpretation, Chinese workers used 88 ‘middle thickness’ fabrics to derive an objective measurement of hand using the concepts of *Weighted Euclidean Distance*[33–35] and *Fuzzy Cluster Analysis*.[36] Using the 16 mechanical properties from the KES-F instruments recommended by the HESC, eight fabric *features* were derived. The authors claimed that these eight different and independent primary hand characteristics of fabrics specified fabric primary hand ‘more completely and reasonably’ than the PHVs developed by Kawabata. The eight characteristics were named stiffness, fullness, smoothness, crispness, elasticity, droopiness, roughness and softness depending on the subjective characteristic and/or mechanical properties with which they correlated most heavily.

Researchers in the USA also demonstrated that relatively fewer mechanical properties were needed to obtain good correlations with the subject hand characteristics of restricted ranges of fabrics. One recommendation used only nine of the 16 properties recommended by the HESC (LT, WT, RT, 2HB, 2HG, RC, T, MIU and MMD). In this instance the measurements were made in a universal tensile tester under conditions that duplicated those in the KES-F instruments.

The second edition of the HESC manual described the use of discriminant analysis to separate different types of fabric on the basis of primary hand values. The PHV values, which can be calculated from properties measured in the KES-F instruments, were combined in a linear equation to calculate one or more discriminators, which separated silk-like, polyester-like and cotton-like fabrics.

A comparison of the block regression analysis used by Kawabata with alternative models was also made:

- A linear model

- Weber–Fechner law: $\text{PHV} = a + \hat{A}\ b_i \log x_i$
- Stevens' law: $\log \text{PHV} = a + \hat{A}\ b_i \log x_i$

In this work the HESC PHV standards were used to rate the set of fabrics, and all fabrics were tested in the KES-F system. The authors claim that Stevens' law was the most suitable for the prediction of PHV.[37]

A range of alternative approaches to condensing or visualising the KES-F data have also been proposed. In addition to the AWTOMEC chart and snake, alternative charts have been proposed, especially for applications of the KES-F for the prediction of performance in garment manufacture. A number of 'radar' plots have also been proposed based on properties measured on the KES-F instruments or derived from them to characterise the fabric.

Engineering evaluation and the SPRINT programme

The *SPRINT* project was funded by the EEC to allow 10 European research institutes to work together to stimulate the use of fabric objective measurement by fabric and garment manufacturers, not only for the prediction of performance in garment manufacture but also for the objective assessment of other related aspects of quality. The objective of the *SPRINT* group was to promote the philosophy behind objective measurements rather than promote specific instruments.

In the TNO Centre for Textile Research, work was done to simplify the operation of the KES-F instruments, the complexity of which was seen as a bar to commercial adoption.[38] The authors proposed a number of changes to the KES-F instruments and to the methodology for testing. The proposed attachment to the KES-F1 allowed a more distortion-free loading of samples so that more uniform shear curves could be obtained and the pre-tension required for the tensile test could be more accurately applied. The degree of tightening of the clamps on the bending meter was also highlighted as a point of difficulty, and in response to this perceived problem, a torsion socket was developed that can be used to tighten the bending with more consistent tension, thereby obtaining less distorted curves from the bending meter. The authors also formulated recommendations concerning the onset of the integration in the compression test, where the compression head can travel a significant distance without being in contact with the sample. In this zone, the integration value used to calculate WC should be zero.

In the shear test, the treatment of the tensile load required to prevent buckling has also been the subject of some discussion. Unlike the recommendations made for the use of a shear attachment for a tensile test machine,[39] the HESC recommendations for the KES-F1 instrument in shear mode do not subtract the effect of the tensile force. This is equivalent to 45 N/m with the heaviest pre-tension bar and 12 N/m for the lightest bar. In a recent study, measurements obtained in simple shear (using KES-F1) agreed well with measurements obtained in bias extension[40] when allowance was made for the effect on shear stress of the tensile load, which must be applied to avoid buckling.

Broader application of the KES-F instrumentation

Although the KES-F instruments were initially developed to measure the properties of woven apparel fabric, they can be used to measure the properties of woven fabrics as diverse as terry towelling and blankets[41] as well as those of warp- and weft-knitted fabric and non-woven fabrics. Plain knitted fabrics tend to curl and this can cause practical difficulties in their measurement. However, double knits and a number of other knitted structures can be tested with only a little more care (due to their ease of distortion) than woven fabrics. The measurement of the residual couple in knit fabrics can be used as a measure of their tendency to curl and the effectiveness of finishing operations.[42]

Modifications of the original test procedures developed for woven fabrics on the KES-F instruments have been described for the testing of shirting, women's thin dress fabric, outerwear knitted fabric, knitted fabric for underwear, and non-woven fabric.[43] These modifications include changes in the strain rates, maximum loads (or strains), and the measurement of different properties. For example, shear hysteresis of knitted fabric is measured at 0.5 deg and 3 deg (rather than the original 0.5 deg and 5 deg) or at 0 deg for high-sensitivity knitted fabric. New parameters are also recommended such as the 'yield curvature' in bending and 'yield angle' in shear on non-woven fabrics. The KES-F instruments can be adjusted to accommodate these changes; however, in some instances such as when there are changes in maximum loads, modifications are required to the formulas used to calculate parameters such as LC and LT from those shown in Table 2.3.

Studies of the mechanical properties of weft knits for outerwear use as a function of structure and density have been published.[44–45] The use of the HESC equations predicting subjective hand characteristics from the mechanical properties of knitted fabrics, although attempted, remains uncertain. It is argued that the equations were developed using a sample set composed of woven fabrics, for an end-use in which knitted fabrics are rarely used and to predict hand terms that may not apply to knitted fabrics. Notwithstanding this, the mechanical properties of a wide range of knitted fabrics can be used directly to gain information on hand.

A more complete study has been conducted in Japan on knitted fabrics.[46–49] Sensory evaluations of bending rigidity, thickness, compressibility, and coefficient of friction on a series of plain and rib weft-knitted structures made from cashmere and polyester textured yarns were found to be in fairly good agreement with the values measured on the KES-F system.

Undoubtedly the largest application of the KES-F instruments has been in the area of the prediction of the performance of woven fabric in garment manufacture. It had been known for many years, particularly following the research done in Sweden, that the mechanical properties important in the assessment of hand were also important in the manufacture of high-quality garments. During the development of the KES-F system, the tailoring industry had found that the measurements of fabric properties determined using the instrumentation could be used to predict performance in the manufacture of high-quality tailored garments. A large amount of research has been done in Japan to develop predictions of tailoring performance (TAV – Total Appearance Value) from measurements made on the KES-F system.[11]

A whole spectrum of predictors have been developed using the KES-F instrumentation and are described in the KN series of equations developed in Japan. More recent work describes TAV in terms of three primary components, called *formability, elastic potential* and *drape*, and uses predictive equations equivalent in form to those used to predict hand.

Charts similar to that of the HESC snake with various zones predicting problems in garment manufacture have also been developed.[50] A description of these studies lies outside the scope of this chapter but references to reviews of the use of the KES-F instrumentation in these applications are given at the end of this chapter.

The KES-F instruments have also been widely used to measure the effect of finishing operations on woven and knitted fabric.[51–55] By measuring the key fabric property affected by individual finishing operations, the extent of the desired changes and any side effects can be monitored and optimised.[56] The KES-F instruments can be used to compare the hand of series of fabrics or compare the effects of hand-modifying chemicals (e.g. softeners) and operations. Measurement of the shear hysteresis has been advocated as a measure of the effectiveness of softeners on a range of fabric types.[57] The measure has application in quality assurance or as a selection tool for fabric softeners.

Scottish workers[58] sounded a further note of warning in the use of the HESC predictive equations for fabric handle in the evaluation of finishing operations. These equations did not predict subjectively observed changes in the hand of cotton–polyester dress fabric in wash and wear cycles. Nevertheless, good correlations ($R > 0.9$) were obtained between the subjective rankings and selected mechanical (shear) and surface properties (SMD – contour).

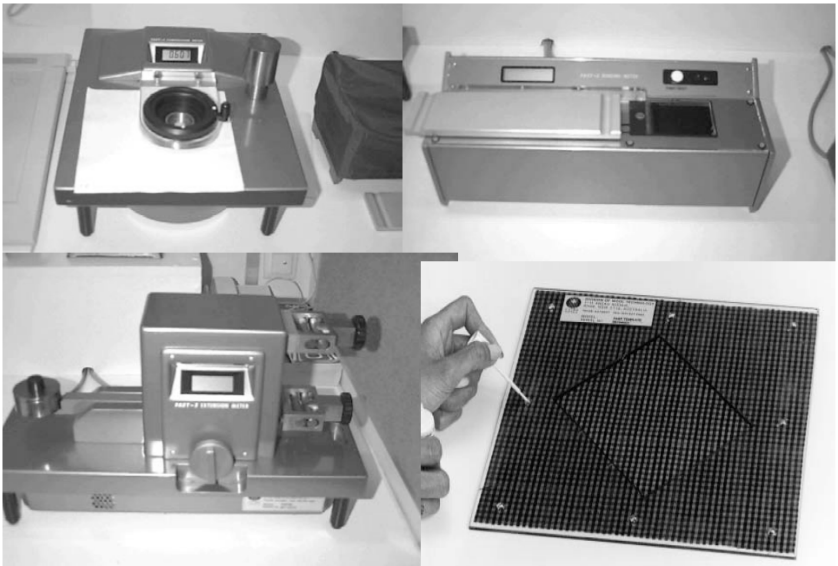
2.3.2 Fabric Assurance by Simple Testing (SiroFAST)[59]

The SiroFAST system for fabric objective measurement of fabric mechanical, physical and dimensional properties was developed by CSIRO[60] in the late 1980s to overcome the perceived disadvantages associated with the KES-F system. In practice, at least outside Japan, the KES-F system had been found to be too complex and expensive for use in a mill environment. The SiroFAST system was designed to be simple to use and to provide robust measurements of fabric properties.[61,62]

An important feature of the SiroFAST system is that it was developed to measure those properties of fabrics important in the manufacture of garments (tailoring) rather than to measure the hand of fabrics in a manner analogous to the KES-F system.

The SiroFAST system consists of three instruments and a test for dimensional stability (shown in Fig. 2.6):

- *SiroFAST-1 Compression Meter*
  This instrument measures the thickness of fabric at two loads: 0.196 kPa (2 gf/cm^2) and 9.807 kPa (100 gf/cm^2). It uses a relatively novel principle of measurement in which a proximity detector measures the change in position of a metal disc when the fabric is placed between it and the detector and the further changes in the position of this disc as an increasing load is added to it.
- *SiroFAST-2 Bending Meter*
  This instrument measures the bending length of the fabric in both warp and fill direction using a cantilever bending test as described in British Standard 3356. The instrument offers advantages over previous cantilever bending instruments in that it uses optical sensors to detect the leading



2.6 SiroFAST instruments.

edge of the fabric and thereby eliminates the errors associated with the judgement of the operator in determining the end point.

- *SiroFAST-3 Extension Meter*
  This instrument measures the extensibility of the fabric in the warp and weft directions under loads of 4.9 N/m (5 gf/cm), 19.6 N/m (20 gf/cm) and 98.1 N/m (100 gf/cm). The instrument is also used to measure the extensibility of the fabric in the bias directions under a load of 4.9 N/m (5 gf/cm width).
- *SiroFAST-4 Dimensional stability test*
  This test method measures the wet relaxation shrinkage of the fabric and the hygral expansion of the fabric from wet to dry.

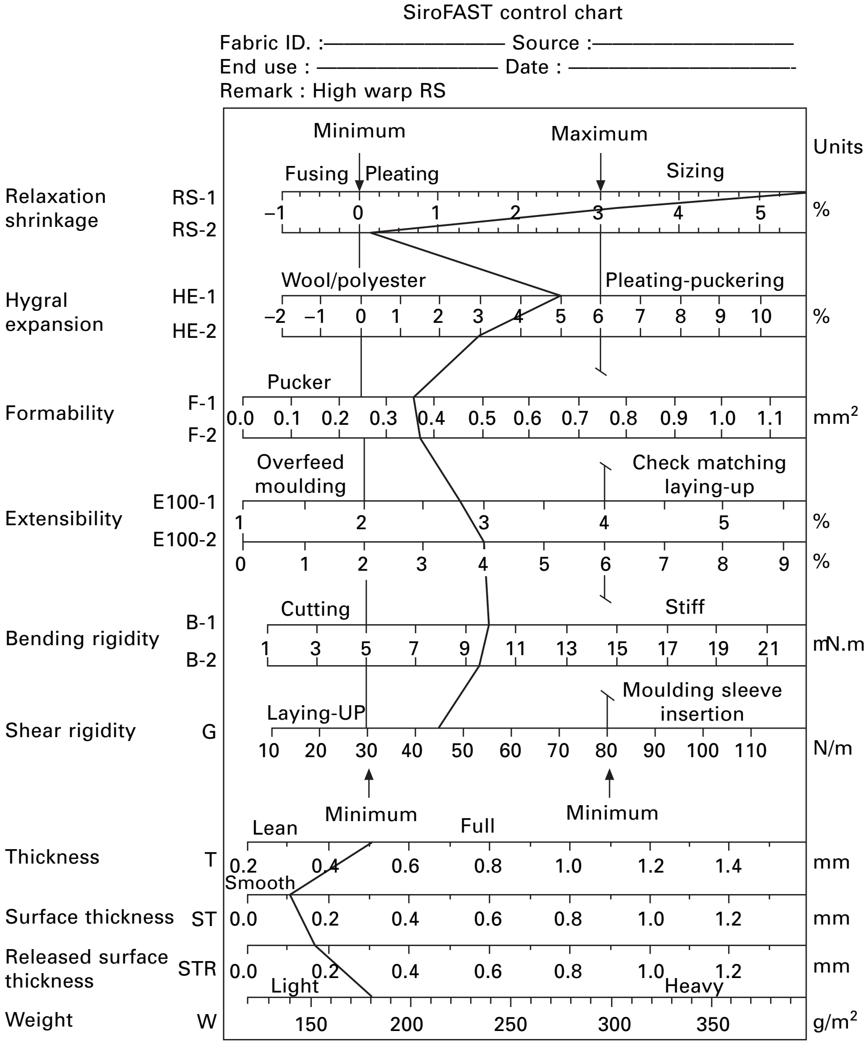
In addition to the measurements taken directly from the instrument, other properties of fabrics are also determined (Table 2.7). In recent times these measures have been further augmented by the concepts of *effective* and *stable flat set*.[63]

Table 2.7 Measurements made on the SiroFAST system

Instrument	Description	Symbol[a]	Measurement
FAST-1 Compression Meter	Thickness at 2 gf/cm^2	T(2)	
	Thickness at 100 gf/cm^2	T(100)	
	Relaxed thickness at 2 gf/cm^2	RT(2)	
	Relaxed thickness at 100 gf/cm^2	RT(100)	
FAST-2 Bending Meter	Bending length	BL	Warp and weft
FAST-3 Extension Meter	Extensibility at 5 gf/cm	E(5)	Warp and weft
	Extensibility at 20 gf/cm	E(20)	Warp and weft
	Extensibility at 100 gf/cm	E(100)	Warp and weft
	Bias extensibility at 5 gf/cm Warp and weft	Eb	Bias
FAST-4 Dimensional stability test	Relaxation shrinkage	RS	Warp and weft
	Hygral expansion	HE	Warp and weft
Physical properties	Weight per unit area	WT	
Calculated measurements	Surface thickness	ST	
	Bending rigidity	BR	Warp and weft
	Shear rigidity	G	
	Formability	F	Warp and weft

[a] BR = WT ¥ (BL)^3 ¥ 9.807 ¥ 10^{-6}
G = 123/Eb
F = BR ¥ [E(20) – E(5)]/14.7
ST = T(2) – T(100)

Although the measurement of fabric properties with the SiroFAST instruments is relatively simple, as with all systems for fabric objective measurement, interpretation of the data in a form that can be used by industry is more complex. Interpretation of the data requires an understanding of the mechanisms by which fabric properties affect its performance in garment manufacture. The SiroFAST system uses a graphical method of presenting and interpreting the data similar to that developed for all the KES-F. The SiroFAST chart is shown in Fig. 2.7. The annotations to the chart make it quite clear that the system has been designed for the predictions of problems in garment manufacture rather than the measurements of hand.



2.7 SiroFAST chart (from the SiroFAST Manual).

The system is supplied with a computer interface to simplify use of the instruments and also software to aid in the rapid interpretation of the data. The precision of measurements of the SiroFAST system has been determined in a series of interlaboratory trials[64] and the confidence intervals associated with the measurements are shown in Table 2.8.

Table 2.8 Reproducibility of measurements on SiroFAST system instruments

Property	Measurement	Critical differences	
		Within laboratories	Between laboratories
FAST-1	Thickness at 2 gf/cm^2	0.016	0.031
	Thickness at 100 gf/cm^2	0.008	0.024
FAST-2	Bending length	0.6	1.12
FAST-3	Extensibility at 5 gf/cm	0.11	0.37
	Extensibility at 20 gf/cm	0.14	0.43
	Extensibility at 100 gf/cm	0.24	0.61
	Bias extensibility (5 gf/cm)	0.27	0.83
FAST-4	Relaxation shrinkage	0.38	0.46
	Hygral expansion	0.60	0.91

The reproducibility of formability, dimensional stability and surface thickness are described in IWTO specifications:
Formability: IWTO Test Method 49
Dimensional stability: IWTO Test Method 50
Finish stability: IWTO Test Method 51.
Source: SiroFAST manual.

The key differences between the SiroFAST and the KES-F systems are:

- The SiroFAST system does not measure the hysteresis/recovery properties of fabrics (RT, 2HB, 2HG, 2HG5, RC). Shear hysteresis measurements have been found to correlate very well with certain aspects of fabric hand, particularly softness. The extent to which SiroFAST can measure hand in these instances is determined by the extent to which the modulus measurements (extensibility, bending and shear rigidity) correlate with the same subjective characteristics. In many instances, particularly in shear deformation, modulus measurements correlate well with hysteresis.[40]
- The SiroFAST system does not measure fabric surface properties (MIU, MMD, SMD). Notwithstanding concerns over the appropriate methods of measurement, the surface properties of fabrics are key determinants of hand. The SiroFAST system cannot provide information on those subjective hand characteristics that are primarily determined by the surface properties of the fabric (e.g. smoothness–roughness).
- The SiroFAST system measures dimensional stability.

Relaxation shrinkage and hygral expansion, determined using SiroFAST-4, do not affect hand but are key properties for predicting performance in garment manufacture and wear.

Although it does not purport to predict or measure overall hand, it is clear that, by measuring low-stress mechanical and physical properties of the fabric, the SiroFAST system can be used to obtain considerable information about fabric hand. All the knowledge obtained using the various alternative measurement systems on the relationship between fabric properties and hand apply equally well to the properties derived using the SiroFAST system. The SiroFAST User Manual supplied with the system recognises the usefulness of the individual fabric properties in determining fabric hand. However, the system does not use equations to predict hand characteristics, as has been done with the KES-F system, or use the concept of overall hand. The developers of the SiroFAST system noted and recommended the use of the relationship of specific objectively measured properties to subjective descriptions of hand.

2.4 Future trends

After the initial excitement and activity caused by the introduction of the KES-F and SiroFAST instrumentation and the prospect of objective measurement of hand using the HESC methodology, there has been a quietening of interest in both systems, particularly in Western Europe and the USA. Many of the high-value-adding producers, particularly of men's tailored garments, adopted and introduced the technology during the 1970s, 1980s and 1990s and have integrated the technologies into their regular testing regimes.

Both KES-F and SiroFAST continue to be used widely for the following:

- Prediction of performance in garment manufacture
- Development of new fabrics and new finishes
- Quality assurance.

In these applications both sets of instruments have now become regular tools of trade for fabric manufacturers, finishers and garment makers, with well over 100 SiroFAST systems and many KES-F instruments being used worldwide. Both systems will continue to be widely used in research and development by universities and research institutes.

It is anticipated that the future will see a wider adoption of objective measurement technology in developing countries. As quality improvements are made by fabric and garment manufacturers in these countries and as they seek to export high-value-added products into the sophisticated markets of Western Europe and the USA, they will need to demonstrate the quality of their products using KES-F, SiroFAST or suitable alternatives.

Attempts to include objective determination of overall hand as part of the trading system appear to have been limited to Japan. There has been little or no use of the methodology outside that country. Nevertheless, the use of sophisticated instruments for the measurement of specific fabric properties remains, and will remain, the method of choice for determining change in hand (due to finishing, etc.) or comparing the hand of a restricted range of fabrics. The exchange of information on such fabric properties will play an increasing part in commercial trade. However, it is unlikely that measurements of 'objective hand' using the KES-F or other types of measurement will be a significant part of commercial communication or trade in fabrics. Overall hand will remain, at least in the short term, a subjective decision.

It is anticipated that the use of the SiroFAST and low-cost alternative systems will continue to expand, particularly in Asia as the production of high-value fabrics and garments increases and quality assurance becomes an important issue. The expansion of the use of the more sophisticated KES-F instruments will probably be slower within the industry for the reasons that have been expounded before – complexity and price. However, it is likely that for both systems, their major use will continue to be in the prediction of performance in garment manufacture rather than for the measurement of any aspect of hand.

The impact of alternative measurement systems on the use of KES-F and SiroFAST remains speculative at this time. As will be discussed in later chapters, many of the measurements made using KES-F and all of the mechanical properties made on the SiroFAST system can be made on tensile test instruments (such as an Instron) with suitable attachments. Although measurement of bending properties on a tensile test machine requires quite sophisticated attachments, alternative simple instruments to measure bending properties are readily available.

Although the use of alternative, simple and less expensive instruments is an option for users of objective measurement equipment, the key to the successful use of fabric objective measurement technology lies not in the measurement but in the interpretation of the measurements made. The value of the existing systems lies in the application of the extensive published background information as well as in that contained within the manuals for the measurement system. Access to information on the interpretation of data and the use of that information in improving quality will remain the main driver for the uptake of the KES-F and SiroFAST systems.

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3

Developments in measurement and evaluation of fabric hand

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3.1 Introduction

Fabric hand may be considered as the first method of fabric testing ever created by humans. It is also one of the everlasting evaluation techniques of fabric. Even with today's technological advances in testing and evaluation, subjective fabric hand still remains one of the most reliable methods of fabric characterization. Through the touch and feel of fabric and with little experience, people can gain information that no other testing technique could fully yield. When fabric hand is compared with other subjective means such as vision, it is always found that the sense of touch has better ability to discriminate and recognize complex stimulus patterns than the visual system does. This is because human skin has a remarkable ability to detect even the slightest touch and any point on the human body can cause a sensation of touch. The primary human organ used for touch is the human hand, a very powerful organ which performs several sensory mechanisms supported by over 17,000 nerve endings that are sensitive to non-noxious mechanical deformation of the skin in the glabrous skin of one hand.

In general, the term 'fabric hand' describes the way a fabric feels when it is touched and manipulated by hand. It is an action noun that implies evaluation of fabric reaction to different modes of low-stress deformation imposed by the human hand. A more general term that is commonly used in the industry is 'fabric handle'. This is an action verb that reflects the evaluation of fabric reaction to different modes of deformation at all levels of applied stress (low or high). In this case, fabric handle may imply different handling actions such as touching, folding, cutting, transporting, sewing, and pressing. In this chapter, we will use the two terms alternately to imply an integrated evaluation of fabric 'manipulability', or the extent of ease of response of a fabric sample through applying a multiplicity of unnecessarily organized manipulative actions. Our interest in fabric 'hand' stems from its relationship with the comfort phenomenon.

The fascination with fabric hand by researchers and technologists in the field has been a result of two basic facts. First, it represents one of the most important initial attractions that draw people's attention to fabrics and garments in the marketplace. Secondly, a great deal of complexity is associated with characterizing it as a result of the multiplicity of interactive factors influencing it.

The issue of fabric hand is commonly addressed in view of two types of perceptions: an active perception resulting from an initiative taken by humans to actually touch and feel (handle) a piece of fabric by hand, and a passive perception resulting from wearing a garment and unintentionally feeling its interaction with the skin and body movement. The significance of distinguishing these two types of fabric hand is that the first one primarily leads to an initial judgment of how the fabric feels, which may influence the appeal and the purchasing decision of a fabric or garment. In this regard, the person handling the fabric typically attempts to characterize his or her perception of fabric hand. At this point, it is often the case that verbal descriptors do not fully reflect the actual perception. This point often creates a problem to researchers analyzing the correlations between subjective hand scaling results and objective hand parameters. On the other hand, the passive fabric hand reflects a true experience with the fabric or garment after a period of wearing experience. In this regard, the information is essentially imposed on the skin, and the wearer has some justification for his or her decision.

Most investigators rely on active hand in establishing correlations between subjective and objective means of fabric evaluation. This approach is simple and very practicable. In addition, it reveals good information, particularly when fabrics of extreme hand characteristics are being compared. However, irreproducibility and unreliability can be of major concern, particularly when fabrics of small hand differences are being compared or when an inappropriate control sample is used.

In this chapter, we summarize some of the developments in fabric hand evaluation and introduce a new technique developed by two of the present authors that has received wide acceptance among researchers and industrial organizations in the US. In addition, we present some interesting hand results for woven and knit fabrics.

3.2 Subjectivity and objectivity in fabric hand

The key question that has been addressed in most hand studies is 'what constitutes fabric hand?'. Despite the extensive research in the area, a universal answer to this question is yet to be fully established. Indeed, every study on fabric handle, including some of the most recent studies, seems to aim at addressing this question using particular fabrics. As a result, and despite the significant developments in the field, a universal quantitative measure of fabric hand has not yet entered the textile database.

The main reason why a universal answer to the question of 'what constitutes fabric hand?' has not been fully established lies in the fact that the subjective aspect of fabric hand represents the driving force toward characterizing this critical phenomenon. Indeed, it is commonly agreed that it is necessary to examine the subjective assessment of hand before examining its relationship to fabric mechanical and surface properties. Since there is no standard format of subjective evaluation, no standard answer is provided. Until such a format is established, research on the subject will continue and many more attempts to address this question will be made.

Standardizing subjective hand evaluation requires translating various personal judgment criteria into reliable characterization categories that reflect true global mutual communication about fabric quality. The fact that personal judgment is typically of a continuous nature calls for utilization of advanced analytical techniques such as fuzzy logic to establish realistic membership functions of fabric hand characterization. This approach will provide many advantages over the traditional discrete psychological scaling. However, standard descriptors must be established first. More critically, a universal quantitative measure of fabric hand should be considered as the basis for developing reliable fuzzy membership functions [1, 2].

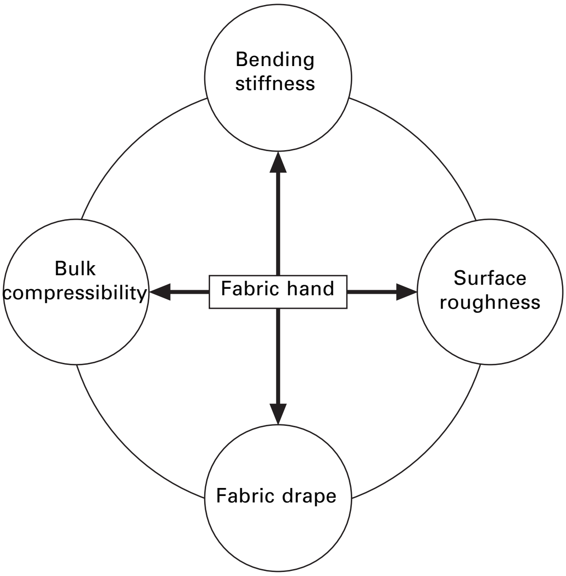
Perhaps the best and most acceptable answer to the question of what constitutes fabric hand was the one established by Peirce [3] in his classic paper in 1930. In this study, Peirce pointed out three basic determinants of fabric handle: bending stiffness, bulk compressibility, and surface friction. Fabric drape was added as another component of fabric hand by later studies. This is because it reflects the fabric's ability to conform to multiple curvatures. Figure 3.1 shows these components. Other parameters such as shear, crease recovery, and fabric thickness were also considered as determinants of fabric handle.

3.3 Developments in fabric hand objective evaluation

The interest in fabric hand (handle) has stimulated many researchers to develop objective ways for characterizing this important phenomenon. Our review of the different developments reveals two main categories of fabric hand (handle) evaluation systems:

- Indirect systems of fabric hand (handle) evaluation.
- Direct methods of fabric hand (handle) evaluation.

The difference between these two categories lies in the types of parameters produced by each category and their associated interpretations. Indirect systems do not characterize handle in a direct fashion. Instead, they produce instrumental parameters that are believed to represent basic determinants of fabric handle



3.1 Components of fabric hand.

such as fabric stiffness, fabric roughness, and compressibility. Only through parallel subjective assessment and cross-correlations are some parameters that are believed to simulate fabric handle estimated. The two common methods in this category are the Kawabata system (KES®) and the FAST (Fabric Assurance by Simple Testing) system. Direct methods of fabric hand (handle) evaluation represent creative techniques that are intended to simulate two or more aspects of hand evaluation and produce quantitative measures that are labeled as hand force or hand modulus. These methods include the ring method and the slot method. It should be pointed out that the term ‘direct’ does not necessarily mean more representative or more accurate in comparison with the indirect systems. These systems are discussed below.

3.3.1 Indirect handle evaluation systems: Kawabata and FAST

The Kawabata and FAST systems are commercial systems that are available in many fabric testing laboratories around the world. Reviews of these systems have been discussed in many papers [4–8]. Although the initial purposes of these systems were to replace subjective hand assessment with objective means, they relied heavily on subjective scaling to produce objective hand characteristics.

The Kawabata system is based on the general agreement that the stimuli leading to the psychological response to fabric handle are entirely determined by the physical and mechanical properties of fabrics [6, 7, 9]. In this regard, these properties are considered only at low loads and extensions and not at the level of load and extension at which fabric failure occurs.

In order to effectively use the Kawabata system, it is typically important to get experts to agree on what aspects of handle are important and the relative contribution of each aspect with respect to the fabric under consideration. In this regards, the Kawabata system establishes the so-called 'primary hand' as a measure characterized by properties such as stiffness, smoothness, fullness/softness, crispness, anti-drape stiffness, scrooping, flexibility with soft feeling, and soft touch. Given the fact that these descriptors may have interpretive differences, particularly when translated to other languages, Kawabata decided to use Japanese descriptors corresponding to these properties. In this regard, these properties were termed *Koshi*, *Numeri*, *Fukurami*, *Shari*, *Hari*, *Kishimi*, *Shinayakasa*, and *Sofutosa*, respectively.

Using the Kawabata system, the subjective assessment values of the primary hand properties are combined together to yield the so-called 'overall rating of fabric hand' of a given fabric category. This is achieved using empirical equations to yield the so-called 'total hand value', which is rated on a five-point scale where 5 is the best rating.

As can be seen from the above descriptors, the terms used exhibit a great deal of overlap and have their share of confusion. In addition, they are certain to be different from one fabric category to another. Indeed, it has been found [10] that there are differences between countries in their perception of what truly constitutes fabric handle with respect to a particular end use.

On the objective side, Kawabata developed a set of instruments to measure appropriate handle-related fabric properties. These include tensile and shearing, bending, compression, and surface friction and variation. The end result to assess fabric handle by the Kawabata system consists of a total of 16 objective mechanical and surface parameters measured all at low levels of force. These parameters are correlated with the subjective assessment of handle using linear regression equations.

It is important at this point to pay tribute and respect to the late Sueo Kawabata, who spent his life seeking objective ways of fabric evaluation and contributed immensely to this complex area. As I came to know him personally, he was a philosopher scientist and a pioneering thinker.

The FAST (Fabric Assurance by Simple Testing) system was designed with a more global view of fabric handle. It was developed by CSIRO for use by goods manufacturers to detect and diagnose problems associated with the process of conversion from fabric to garments. As a result, the system aims at distinguishing loosely constructed fabrics, which are easily deformable, from tightly constructed fabrics. The system consists of three instruments: compression meter, bending meter, and extension meter. The system also provides a method for measuring fabric dimensional stability.

One of the reasonable arguments against the above systems stems from the point that a phenomenon that can be characterized subjectively in a matter of minutes may take hours, if not days, to fully describe. This is particularly true in view of the time consumed to test, analyze, and interpret the results [10–13]. Another argument is associated with cost, which is considerable in view of price, labor, and the maintenance involved.

It is our opinion that the true merit of the Kawabata system is not necessarily in the subjective assessment of fabric handle, but rather in the objective means by which related parameters are instrumentally tested. The analytical approach to link subjective assessment with objective measures is not fully automated or systematic. In addition, there are great doubts associated with the use of multiple regression analysis to develop relationships that are essentially non-linear in nature. However, the systems can provide useful quantitative guidelines particularly in the area of fabric and garment design.

3.3.2 Direct handle evaluation systems: the ring and slot methods

The main purpose of developing direct handle evaluation methods was to provide quick and easy-to-use techniques to analyze fabric hand. The developers of these methods also claim that they are simulative since they are based on pulling a fabric sample through a ring (the ring method) or pushing a fabric sample through a slot (the slot method) and measure the resistances to the pull-through or push-through mechanisms. This in part simulates how a person tends to handle a piece of fabric when he or she is attempting to evaluate it.

As indicated above, the ring method is based on mechanically pulling a sample of fabric with pre-specified dimensions through a metallic ring. As simple as the method may seem, a great deal of argument about its source, and who initiated it, was apparent in the literature. Indeed, there were more arguments about the source of the method than its physical interpretation. With the principle being to measure the resistance to fabric pulling through a ring, different investigators used different sample shapes, sample dimensions and ring diameters [11–18]. Most investigators used circular fabric samples. But some used four radial cuts in addition to circular samples and compared the results to give better evaluation of the effect of the shear stiffness. Typical sample diameters used were 100 or 250 mm and typical ring diameters were 10 to 28 mm.

The key parameter typically obtained from the ring test is the maximum force required to pull the fabric through a ring. In addition, the initial slope of the profile obtained from a chart relating the force to the extraction distance was used as an index of the ease of pulling. In this regard, most studies indicated that the ease of pulling the fabric through the ring may vary depending on fabric variables such as yarn type, weave structure, finishes, and measurement conditions.

The slot method is another direct technique of handle evaluation in which a fabric, a paper, or a plastic film is pulled or pushed through a slot rather than a ring [19–24]. The slot or gap can be adjusted to any desired width between two plates. Examples of this method include the Handle-O-Meter, which was described in a TAPPI-proposed standard for 'softness' [23]. This tester operates with a blade on an arm which pushes the fabric into the slot. Because of the arm, this tester can be operated on-line, at least in principle. A similar test is the Handmeter which is a simple attachment for the Instron tester [24].

The fundamental difference between the ring and the slot test lies in the sample arrangement, which is essentially a 3-D arrangement in case of the ring method and a 2-D arrangement in case of the slot method. This makes interpretation of the slot test using the classic elasticity theory much easier than that of the 3-D ring test. The main parameter obtained from the slot test is the resultant resistance force on the center point of the fabric. The fabric weight and thickness are initially considered to be negligible. The initial slope of the load–deflection curve associated with the slot test was also used to indicate fabric stiffness or flexural rigidity. In addition, the ratio of maximum load to initial slope was used to indicate fabric friction.

3.4 The El Mogahzy–Kilinc hand method

As an integrated part of a larger study on fabric comfort [25, 26] sponsored by the National Textile Center of the USA, a new method of testing fabric hand was developed. This method is called the 'El Mogahzy–Kilinc hand method'. The underlying concept of this method was inspired by the theoretical and experimental efforts made by many of the previous outstanding investigations in the field. However, the method aims at overcoming many of the problems associated with statistical reproducibility and characterization parameters found in previous methods.

The El Mogahzy–Kilinc method shares some common features with previous direct methods including the methods of Grover *et al.* [13] and Alley and McHatton [29]. However, it exhibits distinct features in both the geometrical setup and the critical parameters produced. The uniqueness of this method stems from its simulative and interpretive capabilities. It is perhaps the first method that introduces a single hand index that reflects most of the constituents of fabric hand.

The main premises of the method are as follows:

- The issue of fabric hand is an issue of simulation and interpretation.
- A viable fabric hand evaluation technique should be reproducible and representative of the fabric being studied.

- A single fabric hand index that reflects most of the fundamental components of hand as established by Peirce and many other researchers will represent a major step toward incorporating fabric hand in the fabric quality database.
- The method should be inexpensive and very efficient (it takes only one minute to completely evaluate a fabric sample).

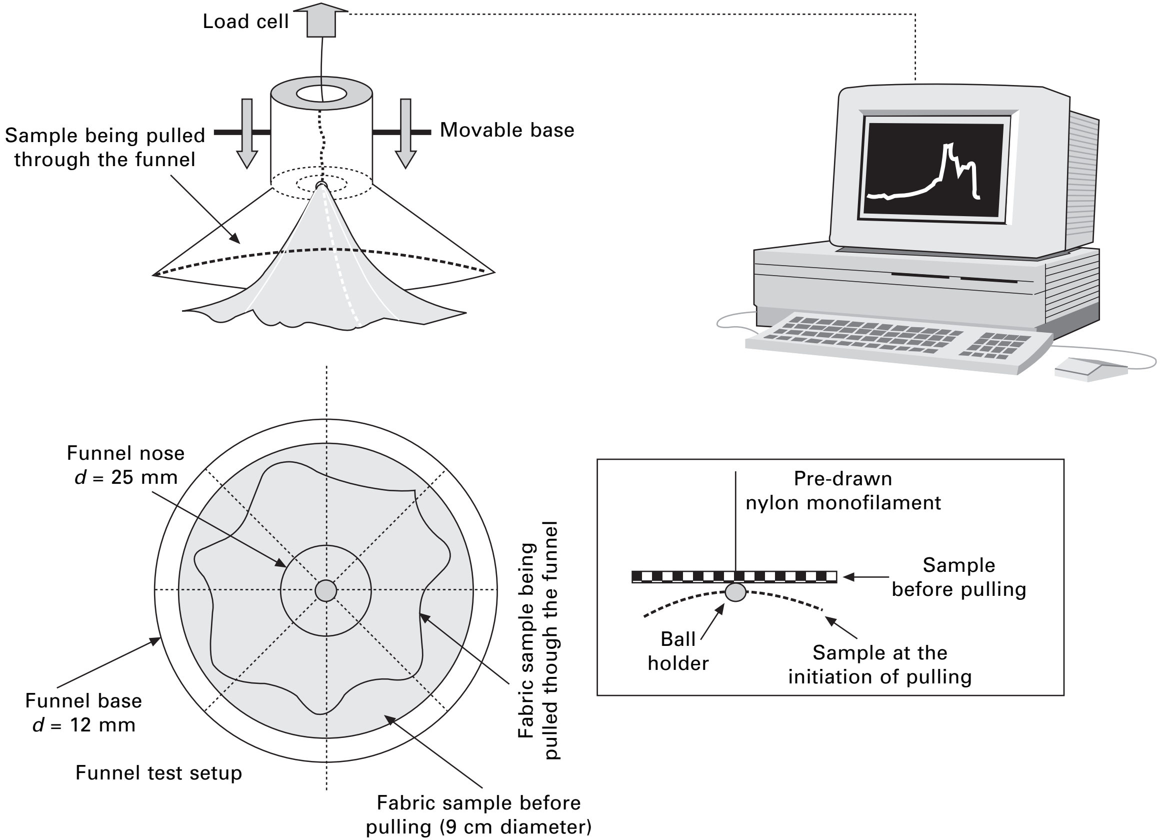
Figure 3.2 shows the basic components of the El Mogahzy–Kilinc hand method. A flexible light funnel is used to represent the medium through which the fabric sample is pulled. The idea of using a funnel medium instead of the ring or the slot arrangement is to provide better simulation of fabric hand. The contoured flexible surface of the light funnel simulates anticipated hand modes such as drapability, stretching, internal sample compression, lateral pressure, and surface friction. These modes are achieved both simultaneously and sequentially. In addition, the funnel medium allows both constrained and unconstrained fabric folding or unfolding, which simulates one of the mechanisms of fabric handle [25, 26].

Different funnel types and sizes can be used; however, funnel material should exhibit a great deal of flexibility (e.g. Teflon® plastic funnels). The funnel is rigidly suspended in a special horizontal attachment that is mounted rigidly on the movable head of the AU® mechanical tester. This machine was designed by El Mogahzy *et al.* [27, 28] for the purpose of performing low-deformation testing applications including tension, compression, stiffness, shear, and friction testing. The AU® mechanical tester is equipped with digital control and a host of software programs that allow monitoring, analyzing and profiling test results.

For the purpose of the hand test, fabric samples are cut circular at 9 cm diameter (smaller than the diameter of the funnel's wide base). However, the sample diameter may be changed if funnels of different dimensions are used as long as a ratio of 0.75 is maintained between the sample diameter and the base diameter. At this ratio, statistically reproducible results were obtained.

In general, as the movable head of the AU® mechanical tester moves downward, the funnel moves downward and the fabric sample is pulled through. During this process, the following sequence of sample behavior takes place:

- Initially, the sample is in a flat horizontal position.
- The initial downward movement of the funnel results in an upward movement of the fabric sample against its own weight and in a freely folding mode. Images taken of the sample at this initial step indicate an unconstrained folding leading to fabric drape. At this point, a very stiff sample will typically exhibit a simple one-dimensional folding similar to that of a piece of paper, and a flexible sample will exhibit multi-curvature drape.
- As the funnel continues to move downward, the sample begins to touch



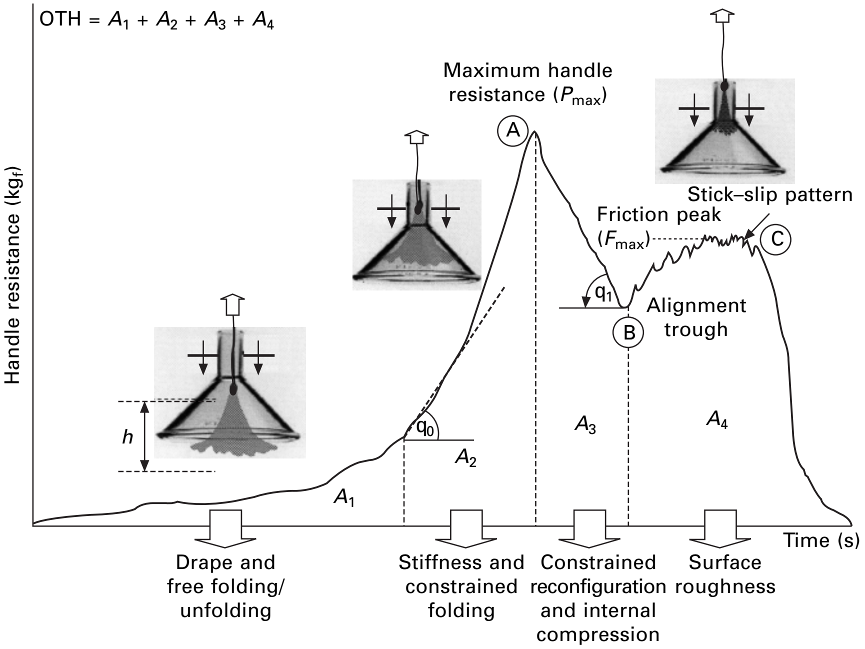
3.2 The El Mogahzy–Kilinc fabric hand method.

the inside wall of the conical part of the funnel at random points determined largely by the initial drape.

- The contact between the fabric sample and the inside wall of the conical part of the funnel initiates a constrained folding similar to that imposed by human hand compression of fabric during subjective evaluation. In addition, the conical shape of the funnel allows a great deal of reproducibility of this constrained folding. The extent of folding at this stage is largely determined by a combination of fabric stiffness and fabric inter-fold friction.
- As the sample attempts to enter the funnel's cylindrical nozzle, tension builds up as a result of a combination of stretching, compression, shear, and initial frictional effects. This tension reaches a peak at some point of the entering process at which the folded sample becomes aligned with the cylindrical nozzle of the funnel. At this point, the tension drops. The tension peak was found to typically occur when approximately two-thirds of the fabric length is inside the cylindrical nozzle. During this process, more constrained folding and surface reconfiguration is applied on the sample to accommodate its alignment with the cylindrical nozzle.
- The momentary tension drop lasts for about one to two seconds after which the tension begins to rise again. The extent of tension drop defined by the tension at the trough, or the difference between the peak tension and the trough tension, is expected to be largely a function of sample ease of reconfiguration, or fabric folding stiffness.
- Inside the cylindrical nozzle, the fabric sample undergoes internal compression, which depends on its folding status at the entrance point. In addition, sliding friction occurs between the points of the fabric that managed to remain on the surface during folding and the internal surface of the cylindrical nozzle. As a result, fabrics of different folding stiffness will exhibit different frictional stick–slip patterns. In addition, internal shear and elongation in the constrained sample is also expected, which increases with the increase in the length of the sample entering the cylindrical nozzle. As a result, another tension build-up occurs.
- The friction mechanism in the cylindrical nozzle is largely determined by the internal lateral pressure created by pressing the sample inside the nozzle and the extent of pre-folding. A stiff sample will result in high lateral pressure, and a flexible sample will result in low lateral pressure.
- The second tension build-up is typically smaller than the initial tension peak. However, for samples of extremely high folding resistance (stiff and rough samples), it can indeed exceed the first peak.
- As the fabric sample exits the cylindrical nozzle, a pressure release progressively occurs leading to a continuous reduction in tension. This pressure release results in internal stress relaxation, unfolding, and some form of crease recovery.

3.4.1 The hand profile

During the duration of the fabric pull through the funnel, a force–time profile is generated, termed the ‘hand profile’. For most apparel fabrics, this profile takes the common shape shown in Fig. 3.3. The hand profile can be divided into four primary zones identified by the areas under the curve A_1, A_2, A_3, and A_4.The first zone expands from the starting point of the test to the point at which the fabric touches the inside wall of the conical part of the funnel. This zone represents a simple case of lifting a flat rounded sample off the base. The area under the curve of this zone, A_1, primarily reflects the work done to lift the sample (mainly a function of fabric weight and the vertical distance, *h*, to the touch point). However, the shape of the curve at this zone was found to reflect the extent of uniformity of sample drape behavior. In most cases, a smooth initial rise of this zone curve was witnessed. However, fabrics that exhibited a great deal of unbalance or spirality were associated with clear irregularity in the initial curve.



3.3 El Mogahzy–Kilinc fabric hand profile.

The second zone of the handle profile begins at the moment the fabric touches the inside wall of the conical part of the funnel and ends at the point of maximum handle resistance (point A). It reflects a combination of stretching, compression, shear, bending stiffness, and fabric inter-fold friction. The maximum resistance (point A) and the slope, q_0, can be interpreted in a similar fashion to that used for the maximum handle peak and the handle modulus parameters considered in previous methods [13, 29]. In addition to these two parameters, we also considered the area under the curve of this zone, A_2. This area primarily reflects the work done to resist the constrained deflection and reconfiguration of the sample. Accordingly, this area is expected to be largely a function of a combination of stretching, compression, shear, bending stiffness, and fabric inter-fold friction.

The third zone of the handle profile begins at point A and ends at the point of tension trough (point B). The slope associated with the tension drop, q_1, as well as the tension trough (point B) quantitatively characterizes the ease of reconfiguration, or fabric folding (alignment) flexibility. The area under the curve of this zone, A_3, primarily reflects the work done in reconfiguring and aligning the fabric sample under lateral deflection.

The fourth zone of the hand profile begins at point B and ends at the end of the test duration period. This zone is characterized by two parameters, the peak resistance of this zone, F_{max}, termed the 'friction peak', and the area under the zone curve, A_4. As indicated earlier, this zone entirely reflects a friction process determined by the internal lateral pressure created by pressing the sample inside the nozzle and the extent of pre-folding. A stiff and rough sample will result in high lateral pressure and high friction. A flexible and smooth sample will result in low lateral pressure and low friction. The progressively increasing tension in this zone is associated with the increase in the sample length entering the cylindrical zone. As was also indicated, this peak is typically smaller than the initial tension peak (point A). However, for samples of extremely high folding resistance (stiff and rough samples), it can indeed exceed the first peak. In this regard, the difference between the two peaks ($P_{\text{max}} - F_{\text{max}}$) is a useful parameter for characterizing the overall manipulability of fabric under a combination of constrained folding and rubbing action. In this regard, a positive difference would indicate a stiff but smooth fabric, and a negative difference would indicate a flexible but rough sample.

3.4.2 Single fabric hand index

As indicated above, the hand profile reflects most possible deformational modes involved in a hand trial. In addition, each zone of the profile reflects a specific mechanism of fabric hand. This point is important particularly when an enhancement of a particular hand-related parameter is required in the process of fabric design. If the goal is to establish a single fabric hand index, the total area under the El Mogahzy–Kilinc hand profile will provide an excellent quantitative parameter. This parameter is termed the 'Objective Total Hand', or OTH, and it is the sum of the four areas discussed above.

Detailed studies in which this parameter was evaluated [25, 26] proved that it is highly correlated to subjective hand assessments of tens of woven and knit fabrics considered in these studies and it is highly related to the different objective parameters constituting fabric hand. Some of these results are presented below.

3.4.3 Some experimental results of fabric hand

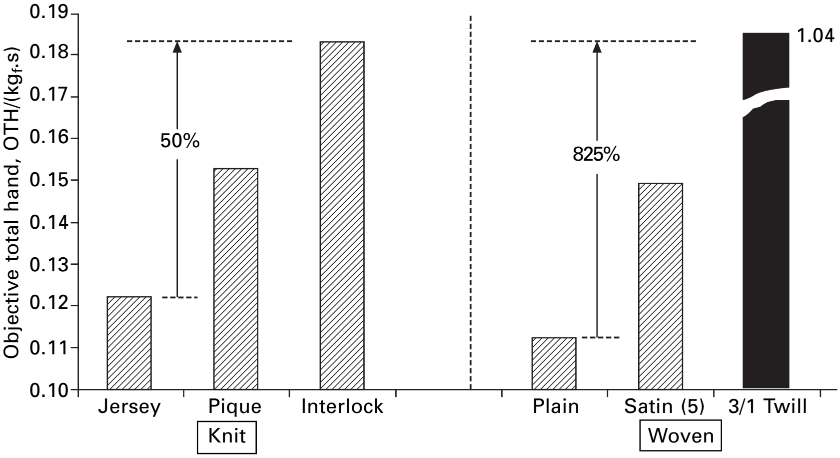
Merits of the hand test method discussed above were clearly realized from extensive testing of different fabrics. Some of the fabric types tested are listed in Table 3.1. These fabrics represent different fabric categories (woven and knit) and different patterns within each category. All fabrics were made from 100% cotton fibers.

Table 3.1 Average values of mechanical tactile parameters

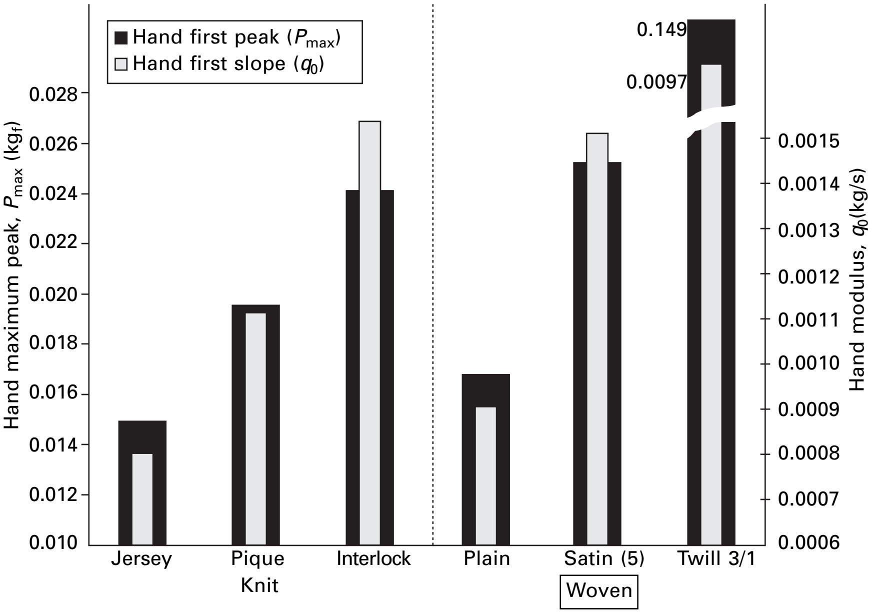
Fabric type	N_e (lengthwise)	N_e (widthwise)	Thread count (lengthwise)	Thread count (widthwise)	Fabric thickness (mm)	Fabric weight (g/m^2)
Plain	35	34	76	66	0.3048	104
Satin (5)	45	44	144	74	0.3302	124
3/1 Twill	7	20	79	65	0.705	290
Jersey	27	27	33	46	0.6215	157
Interlock	44	44	41	40	0.9400	177
Pique	26.5	26.5	26	40	0.793	193

Figures 3.4 and 3.5 show average values of some of the hand parameters described above for the different fabrics of Table 3.1. Among the woven fabrics, the twill fabric, which was made for durable heavy denim, exhibited the highest Objective Total Hand (OTH), the highest maximum peak, and the highest hand modulus. The plain weave, which represents lightweight dress shirt, exhibited the lowest OTH, the lowest maximum peak, and the lowest hand modulus.

Figure 3.6 shows the hand profiles produced for these two fabrics. The hand profile of the plain weave was enlarged (in a separate figure) to illustrate the details of the profile, which were masked by the high magnitude of the twill fabric. As can be seen in Fig. 3.6, the twill weave fabric required substantially higher hand force and hand work at different zones of the profile than the plain weave fabric. In addition, it exhibited a much higher resistance to hand, as demonstrated by the different slopes of the profile, than the plain weave sample. The hand profile of the plain weave sample also showed a tendency to exhibit an early drop in the hand resistance as illustrated by the dotted circles shown in the graph. This early drop is typically



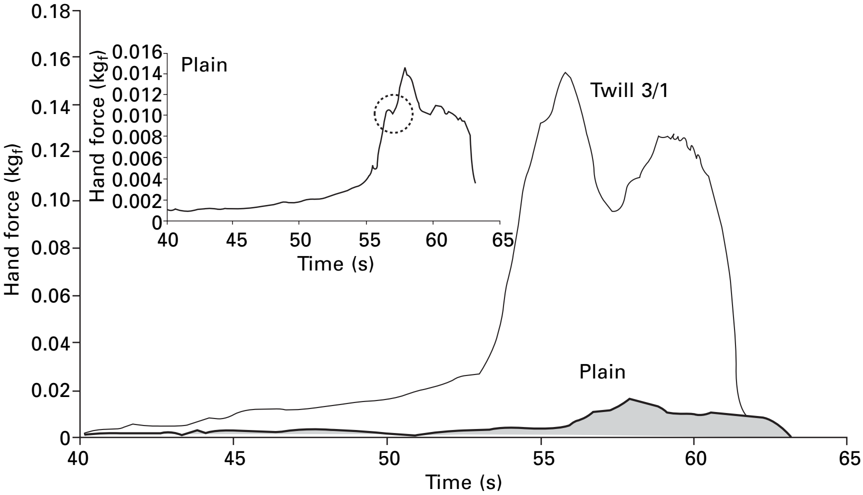
3.4 Objective total hand (OTH) of selected 100% cotton fabrics.



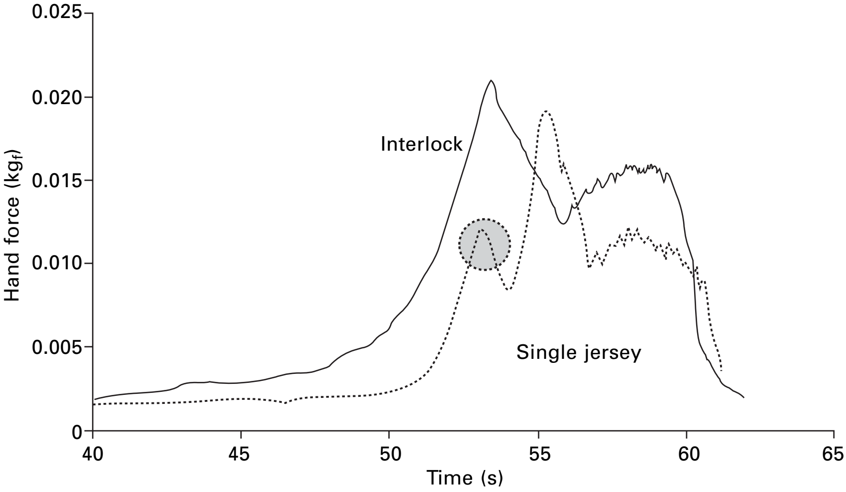
3.5 Hand peak and modulus of selected 100% cotton fabrics.

a result of a release in tension caused by some unfolding of the fabric at the transition stage from free folding to constrained folding.

Among the knit fabrics, Figs 3.4 and 3.5 clearly show that double-knit samples had higher total hand than the single-jersey sample. Figure 3.7 shows the hand profiles produced for the single-jersey and the interlock knit sample. As can be seen in this figure, the interlock double-knit sample required



3.6 Hand profiles of twill and plain weaves.

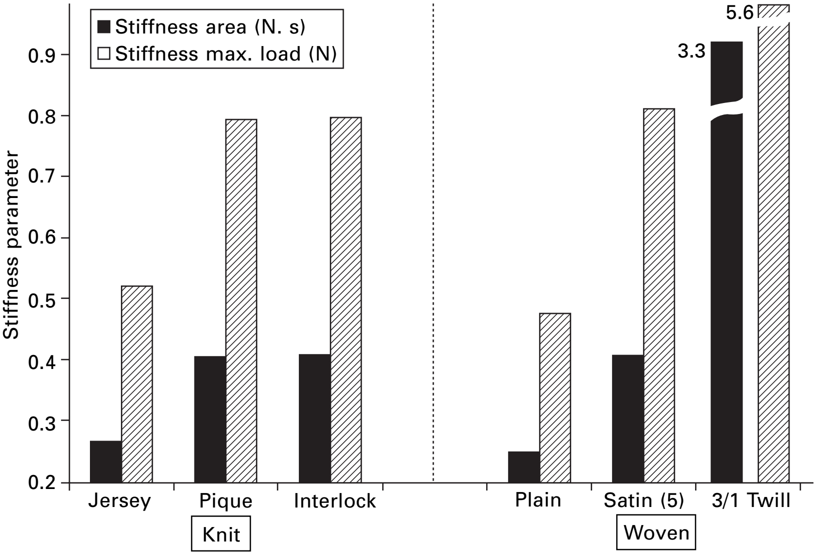


3.7 Hand profiles of jersey and interlock knits.

higher hand force and hand work at different zones of the profile than the single-jersey sample.

As indicated earlier, the El Mogahzy–Kilinc hand test method reflects most of the parameters constituting fabric hand. These include fabric stiffness, fabric drape, and fabric surface roughness. This point can be illustrated by examining the values of these parameters, tested independently, for the selected fabrics described in Table 3.1.

Figure 3.8 shows the values of fabric stiffness for these fabrics. Fabric



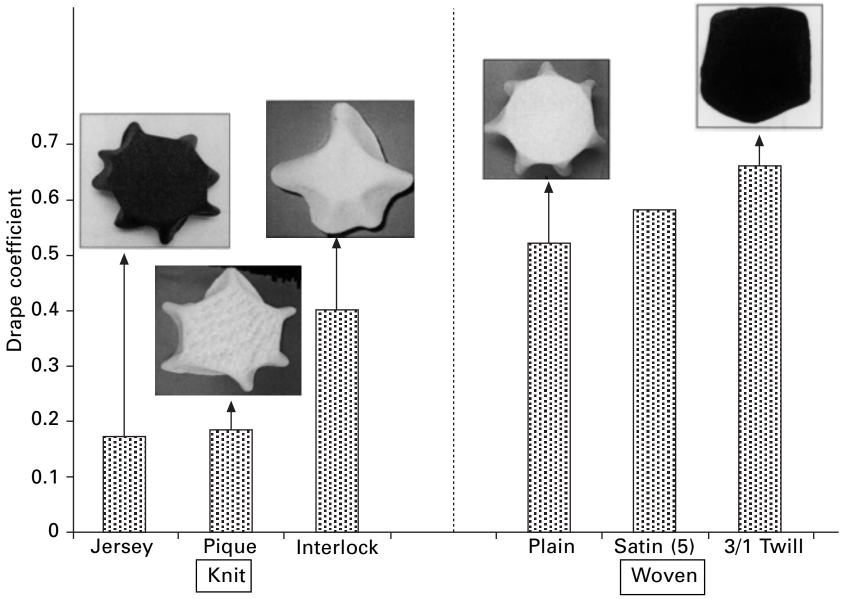
3.8 Stiffness area of selected 100% cotton fabrics.

stiffness was measured using ASTM D 4032–94 Standard Test Method for stiffness of fabric by the circular bend procedure. Additional effort was made to acquire the data during the test duration so that a stiffness profile can be obtained from which two basic measures can be determined: maximum stiffness load (newton), and the area (N.s) under the resistance force–time diagram (stiffness profile). These values reflect the ease of deformation under bending, which is a critical tactile comfort characteristic. This was made possible via the data acquisition program Labview.

As can be seen in Fig. 3.8, among the woven fabrics the twill weave sample exhibited the highest stiffness level and the plain weave sample exhibited the lowest stiffness. Among knit fabrics, the interlock double-knit sample had the highest stiffness and the single-jersey sample had the lowest. These results are in full agreement with the total hand results, the hand resistance values, and the hand modulus values of this set of fabrics.

Figure 3.9 shows the drape coefficient values of the same set of fabrics described in Table 3.1. As indicated earlier, drape is the term used to describe the way a fabric hangs down under its own weight in folds. It has an important bearing on how good a garment looks in use. In addition, it indicates the conformity of garments to body contours. In this study, we measured drape using the familiar BS5058 standard method in which drape is expressed by the so-called ‘drape coefficient’; the higher the drape coefficient, the lower the fabric drapability, or the lower the propensity to drape.

As can be seen in Fig. 3.9, knit fabric samples generally exhibited lower drape coefficients or higher propensity to drape than woven fabric samples.



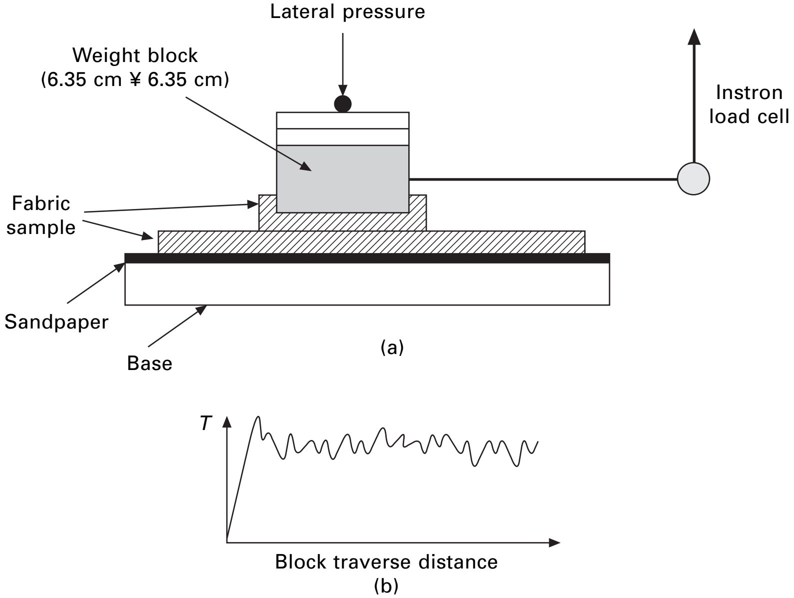
3.9 Drape coefficient of selected 100% cotton fabrics.

In general, it is well known that knitted fabrics are relatively floppy and garments made from them will tend to follow the body contours. Close examination of the values of drape coefficients of different fabrics will indicate a direct correspondence between these values and the initial area of the hand profiles.

Another important factor that contributes to the overall hand quality of fabric is surface roughness. This parameter was measured using geometrical surface image analysis and classic friction tests. In this chapter, we report the frictional results. Fabric friction was tested using the straightforward setup shown in Fig. 3.10 in which the apparent contact area is well defined. This method can be used for fabric-to-metal or fabric-to-fabric friction [25, 26].

The coefficient of friction, m, was determined from the classical law of friction, $F_A = m \cdot P$ (where F_A is the frictional force per unit area, and P is the lateral pressure). This law typically assumes that the coefficient of friction, m, is constant at all levels of lateral pressure and is independent of the area of contact. This assumption has been questioned in previous studies [e.g. 30, 31], and it was generally found to be inappropriate for materials deforming elastically or viscoelastically under lateral pressure. Fibers typically deform visco-elastically under lateral pressure. When the fibers are formed into fibrous structures or assemblies, the assumption of viscoelastic deformation should continue to hold as a result of the porous structure of fiber assemblies.

Many formulae have been developed to model the friction phenomenon



3.10 Sled friction method: (a) schematic of the friction device; (b) stick–slip profile.

of different materials. Gupta and El Mogahzy performed theoretical and experimental analyses aimed at evaluating different relationships between the frictional force F and the normal force N for fibrous materials [30, 31]. They concluded that the best expression that can characterize this relationship is:

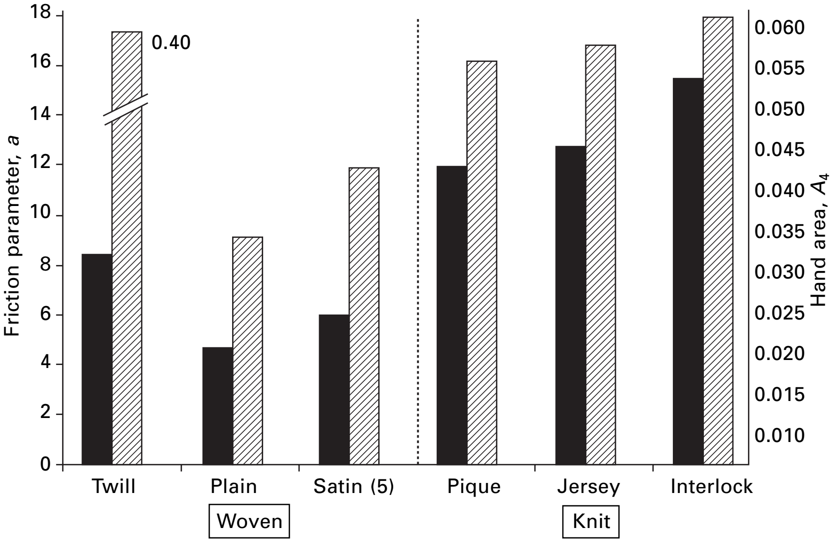
$$F_A = aP^n$$

The above relationship indicates that the frictional coefficient, defined by the ratio F/N, is not constant as suggested by the classic friction law. Instead, it is a function of the normal force, N, applied on the contacting area. This is revealed by the following equation:

$$\mu = \frac{F_A}{P} = aN^{n-1}$$

In this study, the parameters a and n were determined from the relationship between the coefficient of friction, as defined by the classical law ($\mu = F_A/P$), and the lateral pressure P.

Figure 3.11 illustrates the values of the friction parameter a and the hand area, A_4, for the different fabrics listed in Table 3.1. As can be seen in this figure, knit fabric samples generally exhibited higher a values (or higher friction) than woven fabric samples. The point of interest, however, is the relationship between the hand area A_4, which directly reflects the resistance



3.11 Fabric/sandpaper friction parameter *a* of selected 100% cotton fabrics.

to friction in the cylindrical nozzle zone, and the friction parameter *a*. This clearly indicates that the El Mogahzy–Kilinc hand test method is capable of detecting the mechanical hand effects associated with surface roughness.

We should point out that the El Mogahzy–Kilinc method has been used for evaluating fabrics of the same type under different treatments, including dyeing and finishing and washing treatments, and the results clearly showed its usefulness in design and performance enhancement applications [25, 26].

3.5 Conclusion

The phenomenon of fabric hand will continue to interest researchers in different sectors of the textile/apparel pipeline. The subjective nature of this important phenomenon will remain an essential aspect of research and implementation. This is primarily due to the critical importance of human judgment, which is highly variable and often psychologically driven. Unfortunately, subjective evaluation does not yield precise design guidelines except in extreme hand conditions. An objective hand evaluation coupled with subjective assessment seems to be the appropriate approach. In addition, a comprehensive database of hand parameters associated with human judgment scores will be very beneficial. We hope that this chapter will stimulate textile and apparel producers to establish a database of fabric hand of different products. Such a database will be extremely useful as we approach the era of complete Internet shopping in which little or no intimacy with fabrics will be involved in making purchasing decisions.

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4

Application of statistical methods in evaluation of fabric hand

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4.1 Introduction

The principles of textile production have been known for more than 6000 years. Over this long period manufacturing techniques have been optimized. However, the mechanisms affecting the psychophysical appearance of textiles leading to a pleasant feel during wearing are still not fully explained. One of the basic contact properties of textiles is 'hand'. The term 'hand' is difficult to define precisely. It relates to textile quality evaluation as one of the most important usability properties. It is possible to include hand among those subjective feelings evoked by measurable textile characteristics.

It is well known that hand plays an important role as the first characteristic encountered by the consumer. Evaluation is carried out by the consumer on the basis of his or her feeling of contact of the preceptors (fingers and palms) with the textile. With the development of new types of technologies and textile products, the objective characterization of hand becomes more important. The adoption of computer-oriented methods has led to the development of indirect but objective techniques for the prediction of subjective hand based on special regression models (multivariate calibration).

Multivariate calibration for subjective hand prediction is complicated, for the following reasons:

- Evaluation of subjective hand H_s is based on the categorization of respondent tactile sensation. The result is then an ordinal variable, and classical estimators of location (mean value) or variance cannot be directly used.
- Objective (measurable) properties (factors, regressors) connected with hand sensation $\boldsymbol{x} = (x_1, x_2, \ldots, x_m)$ are given in various scales and units. Their contribution to hand feeling is not direct but follows the stimulus response relation.
- Owing to strong interdependencies between regressors, regression-based models are often over-parameterized and the curse of multidimensionality appears.

- There are many methods for multivariate regression-type models predicting subjective hand based on assumptions about the characteristics of H_s. The classical least-squares method is frequently not optimal and more complex methods have to be used.

This chapter is devoted to a description of selected statistical methods capable of treating subjective hand data, checking the quality of potential regressors and creating prediction-type models. The techniques of univariate and multivariate data exploration are used for checking the assumptions about regressor (factor) distribution and dimension reduction.

The utilization of the well-known KES (Kawabata Evaluation System) for creation of regression-type models predicting the median subjective hand of protective fabrics is described. A set of properties correlated strongly with subjective hand is selected. A general methodology of subjective hand prediction based on mechanical and physical properties of textiles is proposed.

4.2 Subjective evaluation of fabric hand

Subjective hand is a result of the touching sensation and therefore is dependent on the mechanisms of human tactile sensation. The somatic senses are those nervous system mechanisms by which sensory information is collected from within the body. The somatic senses are classified in three groups:

1. Mechanoreceptors – stimulated by mechanical displacement of various tissues in the body.
2. Thermoreceptors – stimulated by temperature changes.
3. Nocioreceptors – representing the human pain sense.

The mechanoreceptors include the tactile sense, which includes touching pressure and vibration. The highest density of mechanoreceptors is in the glabrous skin on the palms and fingertips. Especially the thumb and index finger are used for tactile sensation.

Touch sensation results from stimulation of tactile sensors from the tissues immediately below the skin. The Meissner corpuscles and Merkels disks located in the upper layers of skin detect texture. These mechanoreceptors have spatial tactile stimulus. Hardness is identified by Pacinian corpuscles having temporal tactile stimulus. Light touch is detected by the free nerve endings having an amplitude of tactile stimulus [1]. Both these receptors are located deeper in the skin. Thermoreceptors are Rufini corpuscles, and receptors of coldness are Krause corpuscles.

Regarding tactile sensation there are rapidly reacting receptors (reaction time about a few hundred milliseconds) and two-phase reacting receptors (burst activity and then adaptation). The slowly adapting afferent receptors are Merkels disks and Rufini endings, and the rapidly adapting afferent receptors are Meissner and Pacinian corpuscles. The frequency range of these receptors is from 1 Hz (Merkels disks) to 500 Hz (Pacinian corpuscles).

Bolanowski [2] found that four distinct psychophysical channels contribute to tactation in the glabrous skin. From the sum of their complex responses humans can perceive and discriminate between textiles.

A detector's output R to a stimulus is a function of the product of its sensitivity S for that stimulus (the reciprocal of its threshold for the stimulus) and the stimulus intensity I [3]:

$$R = f\,(S \times I) \tag{4.1}$$

In the case of the transducer function, linearity gives $f = 1$ and $R = S \times I$.

The human observer's sensitivity to a stimulus is a nonlinear pooling of the sensitivities S_i of all detectors $i = 1, \ldots, m$:

$$S_{\mathrm{ob}} = k\sqrt{\sum_{i=1}^{m} S_i^k} \tag{4.2}$$

For sensitivities S_i, the following is often valid:

$$S_i(x) = \exp\left[-\left(\frac{|x - x_i|}{K}\right)^Q\right] \tag{4.3}$$

where x_i is the best physical value for the ith detector and x is the physical value of the stimulus. Parameter K determines the bandwidth, and for a rounded sensitivity function, $Q = 3$.

It is then clear that subjective hand sensing is a combination of various receptors responsible for feelings of texture, pressure, stretching, thermal feedback, dynamic deformation and vibration (acceleration).

It has been empirically found that *subjectively evaluated hand* is connected especially with fabric surface, mechanical and thermal properties [4]. The first attempt at hand evaluation of textiles was published in 1926 [5]. Two basic procedures for subjective hand evaluation were proposed [6]:

1. The **Direct method** is based on the principle of sorting of individual textiles according to a subjectively defined ordinal grade scale (e.g., 0 – very poor, 1 – sufficient, 5 – very good, 6 – excellent).
2. The **comparative method** is based on sorting of textiles according to subjective criteria of evaluation (e.g., ordering from the textiles with the most pleasant hand to the textiles with the worst hand).

A wide range of expressions (words) is connected with the term hand, e.g., smooth, full, bulky, stiff, warm, cool, sharp, etc. These expressions are used for denoting *primary hand* (see below) [7]. For prediction of hand using any subjective method, it is necessary to solve the following problems [8]:

- Choice of respondents
- Choice of grade scale
- Definition of semantics.

Choice of respondents

The method of choice of respondents has a very strong influence on the data obtained and therefore also on the results of hand evaluation. It is obvious that subjective evaluation is based on the quality of the sensorial receptors of the individual respondents. Results of evaluation are also dependent on the physical and psychological state of the respondents and the state of the environment. Experts and consumers often give different results because of their different points of view concerning particular textiles. These problems show that it is very difficult to maintain reproducibility, and the choice of respondents has to be strongly defined. Significant differences exist between men and women, too. Men evaluate hand usually closer to the centre of the grade scale compared to women. A special problem is the size of the respondent group. The minimum size for expressing consumer feeling is 25–30 people, and for looking for relations with objective characteristics it is more than 200 people.

Choice of grade scale

If paired comparison is not applied, it is possible to choose the grade scale according to the actual criteria and needs. The size of the grade scale varies from five to 99. The 99-grade scale is more suitable for experts handling fabrics. For consumers, a grade scale length from 5 to 11 is preferred as they have less sensitivity to very small differences. The five-grade Likert scale (categories: strongly unfavourable, unfavourable, neutral, favourable, strongly favourable) is widely used. Generally, the neighbourhood of the grade scale centre is more frequently used than the neighbourhoods of the scale ends.

Definition of semantics

Evaluation of total hand is not sufficient when more precise results are required. Then, it is suitable to introduce primary hand values. Primary hand values are connected with surface, thermal and geometric properties. The following polar pairs are very often used for expressing primary hand values:

- Rough–smooth
- Stiff–flexible
- Open–compact
- Cold–warm.

Paired comparison of several samples is often carried out and then the ranks are obtained. This method is highly suitable for statistical data processing, but is valid only for small sets of textiles.

Influence of surface appearance on subjective judgements

During subjective hand evaluation, visual inspection of samples can influence the final decision. In this section, unpublished findings obtained from evaluation of subjective hand with and without 'visual inspection' are presented. Twenty-eight fabrics for men's suiting were chosen for subjective appearance evaluation and subjective hand evaluation with and without visual inspection. To achieve reproducibility of hand evaluation, two groups of respondents were selected, the first of 92 respondents and the second of 160. The ratio of ages of respondents, and the ratio of men to women, were similar in the two groups.

Consumers were used as respondents. Each of them was precisely informed about what and how to judge. The second group carried out evaluation of hand without visual inspection and appearance evaluation as well. The second group judged one year after the first. The first group rated their findings on a five-grade scale and the second group on an 11-grade scale. For comparison between judgements, Spearman's rank correlation coefficient was applied. The correlation between results of both groups was high (Spearman's rank correlation coefficient was 0.89). It can be said that, if respondents are well informed, it is possible to achieve reproducibility. On other hand, the five-grade scale is less sensitive to differences in judgement and this lower sensitivity leads to a higher loss of information. Correlation between the two types of subjective hand evaluation (with and without visual inspection) was also high (Spearman's rank correlation coefficient was 0.98), indicating that the well-informed respondent is able to restrain visual perception even though the majority of the respondents remarked on its influence through pattern (colour of textile). The correlation between hand and appearance was weaker (Spearman's rank correlation coefficient was 0.52 with visual inspection and 0.47 without). The results indicate that for well-prepared respondents, it is possible to ensure reproducibility of data concerning hand evaluation. Hand can be judged with visual inspection by well-informed respondents.

4.2.1 Statistical analysis of overall subjective hand

In this section the statistical treatment of subjective hand judgements, based on the ordinal nature of data, is discussed [9, 10]. This approach is used for overall subjective hand judgements. There is no problem in using this methodology for primary hand values as well. Generally, for the case of a categorized variable, the population of all events is divided into the categories $c_1, \ldots, c_k$. A special case of the categorized variable is the ordinal variable

[10]. For the ordinal variable, the categories $c_1, \ldots, c_k$ are sorted according to the external criterion (hand). It is assumed that the first category is the worst and the last category is the best, i.e. the category c_{i+1} is better than c_i for all $i = 1, \ldots, k$.

Let a fabric hand H_S be subjectively evaluated by N respondents (judges, raters). Each respondent R_i selects one from the k categories $c_1, \ldots, c_k$. Primary data can then be collected in an N ¥ 1 table containing numbers from 1 to k only. For M fabrics the primary table is N ¥ M. Primary data for subjective hand of TAMA and GOLEM fabrics ($M = 2$) graded to the five categories by 10 selected respondents ($N = 10$) are given in Table 4.1 [11]. This table is extracted from the primary table obtained from 30 respondents. For simplicity, it is used subsequently in this chapter to demonstrate the computations.

Table 4.1 Primary data for subjective hand grading of two fabrics by 10 respondents

Fabric	Respondent									
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
TAMA	3	3	2	4	2	2	2	3	5	5
GOLEM	3	5	4	5	4	2	3	3	3	4

Let n_i respondents select the ith category, c_i. From the primary data table it is then simple to create a table of absolute frequencies for all categories having the general form (see Table 4.2). It is clear that $\overset{k}{\underset{i}{\text{S}}} n_i = N$. Absolute frequencies for the TAMA fabric example are given in Table 4.3.

Table 4.2 Absolute frequencies

Category	c_1	c_2	...	c_i	c_k
Overall grading	n_1	n_2	...	n_i	n_k

Table 4.3 Absolute frequencies of TAMA fabric

Category	c_1	c_2	c_3	c_4	c_5
Overall grading	0	4	3	1	2

Subjective hand H_S as a categorized (ordinal) variable can be modelled by the multinomial distribution $H_S \sim \text{Mult}\,(N, \boldsymbol{p})$ represented by the probability function [12]:

$$f(H_S, N, \boldsymbol{p}) = \frac{N!}{\prod_i n_i!} \times \prod_{i=1}^{k} p_i^{n_i} \tag{4.4}$$

The probability p_i is equal to the probability of selecting H_S to be in category c_i. For a full description of hand H_S, we need to know the vector of these probabilities, $\boldsymbol{p} = (p_1, p_2, \ldots, p_k)$. It is apparent that each category count n_i follows the binomial distribution $n_i \sim \text{bin}\,(N, p_i)$. Thus the expected value of the number of observations falling in the ith category is

$$E(n_i) = N \times p_i \tag{4.5}$$

while the variance is

$$V(n_i) = N \times p_i \times (1 - p_i) \tag{4.6}$$

Since the counts n_i must sum to N, they are negatively correlated with one another, and the correlation coefficient is given by

$$\text{corr}(n_i, n_j) = -\sqrt{\frac{p_i \times p_j}{(1 - p_i) \times (1 - p_j)}} \tag{4.7}$$

The estimators of p_i can be obtained by the maximization of the log likelihood function $L(\boldsymbol{p})$ which is simply equal to log $(f\,(H_S, N, \boldsymbol{p})$. [12, 13].

The maximum likelihood estimator of the probability of hand H_S falling in the ith category is the well-known frequency estimator

$$f_i = n_i/N \tag{4.8}$$

The approximate $100(1 - \alpha)\%$ confidence interval for p_i (sometimes called the Wald interval) is

$$f_i \pm u_{1-\alpha/2} \sqrt{f_i(1 - f_i)/N} \tag{4.9}$$

In this equation, $u_{1-\alpha/2}$ is the $(1 - \alpha/2)$ 100%th quantile of the standardized normal distribution. In most cases the 95% confidence intervals are created and then $\alpha = 0.05$, $(1 - \alpha/2) = 0.975$ and $u_{1-\alpha/2} = 1.98 \sim 2$.

A better confidence interval for the probability p_i based on the central limit theorem [1] has the form

$$f_i \left(\frac{N}{N + Z^2}\right) + 0.5 \left(\frac{Z^2}{N + Z^2}\right)$$

$$\pm \sqrt{\frac{f_i(1 - f_i)}{N} \times \frac{N^2 Z^2}{(N + Z^2)^2} + 0.25 \left[\frac{Z^4}{(N + Z^2)^2}\right]} \tag{4.10}$$

where $Z = u_{1-\alpha/2}$. Because the categories are ordered from the worst (c_1) to the best (c_k), it is possible to define cumulative probabilities

$$C_i = \sum_{j=1}^{i} p_i \qquad C_1 = p_1 \qquad C_k = 1 \tag{4.11}$$

Estimates of these probabilities are the cumulative frequencies F_i defined by the relations

$$F_i = \sum_{j=1}^{i} f_i \qquad F_1 = f_1 \qquad F_k = 1 \tag{4.12}$$

The value C_i denotes the probability of subjective hand H_S occurrence in all categories up to the *i*th. The estimators f_i and F_i for the TAMA fabric are given in Table 4.4.

Table 4.4 Frequencies and cumulative frequencies for TAMA fabric

Category	c_1	c_2	c_3	c_4	c_5
f_i	0	0.4	0.3	0.1	0.2
F_i	0	0.4	0.7	0.8	1
S_i	1	2	3	4	5
R_i	0	0.2	0.55	0.75	0.9

Due to the ordinal character of the data, it is not possible to use standard characteristics of location such as mean value and scale as variance, because of the absence of the metric. It is not possible to say that the difference between the best and the worst is a number, $k - 1$, or that the difference between adjacent categories is 1. Numbers in Table 4.1 are symbols only and can be simply replaced, e.g. by letters. The problem is that probably the majority of the published work dealing with subjective hand avoids this fact and uses standard analysis, as in the case of cardinal continuous variables.

Because of the way the cumulative probability function is constructed, it is possible to use as a location estimator the **median** Mh defined as the 50% dividing point, so that 50% of H_S values are below Mh and 50% of values are above Mh. First, the median category Me is defined by inequalities

$$F_{\mathrm{Me}-1} < 0.5 \text{ and } F_{\mathrm{Me}} \geq 0.5 \tag{4.13}$$

The sample-rating median of the ordinal variable has the form

$$\mathrm{Mh} = \mathrm{Me} + 0.5 - \frac{F_{\mathrm{Me}} - 0.5}{f_{\mathrm{Me}}} \tag{4.14}$$

For characterization of mean hand grade, the sample rating median *Mh* is suitable. The characteristic Mh is an estimator of the population-rating median Med.

Subjective hand variance can be characterized by the **discrete ordinal variance**, dorvar, defined as [10]

$$\text{dorvar} = 2\sum_{l=1}^{k}[F_l(1 - F_l)] \tag{4.15}$$

The maximum value of dorvar is $k - 1)/2$ for the case when one half of the values are equal to 1 and the other half to k.

For practical purposes it is necessary to know the confidence interval for the population median estimator Med. In order to obtain the $100(1 - \alpha)\%$ confidence interval for Med, the following procedure was proposed [10]:

1. Computation of two cumulative frequencies (F_D^*, F_H^*):

$$(F_D^*, F_H^*) = 0.5 + 0.5\left(\frac{u_{1-\alpha/2}}{\sqrt{N}}\right) \tag{4.16}$$

2. Evaluation of categories D and H containing cumulative frequencies (F_D^*, F_H^*). For these categories it has to be valid that

$$F_{D-1} < F_D^* \qquad F_D \geq F_D^* \quad \text{and} \qquad F_{H-1} < F_H^* \qquad F_H \geq F_H^*$$

3. Computation of correction terms:

$$d = \frac{F_D^* - F_{D-1}}{f_D} \qquad h = \frac{F_H^* - F_{H-1}}{f_H} \tag{4.17}$$

4. Creation of $100(1 - \alpha)\%$ confidence interval for Med $(D - 0.5 + d, H - 0.5 + h)$.

This simplified procedure is applicable for the case when $N > 30$.

As an example of the use of this approach to characterize subjective hand, let us compute the median Mh and corresponding confidence interval for the TAMA fabric. It can be seen from Table 4.3 that the median category is equal to Me = 3 (category c_3). Substituting this in eqn. (4.14) leads to the following result:

$$\text{Mh} = 3 + 0.5 - \frac{0.7 - 0.5}{0.3} = 2.83$$

The value of dorvar = 1.22 is computed directly from eqn. (4.15). For the case of the 95% confidence interval and 10 respondents, cumulative frequencies (F_D^*, F_H^*) computed from eqn. (4.16) are equal to (0.1837, 0.8162). The corresponding categories are $D = 2$ and $H = 5$. Substitution eqn. (4.17) leads to correction factors $d = 0.4592$ and $h = 0.081$. Then the 95% confidence interval for the median is bounded by values (1.959, 4.581). Owing to the very small number of respondents this interval is very wide.

The proposed confidence interval can be simply used for *testing the hypotheses* about the statistical significance of subjective hand differences between fabrics. If the 95% confidence intervals of the grading median for two fabrics do not intersect, there is a significant difference in subjective hand grading.

For prediction of subjective hand from indirect measurements, it is possible to use a properly scaled median Mh in the interval (0, 1) i.e. Mp = Mh/k, directly. The second possibility is to use experimentally determined absolute frequencies n_i, $i = 1, \ldots, k$, directly. In the latter case there are problems with non-constant variance and mutual correlations. To avoid these problems, some non-linear transformations are often proposed. The so-called **arcsin transform** has the form

$$y_i = \arcsin\left(\sqrt{\frac{n_i}{N+1}}\right) + \arcsin\left(\sqrt{\frac{n_i+1}{N+1}}\right) \tag{4.18}$$

For higher N, the transformed variable y_i is approximately normally distributed with variance

$$D(y_i) = \frac{1}{N+0.5} \tag{4.19}$$

The empirical **logit transform** has the form

$$y_i = \ln\left(\frac{n_i + 0.5}{N - n_i + 0.5}\right) \tag{4.20}$$

The transformed variable y_i has estimator of variance

$$D(y_i) = \frac{(N+1)(n_i+1)}{N(n_i+1)(N-n_i+1)} \tag{4.21}$$

Some transformations are useful for conversion of categorical responses to numerical ones with the aim of converting a problem with ordinal data to a simpler problem with categorized cardinal data. The simplest possibility is to score the categories as the natural integers 1, 2, 3, …, k or a more suitable monotonic transformation of them. Yates [14] suggested the score for the ith category in the form

$$S_i = (2i - k - 1)/2 \quad i = 1, \ldots, k \tag{4.22}$$

The variable S_i is assumed to be continuous in the interval $[(-(k-1)/2, (k-1)/2]$. In some cases it is useful to use monotonic transformation in the interval (0, 1).

Scores are continuous representative values for categories, and the corresponding weights are f_i. Therefore the classical parametric procedures can be used. For example, the mean is equal to [15]

$$x_S = \sum_{j=1}^{k} S_j f_j \tag{4.23}$$

and the standard deviation is

$$s_S = \sqrt{\sum_{j=1}^{k} f_j s_j^2 - x_S^2} \tag{4.24}$$

The $100(1 - \alpha)\%$ confidence interval of the population mean is given by the well-known relation [15]

$$x_S \pm u_{1-\alpha/2} \times \frac{s_S}{\sqrt{N}} \tag{4.25}$$

where $u_{1-\alpha/2}$ is the quantile of standardized normal distribution as expressed before. For the TAMA fabric, natural scores and ridits (see below) are given in Table 4.4. The mean value is $x_S = 3.1$, the standard deviation is $s_S = 1.1358$, and the 95% confidence interval has bounds (2.381, 3.818). This interval is narrower than the interval for the grading median. Besides the fact that cardinalization by specifying scores is useful for some purposes, the narrower interval leads to avoiding the nature of categories and often offers too rough estimators. On the other hand, it is possible to use analysis of variance (ANOVA) and regression analysis in a very straightforward manner [14].

The very popular **ridit transformation** is defined as

$$R_i = F_{i-1} + 0.5f_i \tag{4.26}$$

For higher N, the transformed variable R_i is approximately normally distributed. **Ridits** are continuous variables defined in the interval (0, 1). Ridits are applicable to the situation when the goal is to compare a reference group with a treated group (e.g. finished and greige fabrics) [16].

It has been proved [17] that applying parametric procedures to ordered categorical data scored by the natural numbers is nothing more than using the ridit approach with the uniform distribution as a reference distribution.

The shifted version of the ridit transformation is the so-called **pridit** and is defined as

$$\mathrm{PR}_i = \sum_{j<i} f_j - \sum_{j>i} f_j \tag{4.27}$$

Pridits are continuous in the interval (–1, 1).

4.2.2 Evaluation of expert ratings quality

Quality of respondents (observers) is a key assumption for subjective hand evaluation. In practice there exist many techniques to facilitate subjective hand rating. One of the best is to use standards for each category and compare an unknown fabric with these standards. The aim of statistical analysis is to compare inter-respondent agreement [18]. Let us have, for simplicity, only two respondents. In this case the primary data in the form of an M ¥ 2 table contains numbers from 1 to k. Assume that the fabrics are randomly selected from the huge population of fabrics targeted for the same utilization area. For further treatment this table is converted to a k ¥ k contingency table. In case of $k = 3$ categories the contingency table is shown in Table 4.5. Let A_i be a situation when respondent A selected category i and B_j be a situation when respondent B selected category j. The absolute frequency n_{ij} is equal to the number of cases when respondent A classified some fabrics in category i and respondent B classified the same fabrics in category j. The corresponding probability p_{ij} is estimated as the relative frequency f_{ij} defined as $f_{ij} = n_{ij}/n_c$.

Table 4.5 Contingency table for two respondents and three categories

	B_1	B_2	B_3	Subtotal
A_1	n_{11}	n_{12}	n_{13}	n_{r1}
A_2	n_{21}	n_{22}	n_{23}	n_{r2}
A_3	n_{31}	n_{32}	n_{33}	n_{r3}
Subtotal	n_{s1}	n_{s2}	n_{s3}	n_c

The symbol n_{ri} denotes the number of cases when respondent A classified fabrics in the selected category i and n_{sj} is the number of cases when respondent B classified fabrics in category j. The corresponding marginal probabilities are p_{ri} and p_{sj} estimated as relative frequencies $f_{ri} = n_{ri}/n_c$ and $f_{sj} = n_{sj}/n_c$. The value of n_c is equal to number of fabrics M. In addition to these probabilities, the so-called conditional probabilities can be computed as well. For example, the probability that respondent B classified a fabric in category j under the condition that respondent A classified the fabric in category i is $p_{j/i}$ estimated as $f_{j/i} = n_{ij}/n_{ri}$. From the elements of probability it is known that respondent A is independent of respondent B (total disagreement) in cases when:

- Conditional probabilities $p_{j/i}$ are independent of the conditions (i), i.e.

  $$p_{j/i} = p_{j/l} \qquad i, l = 1, \ldots, k$$

- Conditional probabilities $p_{j/i}$ are equal to marginal probabilities: $p_{j/i} = p_{s/j}$
- The 'joint' probabilities p_{ij} are the products of marginal probabilities: $p_{ij} = p_{ri}p_{sj}$.

For practical purposes it is better to characterize agreement between raters as the degree of overall satisfaction of classification. A simple way is to use suitable scores for all categories and then calculate the classical correlation coefficient. Let us assume that categories A_i have scores d_i ($d_i < d_{i+1}$) and categories B_j have scores e_i ($e_i < e_{i+1}$). Correlation between observers A and B is then expressed in the form [15]

$$r = \frac{\sum_{i,j} d_i e_j n_{ij} - \left(\sum_i d_i n_{ri}\right)\left(\sum_j e_j n_{sj}\right)}{\sqrt{\left(\sum_i d_i^2 n_{ri} - q_r^2\right)\left(\sum_j e_j^2 n_{sj} - q_s^2\right)}} \tag{4.28}$$

where $q_r = \left(\sum_i d_i n_{ri}\right) \Big/ n_c$ and $q_s = \left(\sum_j e_j n_{sj}\right) \Big/ n_c$.

The test statistic MH = $(n_c - 1)r^2$ has a $\chi^2(1)$ distribution. The MH is known as the Mantel-Haenzsel test statistic. It is possible to choose integers, i.e. $d_i = i$, $i = 1, \dots, k$ and $e_j = j$, $j = 1, \dots, k$, as suitable scores. Another possibility is ridits or the so-called midranks defined by the relations

$$d_i = \sum_{l<i} n_{rl} + (n_{ri} + 1)/2 \qquad e_j = \sum_{l<j} n_{sl} + (n_{sj} + 1)/2 \tag{4.29}$$

In the case of nominal categories (this is not valid for hand categories) the agreement between two respondents A and B characterized by the Cohen kappa coefficient K_e is defined as

$$K_e = \frac{P_o - P_e}{1 - P_e} \tag{4.30}$$

where $P_o = \sum_{j=1}^{k} f_{jj}$ and $P_e = \sum_{j=1}^{k} f_{rj} f_{sj}$. The justification for this coefficient is described in [19]. The range of K_e is $-\infty < K_e \le 1$. The smallest possible value of K_e is equal to K_s where

$$K_s = 1 - \frac{n_c}{n_c - \sum_i f_{ii}} \tag{4.31}$$

The value of K_e is equal to zero if the probability of agreement is identical to the expected probability for independent raters (the case of complete disagreement between respondents). The relation $K_c = 1$ is valid only if the probability of disagreement is equal to zero (the case of complete agreement between respondents). Asymptotic variance of the kappa coefficient is estimated by the following relation:

$$D(K_e) \approx \frac{A + B - C}{n_c (1 - P_e)^2} \tag{4.32}$$

where

$$A = \sum_{j=1}^{k} f_{jj} [1 - (f_{rj} + f_{sj})(1 - K_e)]^2$$

$$B = (1 - K_e)^2 \sum_i \sum_{j \neq i} f_{ij} (f_{si} + f_{rj})^2 \tag{4.33}$$

and

$$C = [K_e - P_e(1 - K_e)]^2 \tag{4.34}$$

The 100(1 – α)% confidence limit for Cohen's kappa coefficient population has the form

$$K_e \pm u_{1-\alpha/2}\sqrt{D(K_e)} \tag{4.35}$$

For ordinal variables as in the case of subjective hand evaluation, it is necessary to introduce weights w_{ij} to allow each (i, j) cell to be weighted according to the degree of agreement between the ith and jth categories. Assigning weights $0 \le w_{ij} \le 1$ and $w_{ii} = 1$, Cohen's weighted kappa K_w can be defined by the following relation:

$$K_w = \frac{P_o(w) - P_e(w)}{1 - P_e(w)} \tag{4.36}$$

where $P_o(w) = \sum_i^k \sum_{j=1}^k w_{ij} f_{ij}$ and $P_e(w) = \sum_{i=1}^k \sum_{j=1}^k w_{ij} f_{ri} f_{sj}$.

In the case of integer scores it is useful to select weights according to the scheme [20]:

$$w_{ij} = 1 - \frac{(i-j)^2}{(k-1)^2} \tag{4.37}$$

After substituting eqn. (4.37) into eqn. (4.36), the weighted kappa reduces to the following form:

$$K_w = 1 - \frac{\sum_i \sum_{j=1}^k (i-j)^2 n_{ij}}{(1/n_c)\sum_i \sum_j n_{ri} n_{sj} (i-j)^2} \tag{4.38}$$

This form of K_w is equivalent to the concordance correlation coefficient used to measure the agreement between two continuous variables. The following relation defines the variance of K_w:

$$D(K_w) \approx \frac{\sum_i \sum_j f_{ij}[w_{ij} - (w_{ri} + w_{sj})(1 - K_w)]^2 - [K_w - P_e(w)(1 - K_w)]^2}{n_c[1 - P_e(w)]^2} \tag{4.39}$$

where

$$w_{ri} = \sum_j f_{sj} w_{ij} \quad \text{and} \quad w_{sj} = \sum_i f_{ri} w_{ij} \tag{4.40}$$

The 100(1 – α)% confidence limit for Cohen's weighted kappa coefficient population has the form

$$K_w \pm u_{1-\alpha/2}\sqrt{D(K_w)} \tag{4.41}$$

The coefficients K_w can also be defined in the case of multiple respondents [19].

Danoch and McCloud [18, 20] proposed an alternative coefficient:

$$D = 1 - \frac{2}{k(k-1)}\sum_{j=1}^{k-1}\sum_{l=j+1}^{k}\frac{f_{jl}\,f_{lj}}{f_{jj}\,f_{ll}} \tag{4.42}$$

The relation $D = 1$ is valid if all pairs of categories are completely distinguishable (total agreement) and $D = 0$ is valid in the case of independence (total disagreement), i.e. $p_{jl} = p_{rj}p_{sl}$.

In practice it is interesting to know respondents' bias as well. Bias refers to the tendency of a respondent to make ratings generally higher or lower than those of other respondents. Respondent bias for the ith respondent can be assessed by calculating the mean rating B_{Ri} of a respondent for all fabrics. For computation of the mean value B_{Ri} it is simple to define scores S_j for each category and use eqns (4.23) and (4.24) where f_j corresponds to the relative frequency of the selection for subjective hand rating the jth category by the ith respondent. High or low B_{Ri} relative to mean rating of all respondents $B_R = \left(\sum_i B_{Ri}\right)\Big/N$ indicates positive or negative respondent bias. This task is formally equal to identification of outliers in the case of a univariate sample. The sample is here composed of values B_{Ri}, $i = 1, \ldots, N$. Because there are B_{Ri} mean values, it is possible to assume normality. There are many different techniques for identifying outliers when a normal distribution of data can be assumed. One of the simplest and most efficient methods seems to be Hoaglin's modification of inner bounds I_{L}^{*} and I_{U}^{*} defined by relations

$$\begin{aligned} I_{\mathrm{L}}^{*} &= B_{R0.25} - K_{\mathrm{I}}(B_{R0.75} - B_{R0.25}) \\ I_{\mathrm{U}}^{*} &= B_{R0.75} + K_1(B_{R0.75} - B_{R0.25}) \end{aligned} \tag{4.43}$$

where $B_{R0.75}$ and $B_{R0.25}$ are upper and lower quartiles computed from sample B_{Ri}, $i = 1, \ldots, N$. The value of parameter K_1 is selected such that the probability $P(N, K_1)$ that no observation from a sample of size N will lie outside the modified inner bounds $[I_{\mathrm{L}}^{*}, I_{\mathrm{U}}^{*}]$ is sufficiently high, for example $P(N, K_1) = 0.95$.

For $P(N, K_1) = 0.95$ and $8 \leq n \leq 100$, the following equation for calculation of K_1 can be used:

$$K_1 \approx 2.25 - 3.6/n \tag{4.44}$$

All respondents corresponding to B_{Ri} lying outside the modified inner bounds $[I_{\mathrm{L}}^{*}, I_{\mathrm{U}}^{*}]$ are considered to be biased. Another simple possibility is to use the ANOVA (analysis of variance) approach [19].

4.3 Analysis of factors affecting fabric hand

The subjective hand H_S (characterized by, e.g., the median Mh) is connected with various objectively measurable fabric properties. Peirce [21] identified a number of simply measured fabric properties such as bending length, flexural rigidity, hardness and compressibility that correlated well with subjective hand. Several other researchers proposed fabric properties suitable for subjective hand prediction [22–28]. The most widely known system for prediction of fabric hand is the Kawabata Evaluation System (KES) [7]. Kawabata's methodology assumes that fabric hand is derived from a combination of primary sensory factors such as softness, stiffness and roughness. A second assumption in Kawabata's approach is that the ultimate judgement of the hand of a fabric is dependent on the specification of the end use area. The unique feature of Kawabata's devices lies in their ability to measure fabric mechanical properties at small strains and to characterize energy loss in mechanical deformation and recovery processes.

Kawabata Evaluation System (KES)

Kawabata proposed a concept of the hand based on these hypotheses:

- One judges the hand mainly by the feel, which comes from the mechanical properties of the fabric.
- Criteria of hand judgement are based on whether or not the fabric possesses suitable properties for its use as a clothing material.

The KES systems of instrumentation for measuring the fundamental mechanical properties of fabric and the regression-type model for prediction of subjective hand are described in [7].

The properties being measured are grouped into seven blocks as follows: tensile, bending, shearing, compression, surface, weight, and thickness. The characteristic values that represent the property of each group have been decided so that the number of characteristic values should be as small as possible, but enough for expressing the property of its block sufficiently. These characteristics are collected in Table 4.6.

Details of the measurement principles, sample preparation and prediction of subjective hand are collected in [7]. Utilization of all 16 regressors (Table 4.6) for subjective hand prediction is often not necessary. Work done at NCSU using the Kawabata Evaluation System confirmed that the translations between subjective hand and fabric properties, measured using the KES, must be customized. The researchers proposed simple linear regression models for specific categories of woven or knitted fabrics:

- *Sheeting* [26]
  $\text{Hand} = 2.51 + 4.34 \log \text{WT} - 1.15 \log \text{MMD} + 1.31 \log \text{SMD} - 2.68 \log \text{W}$

Table 4.6 Basic properties for hand prediction

Property	Symbols		Characteristic value	Unit
Tensile	LT	x_1	Linearity	–
	WT	x_2	Tensile energy	gf.cm/cm^2
	RT	x_3	Resilience	%
Bending	B	x_4	Bending rigidity	gf.cm^2/cm
	2HB	x_5	Hysteresis	gf.cm^2/cm
Shearing	G	x_6	Shear stiffness	gf/cm.degree
	2HG	x_7	Hysteresis at ∅ = 0.50	gf/cm
	2HG5	x_8	Hysteresis at ∅ = 50	gf/cm
Compression	LC	x_9	Linearity	–
	WC	x_{10}	Compressional energy	gf.cm/cm^2
	RC	x_{11}	Resilience	%
Surface	MIU	x_{12}	Coefficient of friction	–
	MMD	x_{13}	Mean deviation of MIU	–
	SMD	x_{14}	Geometrical roughness	μm
Weight	W	x_{15}	Weight per unit area[a]	mg/cm^2
Thickness	T	x_{16}	Thickness at 0.5 gf/cm^2	mm

[a] Expressed in g/m^2 in our prediction equations.

Multiple correlation coefficient $R^2 = 0.98$

- *Men's suiting* [27]
  Hand = 7.87 – 14.61 LC + 0.02 RT
  Multiple correlation coefficient $R^2 = 0.97$
- *Single knits* [28]
  Hand = –8.4 + 20.9 MIU + 3.4 log W
  Multiple correlation coefficient $R^2 = 0.95$
- *Double knits* [28]
  Hand = –5.3 + 5.2 log SMD – 4.2 log B
  Multiple correlation coefficient $R^2 = 0.99$

(All symbols are explained in Table 4.6.) Subjective hand can therefore be predicted using simple linear regression models that incorporate as few as two KES measurements of properties [26–28]. The main problem is to select a suitable form of regression model and use good criteria for model quality evaluation. Another commercially proposed apparatus for evaluation of special properties connected with subjective hand is FAST [29].

Standard methods of measurements

There exist some attempts to replace KES measurements by the standard measurements in the same range of deformation. One of these systems was described by Raheel and Liu [30]. In the work of Militký and Bajzík [31], the prediction of subjective hand was made from eight objectively measurable characteristics selected from four basic groups of properties corresponding to the hand sensorial centres.

1. Fabric **surface roughness** is characterized by:
   - Coefficient of static friction $f_s \equiv x_6$ (dimensionless).
2. **Deformability** is characterized by:
   - Shear resistivity $G \equiv x_1$ (N)
   - Initial tensile modulus $Y \equiv x_8$ (MPa)
   - Stiffness $T \equiv x_7 (10^{-7}\ \mathrm{N\ m^{-2}})$.
3. **Bulk behaviour** is expressed by:
   - Area weight $T \equiv x_7$ ($\mathrm{gm^{-2}}$)
   - Compressibility $S \equiv x_5$ (dimensionless)
   - Thickness $t \equiv x_4$ (mm).
4. The **thermal part** of hand is characterized by:
   - Warm/cool feeling coefficient $b \equiv x_3$ ($\mathrm{W\ m^{-1}K^{-1}}$).

Generally, it is possible to select numerous other properties **x** connected with subjective hand. Before making any predictive model, H_S = function (**x**), it is necessary to solve the following tasks:

- Inspection of individual factors (regressors) x_i, $i = 1, \ldots, m$, of quality with an aim of avoiding problems with outliers and spurious distributions
- Exploration of all variables **x** with an aim of dimensionality reduction, clustering, etc.
- Selection of suitable stimulus – response transformation.

Typically, inputs are m variables measured on the n various fabrics arranged in a matrix:

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{4.45}$$

Each element of this matrix is often the result of some repeated measurements. To demonstrate some statistical techniques, the data obtained from KES for 30 protective fabrics are used. Details of fabric manufacture and primary data are reported in [32]. For univariate data the resilience x_3 is used.

4.3.1 Response stimulus transformation

The objective properties **x** connected with hand are in various units and their contributions to tactile sensation follow the psychophysical rules [3, 33, 34]. Let the **stimulus** intensity I be expressed by the value of the measured variable x, and the **response** R corresponds to the tactile sensation.

Fechner derived that the sensation magnitude differential dR is connected with stimuli level I and just noticeable difference dI:

$$\mathrm{d}R = c \times \frac{\mathrm{d}I}{I} \tag{4.46}$$

Integration of eqn. (4.46) between I_o (absolute threshold) and I yields the so-called 'massformel':

$$R = c \ln \left(\frac{I}{I_o} \right) \tag{4.47}$$

Equation (4.47) is known as the Weber–Fechner psychophysical law. A Weber-Fechner type logarithmic transformation has often been used for treatment of hand results and creation of predictive models [25, 35, 36].

Guilford proposed that dI is proportional to I raised to the power d [33]:

$$\mathrm{d}I = c \times I^d \tag{4.48}$$

For $d = 1$ the Guilford law reduces to the Weber–Fechner law, and for $d = 0.5$ the Fullerton–Cattel law results.

Norwich entropy theory of perception is based on the assumption that more intensive stimuli contain more information (psychophysical entropy E). Sensation R is directly proportional to entropy [33]:

$$R = kE = k \ln(1 + k_1/I^c) \tag{4.49}$$

An alternative way to derive eqn. (4.46) is based on Link's wave theory of sensation. According to this theory, perception of an external stimulus is originated at the body surface by the quantized action of sensory receptors. The Poisson process models this situation. The output of the Poisson process is a similarity transformation of the intensity of the stimulus [33].

Based on the experimental evidence, Stevens proposed the following power function:

$$R = kI^d \tag{4.50}$$

The exponent d varies from much smaller (e.g. $d = 0.33$ for eye) to much greater than unity (intensity of electric current delivered to finger). In the work of Elder *et al.* [37], the Harper Stevens model

$$\log R = (1/b) \log (a + b \log I) + c \tag{4.51}$$

was used for modelling the stiffness psychophysical scale.

It is clear that the majority of these relations show non-linear stimulus–response dependence. Based on these models, the variable x is often replaced by the logarithmic transformation $\ln x$. As is shown in section 4.3.5, the logarithmic transformation is optimal for data measured under conditions of relative error constancy as well.

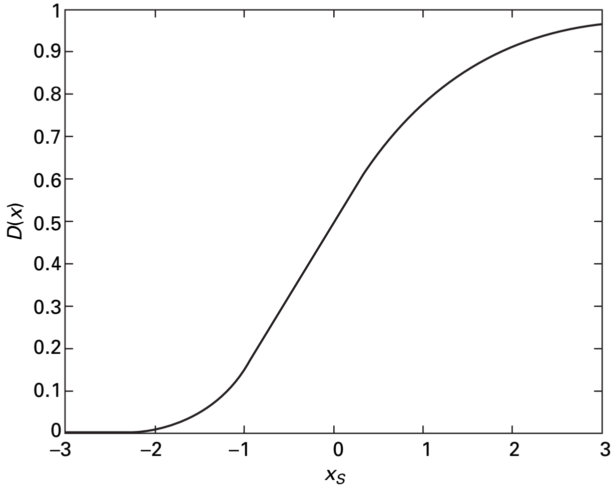
Instead of the stimulus-response relation an alternative possibility is to use the so-called concept of desirability proposed by Harrington [38]. For one-sided parameters, the Harrington function is defined by the relation

$$D(x) = \exp(-\exp(-x_S)) \tag{4.52}$$

where x_S is a properly scaled response of measurement x in physical units. One possibility is to use standardization:

$$x_S = \frac{x - \text{mean}(x)}{\sqrt{\text{variance}(x)}} + 0.3679 \tag{4.53}$$

The trace of the desirability function is given in Fig. 4.1. A better way is to use the knowledge about the just desirable and just undesirable values of x [38].



4.1 Harrington desirability function.

This concept is widely used in situations where it is necessary to combine various characteristics (properties) that have different units and different scales. The Harrington function allows converting physical parameters to the psychological scale of desirability. Desirability is defined in the range (0, 1) and corresponds to the interpretation given in Table 4.7.

The overall desirability function D for n properties is simply the weighted geometric mean of all $D(x_i)$:

Table 4.7 Harrington desirability interpretation

Desirability	Value on scale
Very good	1.0–0.8
Good	0.8–0.63
Fair	0.63–0.37
Poor	0.37–0.2
Very poor	0.2–0

$$D = \prod_{i=1}^{n} D(x_i)^{w_i} = \exp\left(\sum_{i=1}^{n} w_i \ln\left(D(x_i)\right)\right) \tag{4.54}$$

The desirability function D is a combination of all properties and is clearly defined in the interval (0, 1).

4.3.2 Utilization of fuzzy variables

Fuzzy theory has been frequently applied to subjective evaluation based on linguistic terms. The technique of fuzzy set theory introduced by Zadeh [39] is suitable for analysis of linguistic variables. The application of the fuzzy variables approach to rating and ranking of multiple alternatives is described in the work of Baas and Kwakernaak [40]. Rong and Slater [41] used a technique of fuzzy comprehensive evaluation for the assessment of comfort. Raheel and Liu published an application of fuzzy comprehensive evaluation to subjective hand evaluation [42] and prediction of hand from some objective characteristics [30]. Recently an application of fuzzy logic for evaluation and prediction of subjective hand was described by Zeng and Koehl [43]. The neural fuzzy technique for prediction of primary and total hand values was described by Stylios and Cheng [44].

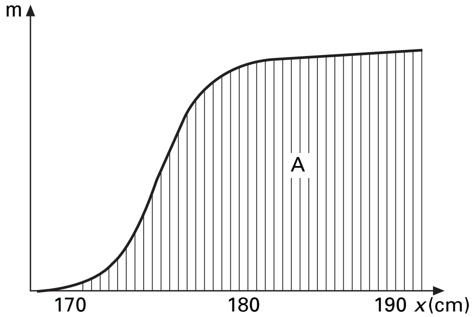
The main difference between the fuzzy approach and the probability approach to subjective hand evaluation based on the respondents' ratings lies in by the nature of primary data. The probability approach assumes that primary data are in fact ordinal random variables and statistical methods can be used for their treatment. The fuzzy approach is based on the concept of uncertainty, which is essentially not random but characterized by linguistic variables. Uncertainty is characterized by a membership function. Strictly speaking, the application of the fuzzy or probability approach is based on the technique of primary data retrieval. In the preceding paragraphs we used primary data H_S obtained from grading of subjective hand into prescribed categories. Typical data for fuzzy modelling are based on the degree of membership to some vague categories. In this paragraph, the main ideas of the fuzzy approach are described without giving details.

Fuzzy variables are characterized by numbers x_i and a membership function

m defined in the interval $0 £ m £ 1$. This membership function describes the degree to which x_i belongs to a prescribed set (category). If a higher x_i is an indication of a higher degree of reaching the given category (e.g. the category of tall people) then the typical membership function is sigmoid and growing. An example of this function is shown in Fig. 4.2. It can be approximated by the empirical expression

$$m(x) = 1 - \exp\,(-|x - a|^2)/b^2 \tag{4.55}$$

where a and b are parameters describing the shape of the function. The general shape of the membership function for linguistic variables when excessively small and large values are indicated to be outside the given category can be simply approximated by a trapezoidal function. For linguistic variables there exist elementary logic operations such as logical summation, multiplication, etc.



4.2 Membership function for linguistic variable 'tall person'.

The model of fuzzy comprehensive evaluation is based on the grading level set $F_1, \ldots, F_M$ that is principally the same as for classical subjective hand evaluation. The second is a group of factors U (U_1, U_m) equivalent to properties connected with subjective hand. The core of fuzzy evaluation is the construction of the $(m ¥ k)$ membership matrix **R**. The ith row R_i evaluates the contribution of factor i to the individual grading levels. Elements $R_{ij} = m(U_i, F_j)$ are membership functions of the contribution of factor i to the grading level F_j. For fuzzy comprehensive evaluation, for each factor it is necessary to define its relative importance characterized by the weight w_i, $i = 1, \ldots, m$. Let the weights be standardized, i.e. $w_i \geq 0$ and $Â\ w_i = 1$. The fuzzy evaluation is then transformation from the weighting vector **w** to the comprehensive grading vector **b** by using the fuzzy transformation matrix R. The appropriate fuzzy transformation is in the form

$$b_j = \underset{i=1}{\overset{m}{S}} w_i R_{ij} \quad j = 1, ^{\circ}, k \tag{4.56}$$

Raheel and Liu [30] used this approach to predict hand from five factors (mechanical properties), namely fabric weight, fabric thickness, flexural recovery, wrinkle recovery and 45° filling elongation. For each factor, the suitable membership function $\mu(x)$ has been selected. The hand value HV for the jth fabric was computed from the formula

$$\mathrm{HV}_j = \sum_{i=1}^{5} w_i \, \mu(x_{ij}) \tag{4.57}$$

where x_{ij} is the value of the ith factor for the jth fabric. Zeng and Koehl used a fuzzy controller to solve this task [43].

4.3.3 Exploration of univariate data quality

This chapter is devoted to exploration of individual variables potentially useful for prediction of subjective hand statistical peculiarities. Without loss of generality, the typical univariate sample x_i, $i = 1, \ldots, n$, is assumed. Here the index i corresponds to the individual fabric and then the sample corresponds to the ith column of the matrix shown in eqn. (4.45). The same approach can be used for treatment of data from repeated measurements on the same fabric. The differences between these tasks are given by the aim of analysis. For data from various fabrics, usability in the predictive regression model is the main goal. For repeated measurements, selection of the proper distribution for parameter estimation is needed. The system of exploratory data analysis based on the concept of quantile estimation can be used for both purposes [15].

From the classical statistical point of view, the analysis of measurement results leads to the identification of a probability model and the estimation of corresponding parameters. Due to the well-known fact that a lot of experimental data does not follow the normal distribution, the classical analysis based on the normality assumption cannot be automatically used. Frequently, textiles are strongly non-homogeneous and technological processes are influenced by many random events. The results of measurements are therefore often corrupted by the outliers (so-called dirty data). Techniques that allow isolating certain basic statistical features and patterns of data are collected under the name exploratory data analysis (EDA). According to Tukey [45], EDA is 'detective work'. It uses various descriptive and graphically oriented techniques as tools that are free of strict statistical assumptions. These techniques are based on the assumptions of the continuity and differentiability of underlying density only. The computationally assisted exploratory data analysis system is described in the book by Meloun *et al.* [15]. EDA techniques are one of the main parts of 'statistical methods mining', which is a collection of classical and modern parametric, non-parametric and function estimation methods for data treatment [46].

Some basic concepts

The EDA techniques for small and moderate samples are based on the so-called order statistics

$$x_{(1)} < x_{(2)} < \ldots < x_{(n)}$$

which are the sample values (assumed to be distinct) arranged in ascending order. Let $F_e(x)$ be the distribution function from which values x_i have been sampled. It is well known that the transformed random variable

$$z_{(i)} = F_e(x_{(i)}) \tag{4.58}$$

independently of the distribution function F_e follows the Beta distribution Be(i, $n - i + 1$). The corresponding mean value is

$$E(z_{(i)}) = \frac{i}{n+1} \tag{4.59}$$

where $E(.)$ is the operator of mathematical expectations. The elements V_{ij} of the covariance matrix $\boldsymbol{V}$ for all pairs $z_{(i)}$, $z_{(j)}$, i, $j = 1, \ldots, n$, are simple functions of i, j and N only. Using back transformations of $E(z_{(i)})$ the relation

$$E(x_{(i)}) = F_\text{e}^{-1}(z_{(i)}) = Q_\text{e}(P_i) \tag{4.60}$$

is obtained. In eqn. (4.60), $Q_\text{e}(P_i)$ denotes the quantile function and

$$P_i = \frac{i}{n+1} \tag{4.61}$$

is the cumulative probability.

Quantile function properties and their advantages for constructing empirical sample distributions are described in the papers of Parzen [46, 47]. From eqn. (4.60), it is obvious that the order statistic $x_{(i)}$ is a raw estimate of the quantile function $Q_e(P_i)$ in the position of P_i. For estimation of quantile $x_{(p)} = Q_e(P)$ at value $i/(n + 1) < P < (i + 1)/(n + 1)$ the piecewise linear interpolation

$$x_{(P)} = (n+1)\left(\frac{Pn + P - i}{n+1}\right)(x_{(i+1)} - x_{(i)}) + x_{(i)} \tag{4.62}$$

can be used. The interpolation (4.62) is useful for estimating sample quantiles x_{Pi} or x_{1-Pi} for $P_i = 2^{-i}$, $i = 1, \ldots, n$. These quantiles are called letter values [48]. All letter values except for $i = 1$ (median) are in pairs. For example, we can estimate lower quartile $x_{0.25}$ ($P_i = 0.25$) and upper quartile $x_{0.75}$ ($P_i = 0.75$), etc. Some proposals for definition of P_i are presented in Looney and Gulledge [49].

Checking of sample distribution

The most popular tool is the so-called quantile–quantile plot (Q–Q plot), having the quantiles $Q_s(P_i)$ along the x-axis and the order statistic $x_{(i)}$ along the y-axis.

Given a random sample, we often need to find whether the data can be regarded as a sample from a population with a given theoretical distribution. To look at the closeness of the sample distribution to a given theoretical distribution, the quantile–quantile plot (Q–Q plot) is suitable. The Q–Q plot allows comparison of the sample distribution being described by the empirical $Q_E(P_i)$ quantile function with the given theoretical one, with the theoretical $Q_T(P_i)$ quantile function. The empirical Q_E function is approximated by the sample order statistic $x_{(i)}$. If there is a close agreement between the sample and theoretical distributions, it must be true that

$$x_{(i)} \sim Q_T(P_i)$$

where P_i is the cumulative probability defined by eqn. (4.61).

When the empirical sample distribution is the same as the theoretical one, a straight line represents the resulting Q–Q plot. To construct this plot, the parameters of location and spread of the theoretical distribution (or their estimates) must be known. For many theoretical distributions, the standardized variable S may be used:

$$S = (x - Q)/R \tag{4.63}$$

where Q stands for a parameter of location or threshold and R for a parameter of spread. The standardized (theoretical) quantile function $Q_s(P_i)$ then contains only shape parameters (their magnitude may be systematically varied).

When there is agreement between the empirical sample and the theoretical distribution, the Q–Q plot is a straight line:

$$x_{(i)} = Q + R \times Q_s(P_i) \tag{4.64}$$

For selected theoretical distributions the x- and y-coordinates of the Q–Q graph are given in Table 4.8 [15]. The symbol $\Phi(s)$ defines the normal distribution function:

$$\Phi(s) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{s} \exp(-0.5 \times u^2)\,du$$

To calculate the inverse function $\Phi^{-1}(P_i)$, the following simple approximate expression may be used:

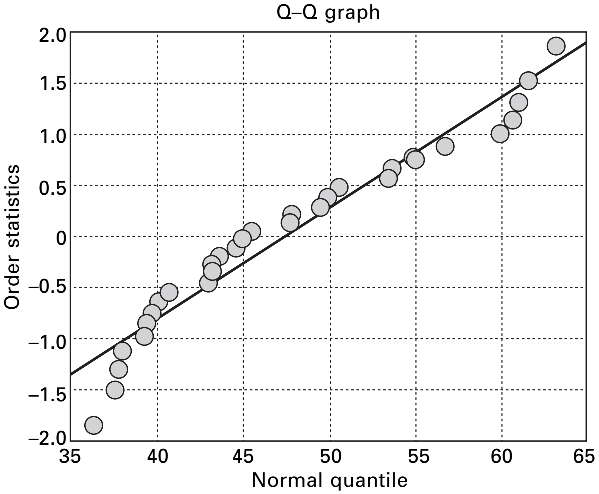
$$\Phi^{-1}(P_i) = u_{P_i} = \frac{-9.4\ln(1/P_i - 1)}{\text{abs}[\ln(1/P_i - 1)] + 14} \tag{4.65}$$

When it is desired to test whether a given random sample can be regarded as a sample from a normal (Gaussian) distribution, the resulting Q–Q plot is called the rankit plot or the normal probability plot (on the x-axis are the standardized normal quantile u_{P_i}). This plot enables classification of a sample

Table 4.8 Standardized frequency $f_T(s)$ and distribution functions $F_T(s)$ and corresponding coordinates (x, y) of the Q–Q plot

	Distribution			
	$F_T(s)$	$f_T(s)$	y	x
Rectangular	s	1	$x_{(i)}$	P_i
Exponential	$1 - \exp(-s)$	$\exp(s)$	$x_{(i)}$	$-\ln(1 - P_i)$
Normal	$F(s)$	$(2p)^{-1/2}\exp(0.5s^2)$	$x_{(i)}$	$F^{-1}(P_i)$
Laplace x £ Q for P_i £ 0.5	$0.5\exp(s)$	$0.5\exp(s)$	$x_{(i)}$	$\ln(2P_i)$
Laplace $x > Q$ for $P_i > 0.5$	$0.5[2 - \exp(-s)]$	$0.5\exp(-s)$	$x_{(i)}$	$-\ln(2(1 - P_i))$
Log-normal	$F[\ln(s)]$	$(2p)^{-1.2}\exp(-0.5\ln s^2)$	$x_{(i)}$	$\exp[F^{-1}(P_i)]$

distribution according to its skewness, kurtosis and tail length. A convex or concave shape indicates a skewed sample distribution. A sigmoid shape indicates that the tail lengths of the sample distribution differ from those of the normal ones. The normal Q–Q plot for tensile resilience of 30 protective clothings [32] is given in Fig. 4.3. The moderate systematic deviation from normality is clearly visible.



4.3 Normal Q–Q plot for tensile resilience data of 30 protective clothings.

Data transformation

When exploratory data analysis proves that the sample distribution strongly differs from the normal one, we are faced with the problem of how to analyze the data. Raw data may require re-expression to produce an informative display, an effective summary, or a straightforward analysis. We may need to change not only the units in which the data are stated, but also the basic scale of the measurement. To change the shape of a data distribution, we must do more than change the origin and/or the unit of measurement. Changes of origin and scale mean linear transformations, and they do not change the shape. Non-linear transformations such as the logarithm and square root transformations are necessary to change shapes.

Data must be examined to find the proper transformation, which leads to symmetric distribution of data, stabilizes the variance, or makes the distribution closer to the normal. Such transformation of original data x to a new variable $y = g(x)$ is based on an assumption that the data represent a non-linear transformation of the normally distributed variable y, according to $x = g^{-1}(y)$.

Transformation for variance stabilization involves finding a transformation $y = g(x)$ in which the variance $\sigma^2(y)$ is a constant. If the variance of the original variable x is a function of type $\sigma^2(x) = f_1(x)$, the variance $\sigma^2(y)$ may be expressed by

$$\sigma^2(y) \approx \left(\frac{dg(x)}{dx}\right)^2 \times f_1(x) = C \tag{4.66}$$

where C is a constant. The variance stabilizing transformation $g(x)$ is the solution of the differential equation

$$g(x) \approx C \times \int \frac{dx}{\sqrt{f_1(x)}} \tag{4.67}$$

In some measuring devices, the relative standard deviation $\delta(x)$ (coefficient of variation) of the measured variable is a constant. This means that the variance $\sigma^2(x)$ is described by a function $\sigma^2(x) = f_1(x) = \delta^2(x) \times x^2 = \text{const} \times x^2$. Substitution of this into eqn. (4.67) leads to the logarithmic form $g(x) = \ln(x)$. Then the optimal form of transformation of these types of data is the logarithmic transformation. This transformation leads to the use of a geometric mean. When the dependence $\sigma^2(x) = f_1(x)$ is of a power nature, the optimal transformation will also be a power transformation. Since for a normal distribution the mean is not dependent on the variance, a transformation that stabilizes the variance makes the distribution closer to normal.

Transformation for symmetry is carried out by a simple power transformation [15]:

$$\begin{aligned} y &= g(x) = x^{\lambda} && \text{for parameter } \lambda > 0 \\ y &= g(x) = \ln(x) && \text{for parameter } \lambda = 0 \\ y &= g(x) = -x^{-\lambda} && \text{for parameter } \lambda < 0 \end{aligned} \tag{4.68}$$

which does not retain the scale, is not always continuous, and is suitable only for positive values of x. Optimal estimates of parameter λ are sought by minimizing the absolute values of particular characteristics of asymmetry. In addition to the classical estimate of skewness $g_1(y)$, the robust estimate $g_{1,R}(y)$ is used:

$$g_{1,R}(y) = \frac{(y_{0.75} - y_{0.5}) - (y_{0.5} - y_{0.25})}{y_{0.75} - y_{0.25}}$$

where $y_{0.25}$, $y_{0.5}$ and $y_{0.75}$ are the lower quantile, median and upper quantile respectively of the transformed data. The relative distance between the arithmetic mean y_a and the median $y_{0.5}$ may also be utilized, because for symmetrical distributions this is equal to zero.

The parameter λ may also be estimated from a rankit plot because for an optimal value of λ_o, the transformed quantiles $y_{(i)}$ will lie on the straight line.

An excellent diagnostic tool enabling estimation of parameter λ is represented by the Hines–Hines selection graph [50]. This graph has the ratio $x_{0.5}/x_{1-P_i}$, on the x-axis and the ratio $x_{P_i}/x_{0.5}$ on the y-axis. The Hines–Hines selection graph is based on an assumption of symmetry of individual quantiles around a median

$$\left(\frac{x_{P_i}}{x_{0.5}}\right)^{\lambda} + \left(\frac{x_{0.5}}{x_{1-P_i}}\right)^{-\lambda} = 2$$

where, for the cumulative probability $P_i = 2^{-i}$, the letter values F, E and D (i = 2, 3, 4) are usually chosen.

To compare the empirical dependence of the experimental points with the ideal one, patterns for various values of the parameter λ are drawn in a selection graph. These patterns represent a solution of the equation $y^{\lambda} + x^{-\lambda} = 2$ in the range $0 \leq x \leq 1$, $0 \leq y \leq 1$:

- For $\lambda = 0$ the solution is a straight line $y = x$
- For $\lambda \leq 0$ the solution takes the form $y = (2 - x^{-\lambda})^{1/\lambda}$
- For $\lambda > 0$ the solution takes the form $x = (2 - y^{\lambda})^{-1/\lambda}$.

The estimate λ is guessed from a selection graph, according to the location of experimental points near to the various theoretical patterns.

Transformation to approximate normality can be achieved in many cases by use of the family of Box–Cox transformations defined as [51]

$$y = g(x) = \frac{(x^{\lambda} - 1)}{\lambda} \quad \text{for } \lambda \neq 0$$

$$y = g(x) = \ln(x) \quad \text{for } \lambda = 0 \tag{4.69}$$

where x is a positive variable and λ is real number. The Box–Cox transformation has the following properties [51]:

- The curves of transformation $g(x)$ are monotonic and continuous with respect to the parameter λ, because $\lim\limits_{\lambda \to 0}(x^{\lambda} - 1)/\lambda = \ln(x)$. All transformation curves share one point $[y = 0, x = 1]$ for all values of λ. The curves nearly coincide at points close to [0, 1], that is, they share a common tangent line at that point.
- The power transformations with exponent –2, –3/2, –1, –1/2, 0, 1/2, 1, 3/2, 2 have equal spacing between curves in the family of Box–Cox transformation graphs.

The Box–Cox transformation defined by eqn. (4.69) can be applied only to positive data. To extend this transformation, x values are replaced by $(x - x_0)$ values, which are always positive. Here x_0 is the threshold value $x_0 < x_{(1)}$.

To estimate the parameter λ in the Box–Cox transformation, the method of maximum likelihood may be used, because for $\lambda_{\text{o}} = \lambda$, a distribution of the transformed variable y is considered to be normal, $\text{N}[\mu_y, \sigma^2(y)]$. The logarithm of the maximum likelihood function may be written as

$$\ln(L(\lambda)) = -\frac{n}{2}\ln(s^2(y)) + (\lambda - 1)\sum_{i=1}^{n}\ln(x_i) \tag{4.70}$$

where $s^2(y)$ is the sample variance of the transformed data y. The function $\ln L(\lambda) = f(\lambda)$ is expressed graphically for a suitable interval, for example $-3 \le \lambda \le 3$ (the log maximum likelihood plot). The maximum value on this curve represents the maximum likelihood estimate λ_{o}.

The asymptotic $100(1 - \alpha)\%$ confidence interval of the parameter λ is expressed by the following relation:

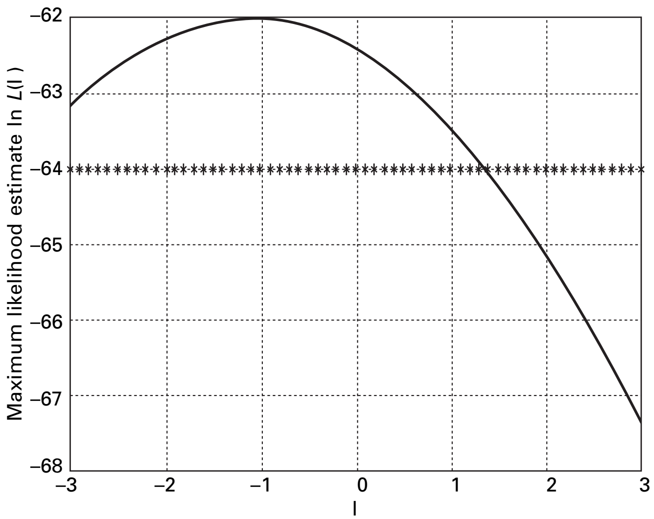
$$2[\ln(L(\lambda_{\text{o}})) - \ln(L(\lambda))] \le \chi^2_{1-\alpha}(1) \tag{4.71}$$

where $\chi^2_{1-\alpha}(1)$ is the quantile of the χ^2 distribution with 1 degree of freedom. This interval contains all values λ for which it is true that:

$$\ln L(\lambda) \ge \ln L(\lambda_{\text{o}}) - 0.5\chi^2_{1-\alpha}(1) \tag{4.72}$$

The Box–Cox transformation is less suitable for wide confidence intervals. When the value $\lambda = 1$ is also covered by this confidence interval, the transformation is not efficient. The value of $\ln L(\lambda)$ as a function of λ in the range $-3 < \lambda < 3$ for tensile resilience of 30 protective clothings [32] is given in Fig. 4.4. The optimal value of λ is $\lambda_{\text{o}} = -1.08$, but the confidence interval covers value 0 and therefore the logarithmic transformation is acceptable as well. Due to this transformation skewness is reduced from 0.4519 to 0.070 and therefore the data are now symmetrically distributed.

After an appropriate transformation of the original data x, the transformed data gives an approximately normal symmetrical distribution with constant variance, and the statistical measures of location and spread for the transformed data (y) can be calculated. These include the sample arithmetic mean y_{a} the



4.4 Plot of ln *L*(*l*) as a function of *l* for tensile resilience data of 30 protective clothings.

sample variance $s^2(y)$, and the confidence interval of the mean $y_a \pm t_{1-a/2}(n - 1)\ s(y)/÷n$. These estimates must then be recalculated for the original data (x). Two different approaches for the re-expression of the statistics for the transformed data exist [15].

Rough re-expressions represent a single reverse transformation x_a, $R = g^{-1}(y)$. This re-expression for a simple power transformation leads to the general mean [15]

$$x_{a,R} = \left[\frac{\sum_{i=1}^{n} x_i^{l}}{n}\right]^{1/l} \quad \text{for } l \neq 0 \quad \text{or}$$

$$x_{a,R} = \exp\left[\frac{\sum_{i=1}^{n} \ln(x_i)}{n}\right] \quad \text{for } \ l = 0 \qquad (4.73)$$

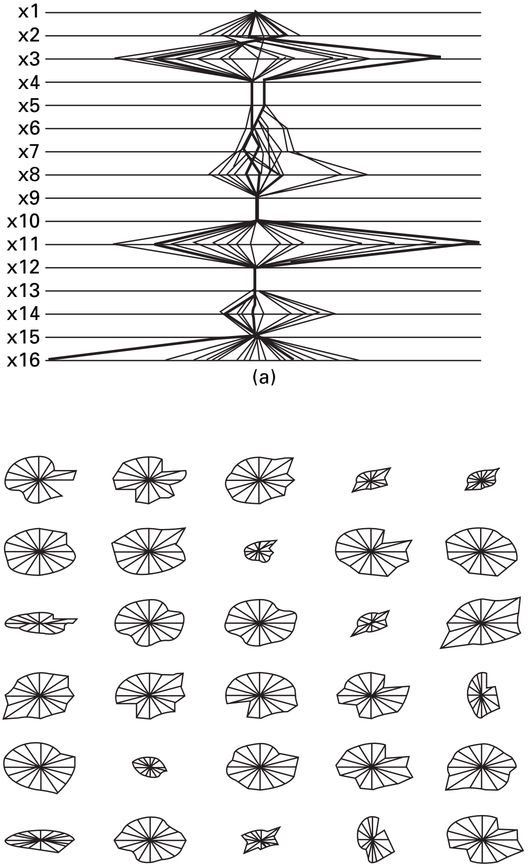
The re-expressed mean $x_{a,R} = x_{a,-1}$ stands for the harmonic mean, $x_{a,R} = x_{a,0}$ for the geometric mean, $x_{a,R} = x_{a,1}$ for the arithmetic mean and $x_{a,R} = x_{a,2}$ for the quadratic mean. More correct expressions based on the Taylor series expansion are presented in [15].

For the subsequent use of individual variables in regression models, transformation stabilizing variance is favourable. Especially, logarithmic transformation has a tendency to reduce the influence of gross errors and is often simple to apply to regression models.

4.3.4 Multivariate data exploration

Let the input data be given as the matrix defined by eqn. (4.45). The main aim of data exploration is investigation of outlying points or clusters of points and identification of various structures in data.

For graphical exploration, techniques based on symbols or scatter diagrams are used. Very simple representatives of symbol graphs are stars and profiles [52]. The profile and symbol graphs for 16 KES variables of 30 protective clothings are given in Fig. 4.5. Scatter graphs are represented by principal component (PC) graphs where original variables are replaced by latent variables with desired properties. PC graphs are useful in cases where the columns of matrix **X** in eqn. (4.45) are correlated. PCA is described in detail section in 4.3.5.



(a)

(b)

4.5 (a) Profile plot and (b) symbol plot for KES variables and protective clothings.

To identify the outliers, it is useful to define the Mahalanobis distance d_i as the distance of individual points from the centre (mean vector $\mathbf{x_A}$) weighted by the covariance matrix **C** [52]:

$$d_i = \sqrt{(x_i - x_\mathrm{A})^\mathrm{T}\,\mathbf{C}^{-1}(x_i - x_\mathrm{A})} \tag{4.74}$$

Outlying points have high Mahalanobis distance, i.e. $d_i > c(p, n, a_N)$. For multivariate normal distribution and large samples $c(p, n, a_N)$ is equal to the quantile of the c^2 distribution:

$$c(p, n, a_N) = c_p^2(1 - a/n) \tag{4.75}$$

For small samples, it is better to use the modified coefficient

$$c(p, n, a_n) = \frac{p(n-1)^2 F_{p,N-p-1}(1 - a/n)}{n(n - p - 1 + pF_{p,N-p-1}(1 - a/n))} \tag{4.76}$$

The main problem in using the Mahalanobis distance is to estimate the mean vector $\mathbf{x_A}$ and the covariance matrix **C**. In the presence of outliers, the classical moment estimators are biased. The 'clean' estimates $\mathbf{x_A}$ and **C** are constructed by various robust methods [52]. A very simple method is the combination of trimming and identification of potential outliers. In the *i*th iteration the trimmed estimators x_{RC} and $\mathbf{C}_C$ are computed. About 30% of the points having maximum Mahalanobis distances d_{i-1}^2 computed in the $(i - 1)$th iteration are trimmed. From the trimmed estimators x_{RC} and $\mathbf{C}_C$, the corrected distances d_i^2 are computed and the iteration is finished.

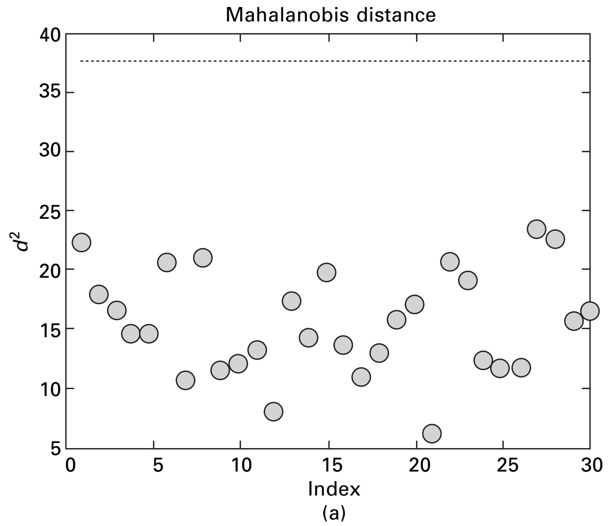
The Mahalanobis distance plot (dependent on the fabric index) and the robust Mahalanobis plot for 16 KES variables of 30 protective clothings are given in Fig. 4.6. It is clear that some fabrics appear to be far from the main group.

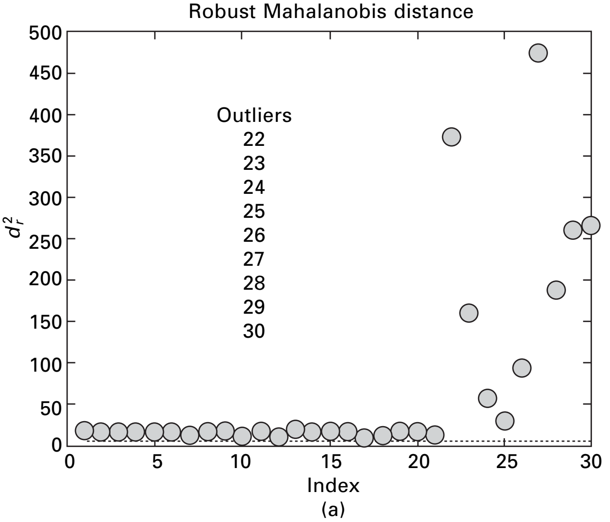
4.3.5 Dimension reduction

One of the main features of multivariate data is their dimension, which is a main source of complication in statistical analysis. Hence it is practical to make data reduction, which is acceptable in the following cases:

- The scatter of some variables is at the level of noise and therefore these variables do not convey useful information.
- There are strong linear dependencies (correlations between the columns of matrix **X**) given by redundant variables or as a result of inherent dependencies between variables. These variables can be replaced by the reduced number of new variables or replaced by artificial ones without any loss of precision.

The main reason for dimension reduction is the curse of dimensionality [53],





4.6 (a) Mahalanobis distance plot and (b) robust Mahalanobis distance plot for KES variables of 30 protective clothings.

i.e. the number of points required to achieve the same precision of estimators is an exponentially growing function of the number of variables. For higher numbers of variables (e.g. in multivariate regression) it leads to parameter estimates with too wide confidence intervals, imprecise correlation coefficients, etc.

One of the simplest techniques enabling dimension reduction is principal component analysis (PCA) as a representative of the so-called linear projection methods [52]. The main aim of principal component analysis is the linear transformation of the original variables x_i, $i = 1, ..., m$, to a smaller group of latent variables (principal components) y_j. Latent variables are uncorrelated, explore major parts of data variability and their number is often very small. Latent variables are commonly called principal components. The first principal component y_1 is a linear combination of the original variables that describes the greatest possible part of overall data variability. The second principal component y_2 is perpendicular to y_1 and describes the maximum part of variability that is not contained in the first principal component. Further principal components are generated in the same way.

The basis of PCA is decomposition of the data covariance matrix **C** to eigenvectors and eigenvalues according to the relation [52]

$$\mathbf{C} = \mathbf{V}\,\mathbf{\Lambda}\,\mathbf{V}^{\mathbf{T}} \tag{4.77}$$

where **V** is an $(m ¥ m)$ matrix containing as columns eigenvectors $\mathbf{V}_j$ and $\mathbf{\Lambda}$ is an $(m ¥ m)$ diagonal matrix containing on the diagonal eigenvalues l_1 £ l_2 £ … £ l_m of the covariance matrix. Matrix **V** is orthogonal, i.e. $\mathbf{V}^{\mathbf{T}}\mathbf{V} = \mathbf{E}$, where **E** is an identity matrix. The variance of the jth principal component $D(y_j) = l_j$ is equal to the jth eigenvalue. The overall variance of all principal components is equal to

$$\mathrm{tr}\,\mathbf{C} = \mathop{\mathrm{S}}_{i=1}^{m} l_j \tag{4.78}$$

where tr (.) is the matrix trace. The relative variance explained by the jth principal component y_j is in the form

$$P_j = \frac{l_j}{\mathop{\mathrm{S}}\limits_{i=1}^{m} l_j} \tag{4.79}$$

If the sum of the first m_1 relative variances P_j is sufficiently high (near to 1, say 0.95), then it is possible to replace m original variables by the first m_1 principal components. Graphical selection of a suitable number of principal components is based on the Scree plot, which is a column diagram of ordered eigenvalues l_1 £ l_2 £ … £ l_m independent of index i.

For a better interpretation of PCA it is suitable to quantify the contribution of the original variables to the principal components. It can be derived that the contribution of each original variable to the length of the jth principal component is proportional to the squared element V_{ij} of the eigenvector matrix **V**. The length of this vector is proportional to $\sqrt{l_i}$. The importance of the ith original variable contribution to the jth principal component is then proportional to $V_{ij}^2 \sqrt{l}$.

The **contribution plot** is a grouped histogram, where each group corresponds to one principal component. Individual columns in groups have heights proportional to $V_{ij}^2 \sqrt{l}$. Individual heights are standardized in such a way that the sum of the relative portions is equal to 1. Based on the contribution plot, it is simple to select important original variables and remove parasite variables with variability at the level of noise.

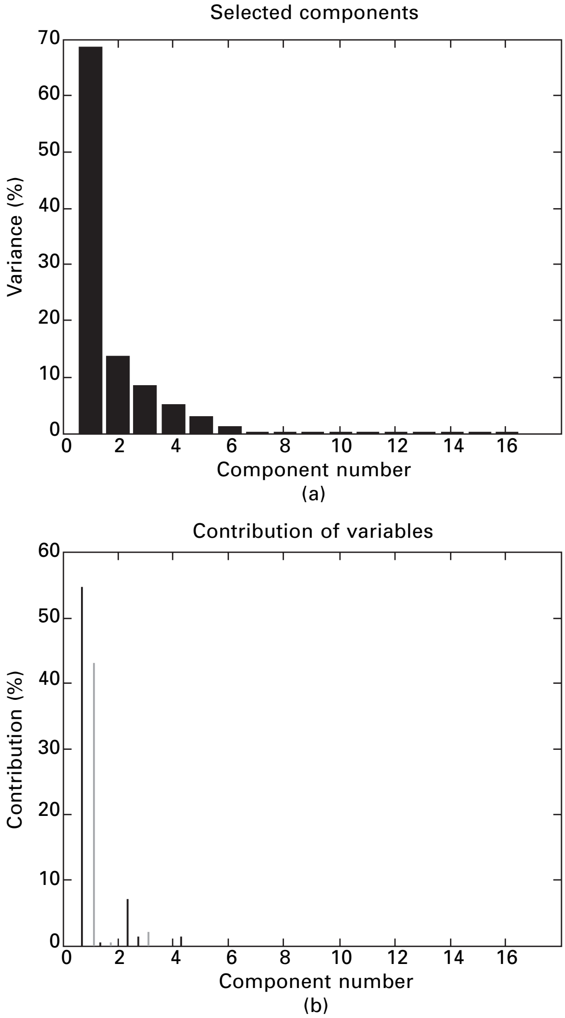
Apart from the linear projection methods such as PCA, there exist many non-linear projection methods [54]. Widely known are the Kohonen sell organized map (SOM), non-linear PCA and topographical mapping. The principle of SOM algorithms is projection to a smaller dimension space preserving approximate distances between points. When d_{ij}^* are the distances between the pairs of points in the original space and d_{ij} are the distances in the reduced space, the target function (reaching a minimum during solution) E takes the following form:

$$E = \frac{1}{\sum\limits_{i<j} d_{ij}^*} \sum_{i<j} \frac{(d_{ij}^* - d_{ij})^2}{d_{ij}^*} \tag{4.80}$$

Minimization of the E function is realized by using Newtonian methods or by heuristic searching. A simple projection technique is the robust version of PCA, when the robust variant $\boldsymbol{S_R}$ replaces the covariance matrix $\boldsymbol{S}$. In this projection, it is simpler to identify point clusters or outliers [52]. The Scree plot and the contribution plot for 16 KES variables of 30 protective clothings are shown in Fig. 4.7. It is apparent from Fig. 4.7(a) that to describe the variability in the data, it is sufficient to use the first four principal components, which explain about 92% of overall variability. The contribution plot shows that only a few of the original variables contributed significantly to explaining the data variability. In Table 4.9 percentage contributions of the important original variables (coded according to Table 4.6) are listed for the first six most important principal components. Clearly, to explain the data variability, the six original variables are sufficient, namely WT (tensile energy), RT (tensile resilience), 2HG5 (shearing hysteresis), RC (compression resilience), SMD (geometrical roughness) and T (thickness). However, it is not possible to say that these variables are the best for subjective hand prediction (see [52]). The projections to the first two principal components and first two robust principal components for 16 KES variables of 30 protective clothings are shown in Fig. 4.8. It is clear that due to the presence of outlying points, the scatter plots are different, and strictly speaking the outlying points here play an important role.

4.3.6 Evaluation of interdependencies

For evaluation of interdependencies between regressors (factors), correlation or regression analysis is useful [52]. Correlation analysis is usually based on the comparison of paired correlation coefficients in the form of a correlation

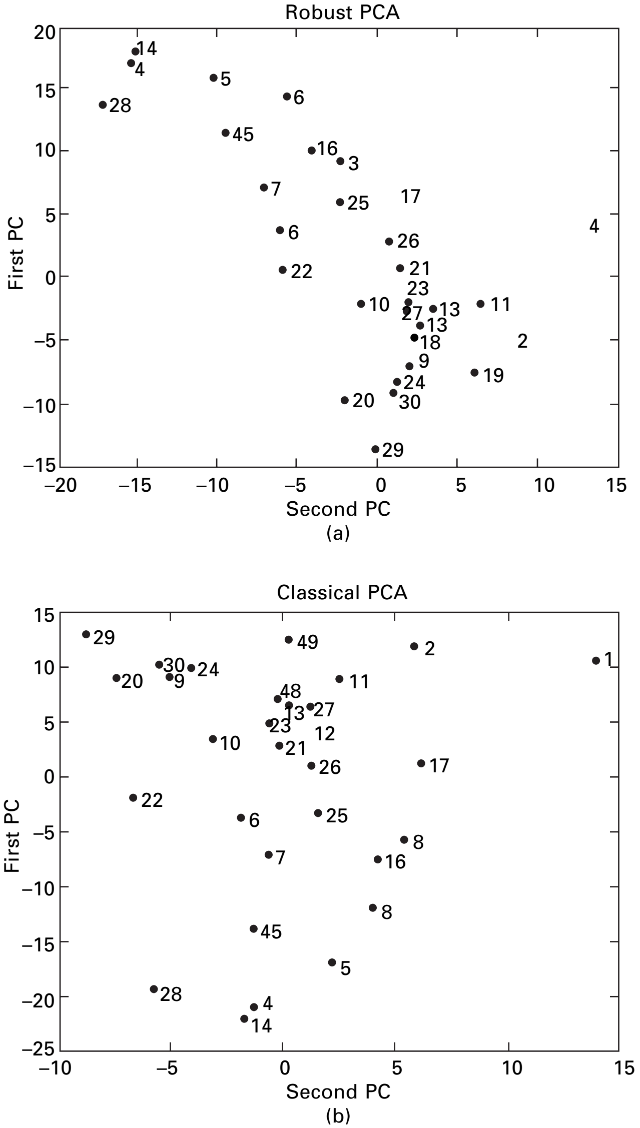


4.7 (a) Scree plot and (b) contribution plot for 16 KES variables of protective clothings.

Table 4.9 Contribution of the most important KES variables (importance in %) for creation of first six principal components PC

KES variable	PC1	PC2	PC3	PC4	PC5	PC6
X2	1.3	0.012	0.19	0.043	0.056	0.16
X3	54.4	0.326	1.44	0.0023	0.0032	0.014
X8	0.176	0.758	0.124	0.3356	0.459	0.0052
X11	43.079	0.113	2.219	0.0025	0.0081	0.03
X14	0.0209	0.122	0.077	1.375	0.21	0.0098
X16	0.496	7.182	0.139	0.13	0.06	0.003

The most significant contribution for each principal component is shaded.



4.8 Projection into (a) first two robust principal components and (b) first two classical principal components for KES variables of protective clothings.

map. A typical correlation map for 16 KES variables of 30 protective clothings is given in section 4.4.1. It should be pointed out that it is better to use partial correlation coefficients for revealing the structure in data more correctly [52]. For finding interdependencies in the case when one variable is treated as the response and the other variables as explanatory variables, the standard method is to use regression analysis. Regression analysis is also a tool for creation of predictive models. In the case of investigation factors (regressors) indirectly influencing subjective hand feeling, the use of regression analysis is less frequent. It should be considered for replacing primary factors by their proper (non-linear) combinations. A general introduction to linear regression for regression model building is given here and its application to predicting subjective hand is presented in section 4.4.1.

Building of regression models

Creation of a multivariate calibration-type model as in the case of subjective hand prediction is a very complex task. Data-based models with good predictive capability are required. Data-based multiple linear and non-linear model building belongs generally to the most complex problems solved in practice. In many cases it is not possible to construct the mathematical form of the model based on the information about the system under investigation. In these cases, the interactive approach to regression-type model building could be attractive. The interactive approach to model building can be divided into the following four steps [52]:

1. Selection of provisional models
2. Analysis of assumptions about the model, the data and the regression methods used (regression diagnostic)
3. Extension and modification of the model, data and regression method
4. Testing of model validity, prediction capability of model, etc.

Some interactive strategy of multiple regression model building based on the above steps is described in [52]. In this strategy of regression model building, graphically oriented methods for estimation of model correctness and identification of spurious data are selected. These methods are based on special projections enabling the investigation of partial dependencies of response on the selected exploratory variable. Classical examples are partial regression graphs or partial residual graphs. Non-linear or special patterns in these graphs can be used to extend the regression model to include non-linear terms or interactions. For identification of spurious data, the so-called LR graphs can be used as well. For evaluation of model quality, the characteristics derived from the predictive capability are used. Some statistical tools for realization of the above-mentioned techniques are described in [52].

Summary of linear regression

A *linear* regression model is a model formed by a linear combination of explanatory variables $\mathbf{x}$ or their functions. For an additive model of measurement errors, the linear regression model has the form

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\epsilon} \tag{4.81}$$

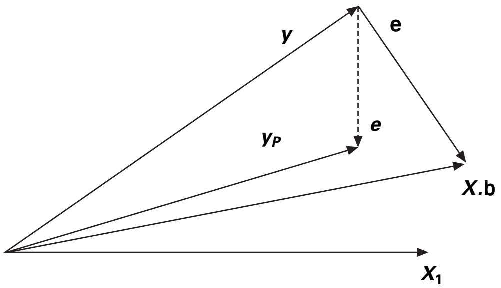
In eqn. (4.81), the n ¥ m matrix **X** contains the values of m explanatory (predictor) variables at each of n observations, $\boldsymbol{\beta}$ is the m ¥ 1 vector of regression parameters, and $\boldsymbol{\epsilon}_i$ is the n ¥ 1 vector of experimental errors. The **y** is an n ¥ 1 vector of observed values of the dependent variable (response). Columns $\mathbf{x}_j$ i.e. individual explanatory variables, define geometrically the m-dimensional coordinate system or the hyperplane L in n-dimensional Euclidean space E^n. The vector **y** does not usually lie in this hyperplane L. Least squares is the most frequently used method in regression analysis. For linear regression, the parameter estimates **b** may be found by minimizing the distance between the vector **y** and the hyperplane L. This is equivalent to finding the minimum length of the residual vector $\mathbf{e} = \mathbf{y} - \mathbf{y}_\mathrm{P}$, where $\mathbf{y}_\mathrm{P} = \mathbf{Xb}$ is the *predictor vector*. This is equivalent to the requirement of minimal length of the residual vector $\mathbf{e} = \mathbf{y} - \mathbf{y}_\mathbf{P}$. In Euclidean space, the length of the residual vector is expressed as

$$d = \sqrt{\underset{i=1}{\overset{n}{\mathrm{S}}} e_i^2} \tag{4.82}$$

The geometry of linear least squares is shown in Fig. 4.9. The classical least squares method is based on the following assumptions:

- Regression parameters **b** are not restricted,
- The regression model is linear in parameters and the additive model of measurements is valid (see eqn. (4.81)).
- The design matrix **X** has a rank equal to n.
- Errors e_i are i.i.d. random variables with zero mean $E(e_i) = 0$ and diagonal covariance matrix $D(\mathbf{e}) = s^2\mathbf{E}$, where $\mathrm{s}^2 <$ • .

For testing purposes, it is assumed that errors e_i have normal distribution N(0, s^2). When these four assumptions are valid, the parameter estimates **b** found by minimization of the least squares criterion



4.9 Geometry of linear least squares.

$$S(\mathbf{b}) = \sum_{i=1}^{n}\left[y_i - \sum_{j=1}^{m} x_{ij} b_j\right]^2 \tag{4.83}$$

are called best linear unbiased estimators (BLUE) [52]. The conventional least squares estimator **b** has the form

$$\mathbf{b} = (\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{y} \tag{4.84}$$

where $\mathbf{A}^{-1}$ denotes the inverse of matrix **A**. The estimates **b** have an asymptotic multivariate normal distribution with covariance matrix $\mathrm{D}(\mathbf{b}) = \sigma^2 (\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}$. The perpendicular projection of **y** into the hyperplane L can be made using the projection matrix **H** and may be expressed as

$$\mathbf{y}_{\mathbf{P}} = \mathbf{X}\mathbf{b} = \mathbf{X}(\mathbf{X}^{\mathbf{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{y} \tag{4.85}$$

where **H** is the projection matrix. The residual vector $\mathbf{e} = \mathbf{y} - \mathbf{y}_{\mathrm{P}}$ is orthogonal to the subspace L and has the minimum length. The variance matrix corresponding to the prediction vector $\mathbf{y}_{\mathrm{P}}$ has the form $\mathrm{D}(\mathbf{y}_{\mathrm{P}}) = \sigma^2\mathbf{H}$ and the variance matrix for residuals is $\mathrm{D}(\mathbf{e}) = \sigma^2(\mathbf{E} - \mathbf{H})$. The residual sum of squares has the form $\mathrm{RSC} = S(\mathbf{b}) = \mathbf{e}^{\mathbf{T}}\mathbf{e} = \mathbf{y}^{\mathbf{T}}(\mathbf{E} - \mathbf{H})\mathbf{y} = \mathbf{y}^{\mathbf{T}}\mathbf{P}\mathbf{y}$, and its mean value is $E\,(\mathrm{RSC}) = \sigma^2\,(n - m)$. The unbiased estimator of the measurement variance σ^2 is equal to

$$s^2 = \frac{S(\mathbf{b})}{n - m} = \frac{\mathbf{e}^{\mathbf{T}}\mathbf{e}}{n - m} \tag{4.86}$$

The statistical analysis related to least squares is based on the normality of estimates **b**. The quality of regression is often (not quite correctly) described by the multiple correlation coefficient R defined by the relation

$$R^2 = 1 - \frac{\mathrm{RSC}}{\sum(y_i - \sum y_i/n)^2} \tag{4.87}$$

For model building, the multiple correlation coefficient is not suitable. It is a non-decreasing function of the number of predictors and therefore the over-parameterized model results. The prediction ability of the regression model can be characterized by the quadratic error of prediction (MEP) defined for linear models by the relation

$$\mathrm{MEP} = \sum_{i=1}^{n}(y_i - x_i^{\mathrm{T}} b_{(i)})^2/n \tag{4.88}$$

Here $\mathbf{b}_{(i)}$ is the estimate of regression model parameters when all points except the *i*th are used. The statistics MEP for linear models uses the prediction $y_{P_i} = \mathbf{x}_i^{\mathrm{T}}\mathbf{b}_{(i)}$ which was constructed without information about the *i*th point. The estimate $\mathbf{b}_{(i)}$ can be computed from the least squares estimate **b** as follows:

$$\mathbf{b}_{(i)} = \mathbf{b} - [(\mathbf{X}^T\mathbf{X})^{-1}\,\mathbf{x}_i\, e_i] \,/\, [1 - H_{ii}] \tag{4.89}$$

Here H_{ii} is a diagonal element of the projection matrix **H**. An optimal model has a minimal value of MEP. The MEP can be used for definition of the predicted multiple correlation coefficient PR [52].

$$\mathrm{PR}^2 = 1 - \frac{n \times \mathrm{MEP}}{(\Sigma y_i - (1/n)\Sigma y_i)^2} \tag{4.90}$$

The PR is attractive especially for empirical model building. It is closely connected with the well-known method of cross-validation or single leave-out statistics. Analysis of various types of the regression residuals, or some transformation of the residuals, is very useful for detecting inadequacies in the model or problems in the data [52].

Graphical aids for model creation

In multiple regression one usually starts with the assumption that the response variable y is linearly related to each of the predictors. The aim of graphical analysis is to evaluate the type of non-linearity due to the function of predictors describing the experimental data well. The power-type function of predictors is suitable when the relation is monotonic. Several diagnostic plots have been proposed for detection of the curve between y and x_j [52]. Very useful for experiments designed without marked collinearities is the partial regression plot (PRL). This plot uses the residuals from the regression of y on the predictor x_j, graphed against the residuals from the regression of x_j on the other predictors. This graph is now a standard part of modern statistical packages and can be constructed without recalculating the least squares estimates. To discuss the properties of this plot, let us assume the regression model in the matrix notation

$$\mathbf{y} = \mathbf{X}_{(j)}\boldsymbol{\beta}^* + \mathbf{x}_j c + \boldsymbol{\epsilon} \tag{4.91}$$

Here $\mathbf{X}_{(j)}$ is a matrix formed by leaving out the jth column $\mathbf{x}_j$ from the matrix **X**, β^* is an $(n - 1) \times 1$ parameter vector and c is a regression parameter corresponding to the jth variable $\mathbf{x}_j$. For the investigation of partial linearity between y and the jth variable $\mathbf{x}_j$, the projection into subspace L orthogonal to space defined by the columns of matrix $\mathbf{X}_{(j)}$ is used. The corresponding projection matrix into the space L has the form $\mathbf{P}_{(j)} = \mathbf{E} - \mathbf{X}_{(j)}(\mathbf{X}_{(j)}^T\mathbf{X}_{(j)})^{-1}\mathbf{X}_{(j)}^T$.

Applying this projection to both sides of eqn. (4.91), the following relation results:

$$\mathbf{P}_{(j)}\,\mathbf{y} = \mathbf{P}_{(j)}\,\mathbf{x}_j\, c + \mathbf{P}_{(j)}\,\boldsymbol{\epsilon} \tag{4.92}$$

The product $\mathbf{P}_{(j)}\,\mathbf{X}_{(j)}\,\boldsymbol{\beta}^*$ is equal to zero because the space spanned by $\mathbf{X}_{(j)}$ is orthogonal to the residuals' space. It is clear that the term $\mathbf{v}_j = \mathbf{P}_{(j)}\,\mathbf{x}_j$ is the residual vector of regression of the variable $\mathbf{x}_j$ on the other variables which form the columns of the matrix $\mathbf{X}_{(j)}$, and the term $\mathbf{u}_j = \mathbf{P}_{(j)}\,\mathbf{y}$ is the residual vector of regression of variable $\mathbf{y}$ on the other variables which form the columns of the matrix $\mathbf{X}_{(j)}$. The partial regression graph as dependence of vector $\mathbf{u}_j$ on vector $\mathbf{v}_j$ is created. If the term $\mathbf{x}_j$ is correctly specified the partial regression graph forms a straight line. Systematic non-linearity is an indication of the incorrect specification of $\mathbf{x}_j$. The random pattern shows the unimportance of $\mathbf{x}_j$ for explaining the variability of $\mathbf{y}$. The **partial regression graph (PRL)** has the following properties:

- The slope c in the PRL is identical with the estimate b_j in a full model.
- The correlation coefficient in the PRL is equal to the partial correlation coefficient R_{yxj}.
- Residuals in the PRL are identical with residuals for the full model.
- The influential points, non-linearities and violations of least squares assumptions are markedly visualized.

4.4 Prediction of subjective hand

Many methods are used for *indirect objective hand evaluation.* These techniques can be divided into three groups according to the instruments used:

1. **Special instruments**. Hand is the result of the measurement. Drawing a textile through a nozzle of defined shape and evaluating 'strength–displacement' dependence is the usual principle [5].
2. **Sets of special instruments** for measuring properties corresponding to hand. Kawabata's evaluation system (KES) belongs to this group.
3. **Standard instruments** for evaluation of fabric properties connected with hand [5].

Techniques of objective hand evaluation can be divided into two groups according to the way the data are processed:

1. The result is **a single number** characterizing hand. This number is very often obtained from multivariate calibration (for example in the regression model), where subjective hand is an endogenous variable and measured properties are exogenous ones [6].
2. The result is a **vector of numbers** characterizing hand. Comparison of hand is then carried out on the basis of multivariate statistical methods [7] (for example factor analysis, discrimination analysis and cluster analysis).

In this section, some methods for creation of models for prediction of subjective hand are described.

Because subjective hand, in fact, is an ordinal variable it is necessary to take this into account for building the model for predicting hand H_s based on continuous covariates (regressors). These covariates are selected from a set of measured properties on KES or from another set of properties.

There are two main categories of model:

I. Prediction of location characteristics only (typically scaled grading median M_p).
II. Information about probabilities or representatives in each category.

For **category I**, it is possible to use ordinary least squares. In this case, the main problems are due to the limited range of M_p and the unknown distribution of this variable. The corresponding variances of M_p will be non-constant and then weighted regression will be more correct.

A common approach to handling the data for **category II** models is to use just ordinary least squares regression with the category membership identifier as the target variable (response). This often works reasonably well, but there are some serious problems with using it:

1. An integer response variable is inconsistent with the assumption of continuous (normal) errors.
2. The ordinal variables exhibit less variability near the limits of their scale and the assumption of constant error variance is violated.
3. Prediction from ordinary regression models does not give integers, resulting in difficulties in interpretation.
4. Least squares regression implicitly assumes that the categories are equally distant from each other.

The solution of these problems is to generalize the well-known logistic regression for ordinal data. There exist several techniques to do this, leading to similar inferences about the ordinal structure of data [18, 55].

Because the models from **category I** are directly predictive models for subjective hand, we will discuss this approach in detail. Models from **category II** are only briefly mentioned. As a working example of regression-type models, we used data from subjective hand evaluation and KES measurement of 30 protective fabrics that are used frequently in the Czech Republic [56]. Protection against heat was realized by using a flame-retardant finish, special fibres (e.g. aramides) or blends of special fibres with properly finished classical ones (cotton). A classical cotton-type fabric was added for comparison as well. This set of fabrics covers the range of highly heat-protective textiles. Material characterization and basic construction parameters are given in [32].

In order to obtain the hand prediction equation, the characteristics measured on the KES system were selected. Raw data and total hand values THV are given in [32]. Subjective hand was judged by a group of 20 well-informed respondents. They classified hand into a $k = 12$ order grade scale (1 – very bad, …, 12 – excellent). The estimations of median values from subjective evaluation results were treated by means of the technique described in section 4.2.1. Results are given in [32]. For models from **category I** the median of the ordinal variable divided by 12 was used as *relative subjective hand* $M_{pi} = y_i = M_{hi}/12$.

4.4.1 Building of multiple linear regression models

The procedure of the regression-type predictive model for subjective hand is here demonstrated on the problem of protective clothing hand evaluation by using Kawabata measurements [56]. This procedure is general and can be used for any kind of cardinal factor (repressors). One example of the application of this approach (prediction of PET/cotton fabric hand for data from the usual devices) is given in [31]. Raw data are in the form y_i, x_1, …, x_{16i}, i = 1, 2, …, 30. The factors x_i are mean values computed from five repeated measurements. The median M_p is the response variable y_i.

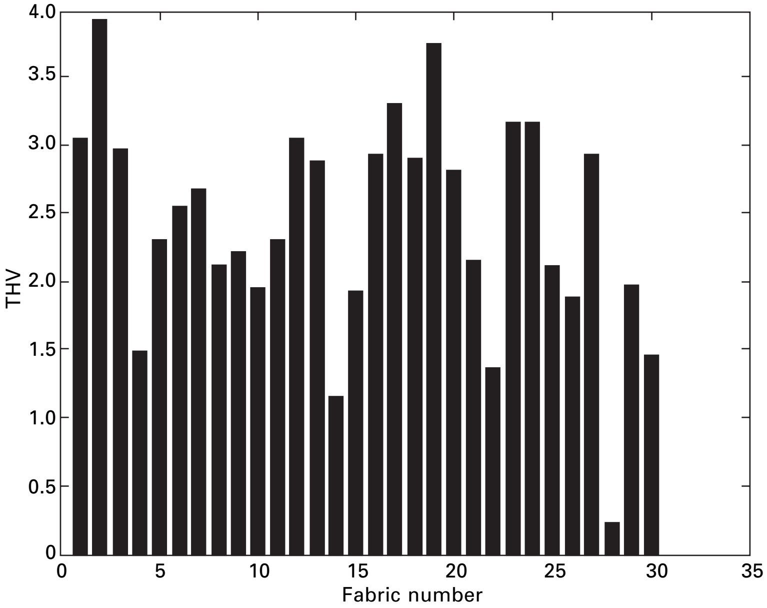
The procedure for the creation of a predictive model can be divided into the following parts:

- Selection of characteristics connected with subjective hand
- Data pretreatment
- Creation of regression model.

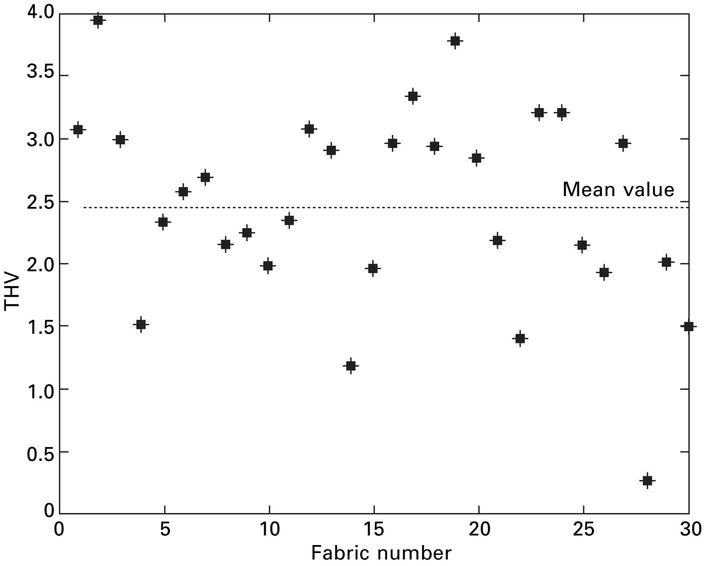
In KES these parts have been solved (see [7]) but only for clothing-type textiles. THVs for the investigated protective textiles computed from KES constants for men's winter suits are given in Fig. 4.10. In Fig. 4.11 the individual THVs for barrier fabric are compared with the mean value. It is seen that many fabrics have very poor hand and in some cases the THV values are near zero. The mean value of hand is comparatively small. The reason is the use of constants that are not valid for these textiles. A comparison of THV with relative subjective hand is given in Fig. 4.12. Moderate linearity is visible but the results are shifted in both intercept and slope. The main shortcoming is the huge number of characteristics (16) for computation of THV.

Selection of sufficient factors

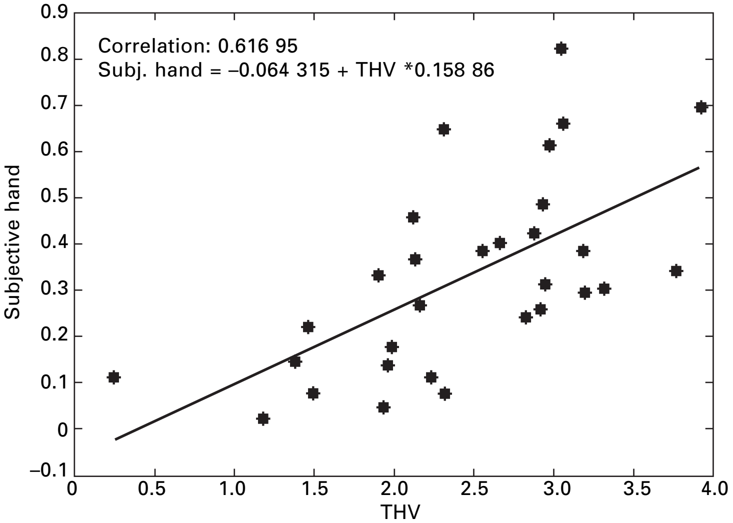
Because the results of KES are 16 factors, i.e. characteristics of mechanical and physical properties connected with hand, the aim is to inspect mutual correlations and correlation with subjective hand. The individual characteristics are numbered x_1, …, x_{16}, and the median of subjective hand is x_{17}. (see Table 4.6). The correlation map for all characteristics and relative subjective hand is shown in Fig. 4.13. The grey degree corresponds to the strength of correlation. The white indicates perfect correlation (paired correlation coefficient is equal to one) and the black is absence of correlation (paired correlation coefficient



4.10 THV computed from KES for men's winter suit parameters.



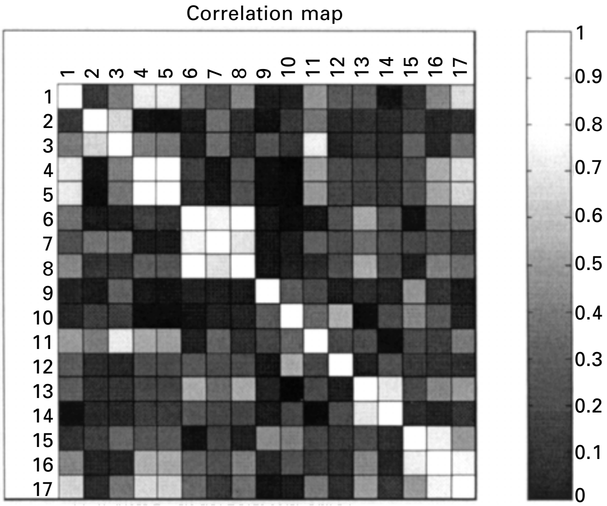
4.11 THV computed from KES for men's winter suit parameters and mean THV.



4.12. Comparison of relative subjective hand with THV.

is equal to zero). The following results can be simply obtained by inspection of Fig. 4.13:

- Subjective hand correlates strongly only with x_1, x_4, x_5 and x_{16}. There is moderate correlation with x_{13} and x_{15}.



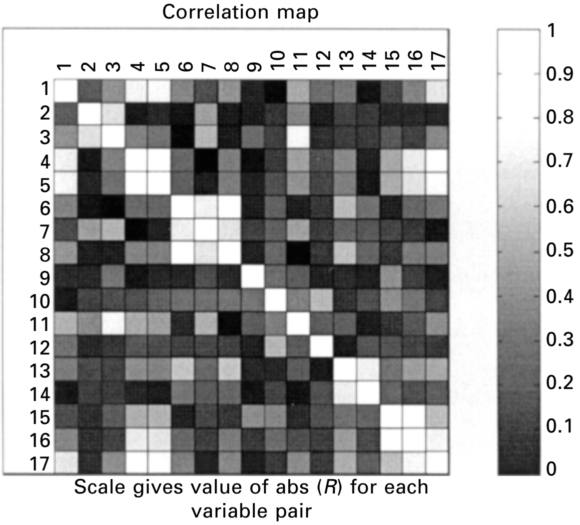
Scale gives value of abs (*R*) for each variable pair

4.13 Correlation map for characteristics of hand (1–16) and relative subjective hand (17).

- There are a lot of very strong correlations between the characteristics, mainly in individual groups of properties.
- Correlations of properties with thickness (16) are very similar to correlations with subjective hand.

The properties LT, B, 2HB and T correlate highly with relative subjective hand (paired correlation coefficient is above 0.6).

In the KES some characteristics are transformed to the logarithmic scale to avoid problems with skew distribution. The correlation map for the transformed characteristics (see [7]) and the relative subjective hand is shown in Fig. 4.14. It is evident that the logarithmic transformation has very little influence on paired correlations between parameters and relative subjective hand.



4.14 Correlation map for transformed characteristics of hand (1–16) and relative subjective hand (17).

Data pretreatment

The main aim is data standardization and transformation to a suitable scale. Standardization is obtained by using the relation

$$u_{ji} = \frac{x_{ji} - x_j^*}{s_j} \tag{4.93}$$

where x_j^* is the sample mean and s_j is the corresponding standard deviation for the jth variable (characteristic). This standardization leads to dimensionless variables and is also realized in the Kawabata system. The logarithmic transformation for avoiding skewness was used by Kawabata. It limits the influence of extreme high values only. Because the meaning of hand comes from its psychophysical nature, it is preferable to use a non-linear transformation of the 'stimulus–response' type. The Harrington transformation was used here (see eqn. (4.52)). This transformation is able to constrain the influence of extremes from both sides. Its main advantage in use lies in the absence of extra parameters. The Harrington-type transformation combined with standardization has been used for all characteristics $x_1, \ldots, x_{16}$.

Creation of regression model

In the KES the quadratic-type regression model is used [7]. For flexibility and simplicity, the following **regression sub-models** were specified in this study:

$$\text{LIN} \qquad y_i = b_0 + \sum_{j=1}^{16} b_j w_{ji} + \varepsilon_i \tag{4.94}$$

$$\text{LINL} \qquad y_i = b_0 + \sum_{j=1}^{16} b_j \ln(w_{ji}) + \varepsilon_i \tag{4.95}$$

$$\text{LOGL} \qquad \ln(y_i) = b_0 + \sum_{j=1}^{16} b_j w_{ji} + \varepsilon_i \tag{4.96}$$

$$\text{GEOM} \qquad \ln(y_i) = \ln b_0 + \sum_{j=1}^{16} b_j \ln(w_{ji}) + \varepsilon_i \tag{4.97}$$

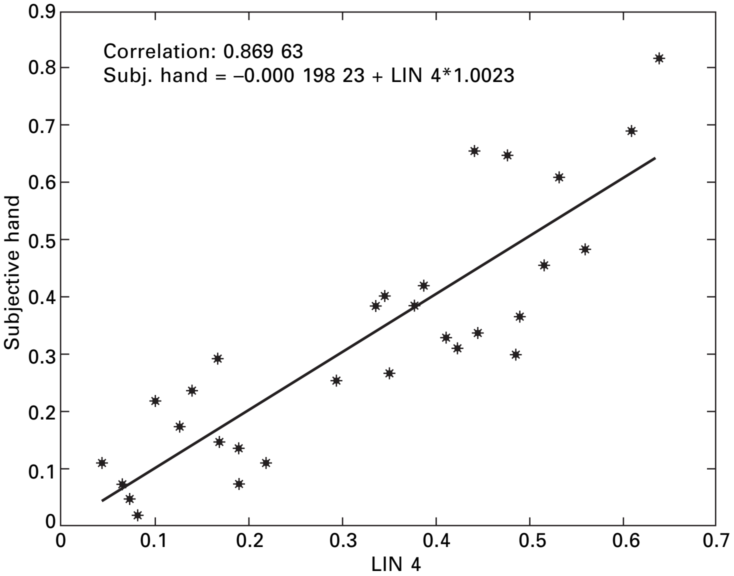
These models were used in the case of all variables ($x_1, \ldots, x_{15}$). For the six (x_1, x_4, x_5, x_{13}, x_{15} and x_{16}) and four (x_1, x_4, x_5, and x_{16}) statistically most important variables only the LIN model has been used. These cases are abbreviated, e.g. LIN6 or LIN4. The simple regression line for x_{16} (LIN1) was computed for comparative purposes as well. The predicted correlation coefficient R_p and mean quadratic error of prediction MEP were used to determine regression model quality. For the above-mentioned models, the characteristics R_p and MEP are shown in Table 4.10. It is evident that from the point of view of prediction ability, the LIN4 model is the best one. The model with all 16 characteristics is clearly over-parameterized. The simple line is surprisingly good (the correlation coefficient of 0.799 is slightly higher than the correlation coefficient for THV). The estimations of parameters $b_0, \ldots, b_4$ together with standard deviations are presented in Table 4.11. Figure 4.15 compares relative subjective hand and LIN4, i.e. hand predicted from the LIN4 model with parameters from Table 4.11. In comparison with Fig. 4.12 for THV values, higher correlation and absence of bias are visible. The higher prediction capability is bounded by the uncertainty in subjective hand prediction.

Table 4.10 Characteristics of regression model quality for various models

Model	R_p	MEP
LIN	0.787	0.0158
LINL	0.782	0.286
LOGL	0.790	0.0156
GEOM	0.794	0.271
LIN6	0.7964	0.0152
LIN4	0.8126	0.0141
LIN1	0.769	0.0169

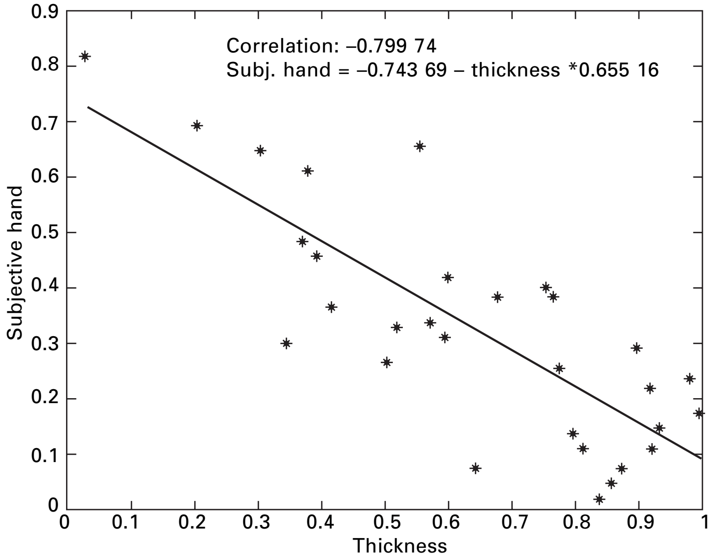
Table 4.11 Regression results for LIN4 model

Parameter	Estimate	Standard deviation of estimate
b_0	0.827	0.0617
b_1	–0.251	0.122
b_2	–0.439	0.725
b_3	0.302	0.721
b_4	–0.429	0.109



4.15 Comparison of relative subjective hand with hand predicted from the LIN4 model.

The regression line for dependence of subjective hand on normalized and transformed thickness of fabrics (x_{16}) is given in Fig. 4.16. From these results the following conclusions can be drawn:



4.16 Dependence of subjective hand on fabric thickness.

- The fabric thickness T (x_{16}) plays a very important role in the hand of protective textiles. The correlation coefficient of relative subjective hand with the transformed thickness is much higher in comparison with the THV.
- The linear model having only four characteristics, namely LT (x_1), B (x_4), 2HB (x_5) and T (x_{16}), is the best for prediction of subjective hand.
- MMD (x_{13}) and WC (x_{10}) have a moderate influence on hand.

The hand of protective fabric is therefore dependent on the *fabric geometry* (and weight), *tensile and bending properties* and variability of *surface friction*. These parameters can be modified in practice by using special softening agents (finishing) or by proper design of raw fabric.

Limitations

The methodology described is based on the assumptions of unbounded response and unbounded factors (explanatory variables). Strictly speaking, both variables are bounded and the bounds are known. The correct procedure in this case is to use the methodology described in the work of Oman [57]. This is based on checking the length of the parameter vector. For higher lengths, it is possible to derive optimal shrinking of parameters (in fact, this is so-called ridge regression). Where the parameter vector length is sufficiently small, the classical least squares estimators as used here are acceptable. These constraints should be imposed on the more precise estimation strategy. In the case presented above, there were no marked non-linearities and the degree of fit was very good, so the improved strategy was not applied. The second improvement is to use non-constant weights based on dorvar variance.

4.4.2 Logistic and polytomous models

The models from **category II** are created by logistic regression for ordinal data [18, 55]. The ordinal response Y_i takes values in k ordered categories; let F_{ij} be the estimate of cumulative probability that Y_i falls in the jth category or lower. There exist several techniques to do this, leading to similar inferences about the ordinal structure of the data [55]. For calculation of these models the special software in SAS, S Plus and STATA packages, is available [58]. As raw explanatory variables, for each fabric, it is necessary to use individual judgements (grades) or relative frequencies for each category [58].

The proportional odds model

The proportional odds model is based on the so-called **cumulative logits.** Consider a model with regressors $x = (x_i, \ldots, x_m)$ and target identifier T. Cumulative logit is defined by the relation

$$\mathrm{CL}_j(\mathbf{x}) = \mathrm{logit}(F_j(\mathbf{x})) = \log\left(\frac{F_j(\mathbf{x})}{1 - F_j(\mathbf{x})}\right) \quad j = 1, \ldots, k - 1 \tag{4.98}$$

where $F_j(x) = P(T \le j/x)$ is the cumulative probability for the jth category. The target identifier T takes values 1, 2, …, k. The $\mathrm{CL}_j(x)$ is then log odds of $Y \le j$ versus $Y > j$. The proportional odds linear model has the form

$$\mathrm{CL}_l(\mathbf{x}) = a_{0,j} + \sum_{l=1}^{k-1} a_i x_l \quad j = 1, \ldots, k - 1 \tag{4.99}$$

where a_{0j} ($j = 1, \ldots, k - 1$) and a_l ($l = 1, \ldots, k - 1$) are regression parameters. A positive value of a_l implies increasing probability of being in lower categories with increasing x_l. To avoid this problem the negative sign is often used in eqn. (4.99). This model is motivated by using a latent continuous response T^* of actual hand feelings. Then for class boundaries $-\infty \le b_1 \le \ldots \le b_k \le \infty$ the observed response T (category membership) is categorized according to the rule

$$T = j \text{ for } b_{j-1} < T^* < b_j \tag{4.100}$$

This is the so-called grouped continuous model.

If the latent variable $T^*(x)$ given the regressor setting x has the logistic distribution, the probabilities $p_j(x)$ satisfy the proportional odds model $\mathrm{CL}_j(x)$.

An alternative to the grouped continuous approach to modelling an ordinal variable is to focus directly on the specific probability relationship through the logits. *The adjacent categories logit* uses the following model:

$$\log\left(\frac{f_{j+1}}{f_j}\right) = a_{0j} + \sum_{l=1}^{k-1} a_l x_l \quad j = 1, \ldots, k-1 \tag{4.101}$$

This model is a special case of the multinomial logit model. The logit equations (4.101) can be re-expressed in terms of baseline category c_k using the identity

$$\log\left(\frac{f_{j+1}}{f_j}\right) = \log\left(\frac{f_{j+1}}{f_k}\right) - \log\left(\frac{f_j}{f_k}\right) \tag{4.102}$$

These logit models assume the existence of a continuous *latent* variable *T*. This is not correct for subjective hand, because categories here are truly discrete. For these cases it is better to use *stereotype models* based on the polytomous repression models [59].

One of the main advantages of the stereotype model is that it does not assume *a priori* ordering. The ordinality is built into it by imposing a structure on the regression coefficients. Starting from the stereotype model is similar to the adjacent category logit expressed in eqn. (4.101) for base category f_1:

$$\log\left(\frac{f_{j+1}}{f_1}\right) = a_{0j} + \sum_{l=1}^{k-1} a_{jl} x_l \quad j = 2, \ldots, k \tag{4.103}$$

From the model expressed in eqn. (4.103), it is clear that the ordinal nature of categories is not accounted for. The ordinality is reached by imposing a structure on the regression coefficients b_{jl} ($l = 1, \ldots, m$). One possibility is to use factorization:

$$b_{jl} = f_j b_l \quad i = 2, \ldots, k; \quad l = 1, \ldots, m \tag{4.104}$$

where b_l is a list of new parameters and f_i can be thought of as scores S_i attached with category c_i. There are two constraints: $f_1 = 0$ and $f_k = 1$. After substitution of these into eqn. (4.103), the stereotype model results:

$$\log\left(\frac{f_{j+1}}{f_1}\right) = a_{0,j} + f_j \sum_{l=1}^{k-1} a_l x_l \tag{4.105}$$

The stereotype model contains a set of parameters f_i and a single parameter b_l for each regressor. Weight parameters f_i can be selected as *a priori* fixed scores or can be computed [60].

4.4.3 Neural network models

Lack of theoretical models for prediction of subjective hand is the main reason for utilization of soft models or non-parametric regression techniques such as neural networks. In these cases, the response is simply selected as the scaled sample grading median y = Mp, and as explanatory variables **x**, important measured characteristics can be used (see section 4.3).

Neural networks (NN) have recently received widespread application in many fields in which statistical methods are traditionally employed [61]. Recent possibilities for application of neural networks to textiles are described in [62]. From a statistical point of view NN are a wide class of flexible non-linear regression and discrimination models, data reduction models, and non-linear dynamic systems [63].

Basic ideas

Artificial neural networks have been developed as generalizations of mathematical models of human cognition or neural biology, based on the following assumptions:

1. Information processing occurs at many simple elements called neurons.
2. Signals are passed between neurons over connection links.
3. Each connection link has an associated weight, which in a typical neural net multiplies the signal transmitted.
4. Each neuron applies an activation function (usually non-linear) to its net input (sum of weighted input signals) to determine its output signal.

The use of neural networks offers the following useful properties and capabilities:

1. **Non-linearity**. A neuron is basically a non-linear device. Consequently, a neural network, made up of an interconnection of neurons, is itself non-linear. Moreover, the non-linearity is of a special kind in the sense that it is distributed throughout the network.
2. **Input-output mapping**. A popular paradigm of learning called supervised learning involves the modification of the synaptic weights of a neural network by applying a set of labelled training samples.

Neural network structure

A neural net consists of a large number of simple processing elements called neurons, units, cells, or nodes. Each neuron is connected to other neurons by means of directed communication links, each with an associated weight. The weights represent information being used by the net to solve a problem. Each neuron has an internal state, called its activation or activity level, which is a function of the inputs it has received. Typically, a neuron sends its activation as a signal to several other neurons. It is important to note that a neuron can send only one signal at a time, although that signal is broadcast to several other neurons.

For example, consider a neuron j, which receives inputs from neurons X_1, X_2, …, X_n. Input to this neuron is created as a weighted sum of signals from other neurons. This input is transformed to the scalar output y_j. The classical McCulloh and Pit neuron has an adjustable threshold μ_j. The output is then defined as

$$y_i = h\left(\sum_j (w_{ij} x_j - \mu_j)\right) \quad h(x) = 1 \quad \text{for } x \geq 0, \quad h(x) = 0 \quad \text{for } x \leq 0 \tag{4.106}$$

The activation y_j of the neuron can be given by some function of its net input, $y = h(y_{\text{in}})$, e.g., the logistic sigmoid function (S-shaped curve).

The neurons are arranged in layers. The standard three-layer structure has one input layer, one output layer and one hidden layer. The signals go through the layers in one direction. After a set of inputs has been fed through the network, the difference between the true or the desired output and the computed output represents an error. The sum of squared errors ESS is a direct measure of performance of the network in mapping inputs to desired outputs. By minimizing ESS, it is possible to obtain the optimal weights and parameters of the activation function $h(.)$.

Radial basis functions and NN

The radial basis functions are a special kind of neuron activation. Their characteristic feature is that their response decreases (or increases) monotonically with distance from a central point. The centre, the distance scale and the precise shape of radial functions are adjustable parameters. A typical Gaussian radial function has the form

$$h(x) = \exp\left(-\frac{(x-c)^2}{r^2}\right) \tag{4.107}$$

where c is the centre and r is the radius. Radial basis functions are frequently used for creation of NN for regression-type problems. Traditionally, a single layer network with m neurons is expressed by the model

$$f(x) = \sum_{j=1}^{m} w_j h_j(x) \tag{4.108}$$

where w_j are weights. For the training set x_i, y_i, $i = 1, \ldots, p$, the computation of weights is based on the minimization of the criterion

$$S = \sum_p (y_p - f_p)^2 \tag{4.109}$$

If a weight penalty term is added to the sum of squared errors, the ridge regression criterion occurs:

$$C = \sum_{p} (y_p - f_p)^2 + \sum_{j=1}^{m} \lambda_j w_j^2 \tag{4.110}$$

where λ_j are regularization parameters. For fixed parameters of functions $h(x)$, weight estimation is a typical linear regression task.

Regularized forward selection

The basic algorithm (FS2) starts with a set of candidate RBFs with different positions but of the same size, and an empty network [64]. Candidates are selected and added to the network one at a time while keeping track of the estimated prediction error. At each step the candidate that most decreases the sum of squared errors and has not already been selected is chosen to be added to the network. Initially, predicted error decreases, but as the network becomes bigger, its complexity increases and it eventually begins to over-fit the data. At that point, the predicted error starts to increase and the algorithm stops adding RBFs. As an additional safeguard against over-fitting, the method uses ridge regression and the regularization parameter λ is re-estimated after each iteration. The locations of the candidate RBFs are determined by the inputs in the training set so there are as many candidates as there are cases. The nominal width in each dimension is equal to the total spread of input values and is the same for each candidate. The FS2 strategy is frequently used for creation of NN regression models.

The utilization of neural networks for creation of non-parametric models predicting subjective hand grading is relatively simple. The resulting fit is usually sufficient and there are no problems with multi-collinearities and non-linearities. On the other hand, the resulting model contains a relatively high number of parameters and it is not simple to distinguish between the important and unimportant variables.

4.5 Concluding remarks

The statistical analysis of hand data is not a simple task and there exist plenty of possibilities. The selection of strategy is based on the manner of primary data extraction and the creation of a model is based on the probability or other assumptions. There exist many good techniques but the overall quality of the results of such analysis is critically dependent on the amount and quality of the primary data. Statistical techniques are capable of revealing some problems in the data according to the aim of the application. Generally, it is not possible to improve bad data or add new information without new and properly designed relevant measurements.

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5

Comparison of fabric hand evaluation in different cultures

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5.1 Introduction

In recent years, international trade in textile products, and specifically in apparel, has shown a dramatic increase, mainly due to trade agreements such as NAFTA, WTO, and GATT. Globalization, turning the world into a village, has made communication among trading countries a potential problem area, involving such factors as differences in meanings and definitions and (in terms of comprehension in the field of fabric hand) across cultures. Such differences could influence consumers' selections of apparel and textiles. Many studies have highlighted the possibilities of cultural differences in response to fabric hand (e.g. Anttila [1], Behery [2], and Fritz *et al.* [3, 4]). Presently, there are data to confirm this, covering culture and language differences that may affect verbal responses to fabric hand.

In the last 40 years, progress in the design of textile machinery has been remarkable, especially with respect to improvement of efficiency, automation, and productivity. The machines have been designed largely for high-speed production of textile products which can be supplied to textile consumers at competitive prices. However, the quality of textile materials produced by modern high-production textile processing sequences is not necessarily as good as that produced by traditional machines; rather, the quality of our textile materials is becoming poorer in many cases. This general trend towards lower-quality textile products is of particular significance in the case of wool fabrics and garments, which traditionally occupy the 'up-market' end of the spectrum of textile products because of their superiority in the important quality features of fabric hand, garment appearance and comfort.

Over the years, and in most of the literature reported, assessment of fabric hand has been made subjectively by various experts within the textile and clothing industries, as well as by the ultimate consumers themselves. This has made it necessary to study the comparison of fabric hand assessment as a result of different cultures and other human factors.

This chapter presents studies of the comparison of fabric hand assessment, both subjective and objective, covering the effects of cultures, measuring techniques and instruments. Also, the effect of language differences, terminologies and definitions will be discussed for the following countries (in alphabetical order):

- Australia
- China
- Hong Kong
- India
- Japan
- Korea
- New Zealand
- Taiwan
- United Kingdom (UK)
- United States of America (USA)

In addition, a survey of an international fabric hand, together with the basic requirements of an international objective measurement program, will be outlined.

5.2 Effects of culture, language and male vs female on fabric hand evaluation and their interaction (USA and Korea)

A study was conducted by Kim and Winakor [5] to explore the possibility of developing comparable sets of unipolar adjectives for consumer evaluation of fabric hand in the United States and Korea. Untrained judges were selected because results were intended to apply to consumers, not to textile professionals; unipolar adjectives avoided problems inherent in use of bipolar adjectives, particularly when two languages are involved. The Judges were native English-speaking residents of the United States and native Korean-speaking residents of Korea. A scale of 11 points was chosen for its ease of use, the need to avoid fatigue when judging several fabrics, and theoretical concerns. As in making real-life choices, judges could both see and touch fabrics. Fabrics were limited to seven shirting fabrics. Tentative explanations of cultural and language differences were proposed.

Three hypotheses were developed in this study:

1. USA and Korean consumers do not differ in their responses to fabric hand.
2. Male and female consumers do not differ in their responses to fabric hand.
3. For a specific end use, consumers prefer the same fabrics for members of their own gender as they prefer for the other gender.

5.2.1 Experimental design of the study

The study included four phases:

1. Focus group interviews
2. Word list development
3. Training
4. Final correction.

Stimuli were selected to represent shirting fabrics that might be worn by USA and Korean consumers, both male and female. All fabric swatches were white to reduce color effects. An 11-point unipolar scale was used.

Focus group interviews were designed to collect hand descriptors of fabrics and to explore gender and cultural differences among natives of Korea and the USA. Following a trial focus group, four focus groups were conducted, each consisting of participants representing one gender and one language. Stimuli for focus group discussions were five white fabrics, cut into 44 ¥ 44 cm swatches and selected for variety and familiarity to consumers so that respondents could give diverse and clear descriptions.

The list of unipolar adjectives was developed by collecting fabric hand descriptors from focus group interviews and literature review and by translating them into English or Korean. Textile experts who were fluent in both Korean and English reviewed the translations. Twenty-three adjectives and two preference statements were selected for the trial instrument. The six white shirting fabrics selected for the trial were cut into 20 ¥ 20 cm swatches. Twenty each of native Korean-speaking males and females and 20 each of native English-speaking males and females participated in trial administrations. Reponses to the 25 items were translated to approximately normalized ranks, which could range from –8 to +8.

After analysis of responses, 18 adjectives and the two preference statements survived for final data collection. Seven white shirting fabrics were selected from retail stores in the USA and Korea; swatches were prepared as for the trial (Table 5.1). Korean data were collected in the summer, from 140 students at Seoul National University in Seoul, half males and half females. USA data were collected in the fall, from 155 students at Iowa State University in Ames, 87 males and 68 females. Of the 87 male students, 17 were ineligible because they were not native English speakers. Therefore, 70 male students were retained for analysis. The 11-point certainty scale and transformation of responses to approximately normalized ranks were used, as in the trial.

Plots of means and standard deviations of responses of US and Korean males and females compared response patterns by gender and country of respondents. Analyses of variance were performed separately for each item using the total data set and using sub-samples by country and gender. The model for the total sample is:

Table 5.1 Description of fabrics for the final data collection

Fabric	Fiber content	Symbol	Whiteness	Description
Carded blend twill	65% rayon 35% polyester	A	White with medium yellowish cast	Twill weave, spun yarn
Crash	100% linen	B	White with slight yellowish cast	Plain weave, spun yarn
Flat crêpe	100% polyester	C	White with slight yellowish cast	Crêpe weave, filament yarn
Moss crêpe	80% acetate 20% rayon	D	White with slight greenish cast	Granite weave, filament yarn
Balanced taffeta	100% polyester	E	White with slight greenish cast	Plain weave, filament yarn
Oxford cloth	60% cotton 40% polyester	F	White	Half basket weave, spun yarn
Crash	50% polyester 50% rayon	G	White with medium yellowish cast	Plain weave, spun yarn

Source: 'Fabric hand as perceived by US and Korean males and females', by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

$$\begin{aligned} Y_{ijkl} &= \mathrm{m} + C_i + F_j + CF_{ij} + S_k + CS_{ik} + FS_{jk} \\ &\quad + CFS_{ijk} + \mathrm{e}_{ikl} + \mathrm{e}_{ijkl} \end{aligned} \tag{5.1}$$

where: C = country, i = USA or Korea
F = fabric, j = A, B, C, D, E, F, G
S = gender, k = male or female
$I = 1, \ldots, 70$ or $I = 1, \ldots, 68$ (respondents (R)
m = population mean
e_{ikl} = error term for country, gender, and their interactions; respondents within country and gender
e_{ijkl} = error term for fabrics and their interactions.

The term e_{ikl} represents the fact that subjects responded to the same items for each of the seven fabrics. Thus, the model could be described as a 'repeated measures' design. The model assumes that variances and correlations among fabrics are the same. To examine the possibility that this assumption was incorrect, the denominator degree of freedom for fabrics and interactions involving fabric was divided by 6, the degrees of freedom for fabric (that is, the denominator would be 324 rather than 1945). This did not change conclusions regarding significance.

Analysis of data separately by gender and country revealed differences in details, as compared with analysis of all data combined. However, no major new conclusions resulted from the analysis of data by sub-samples. For these data, observed differences in variances of means by gender or country seemed to have limited impact on the outcome of the analysis of variance and overall results.

5.2.2 Results of the study of fabric hand as perceived by US and Korean males and females

The results focused on the main effects of gender and country, plus the interaction of gender by country. Results are described as significant when the F-value exceeded the 5% level.

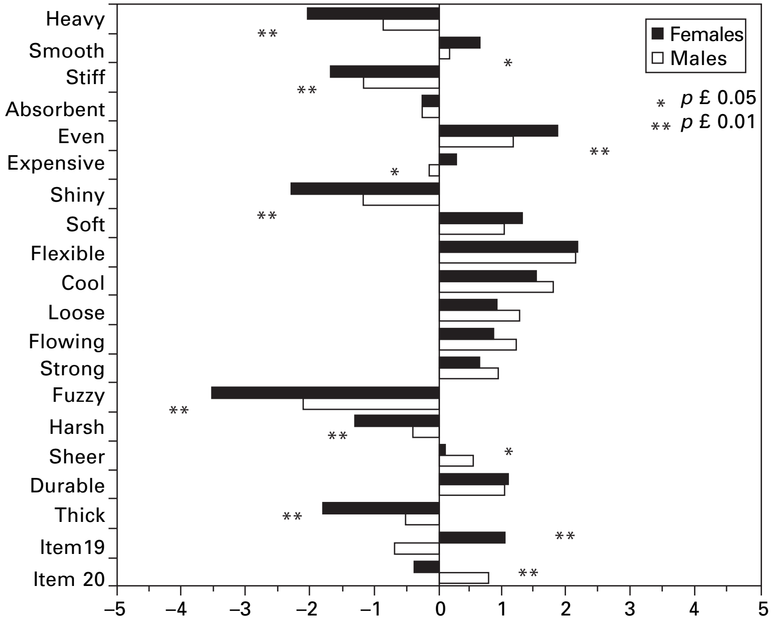
Effects of gender, country and their interactions

The main effects of gender and country, as well as the interaction of gender by country, are significant for two words: smooth and harsh (Table 5.2). Figure 5.1 indicates that females were more certain than males when the fabrics were smooth and not harsh. English-speaking judges were quite certain that the fabrics were smooth and not harsh; Korean-speaking judges were of the opposite opinion but not very certain (Fig. 5.2). Figure 5.3 illustrates the interaction of gender and country; for smooth, Korean males and females

Table 5.2 F-values for analysis of variance of transformed responses using total sample for 20 items

Item	Fabric	Sex	Country	S ¥ F	C ¥ F	C ¥ S	S ¥ C ¥ F
Heavy	300.50**	31.31**	18.64**	2.48*	4.02**	0.34	2.68*
Smooth	243.73**	5.16*	64.37**	3.41**	6.40**	5.90*	0.62
Stiff	386.39**	8.19**	16.56**	8.80**	2.44*	0.03	3.63**
Absorbent	65.14**	0.00	0.06	6.95**	4.28**	2.87	3.40**
Even	129.08**	8.51**	0.34	2.28*	2.22*	0.26	0.48
Expensive	71.52**	5.00*	3.73	2.59*	5.48**	0.64	2.98**
Shiny	118.09**	19.34**	16.24**	1.78	3.88**	0.20	1.71
Soft	392.77**	2.47	4.32*	6.10**	11.42**	5.15*	0.53
Flexible	324.20**	0.03	22.04**	5.90**	9.29**	0.73	1.45
Cool	143.25**	1.81	28.53**	1.61	55.80**	15.76**	3.08**
Loose	75.19**	2.52	39.96**	2.28*	3.67**	5.74*	0.69
Flowing	258.13**	2.74	3.70	22.91**	2.49*	10.57*	1.38
String	97.23**	1.78	36.52**	1.63	0.36	0.09	1.37
Fuzzy	108.63**	28.25**	11.22**	3.15**	5.53**	1.63	1.51
Harsh	221.26**	18.64**	109.82**	4.82**	6.08**	11.83**	2.36*
Sheer	216.96**	3.93*	8.15**	3.58**	26.07**	0.11	3.69**
Durable	87.02**	0.06	12.54**	1.26	5.16**	0.01	1.08
Thick	266.8**	40.36**	0.26	2.96**	2.57*	0.22	1.68
Item 19	22.81**	41.96**	2.85	17.27**	21.74**	10.59**	6.30**
Item 20	22.00**	19.50**	0.43	70.43**	28.32**	0.05	2.93**

$^{*}p < 0.05$
$^{**}p < 0.01$
Source: 'Fabric hand as perceived by US and Korean males and females', by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

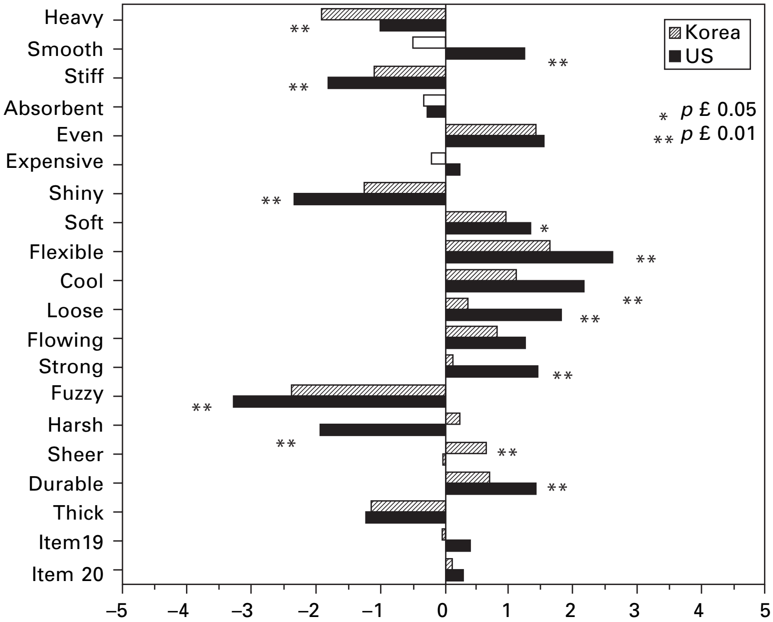


5.1 Means for male and female judges for 20 items for both countries across all fabrics. *Source:* 'Fabric hand as perceived by US and Korean males and females,' by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

responded nearly identically that the fabrics were not smooth. US males and females were both certain that smooth described the fabrics, but females were more certain about this than males were. Thus, the significant main effect for gender resulted from the responses of US females. The pattern was similar for harsh, but in the opposite direction (i.e. not harsh).

The main effects of gender and country but not the interaction between them are significant for heavy, stiff, shiny, fuzzy, and sheer. For four of these adjectives – all but sheer – both Korean and US females were more certain than males of their own cultures that the words did not describe the fabrics (Fig. 5.3), Korean judges were more certain that the fabrics were not heavy, while US judges were more certain that the fabrics were not stiff, shiny or fuzzy. In contrast, males were more certain than females that sheer described the fabrics and Korean judges were more certain of this than US judges were; these differences, while significant, were moderate. Figure 5.3 shows that US males and Korean females responded nearly identically to sheer, while US females and Korean males responded in opposite directions.

The main effect of gender, but not of country nor the gender by country interaction, is significant for even, expensive and thick. Females were more certain than males that the fabrics were even and not thick. For both even

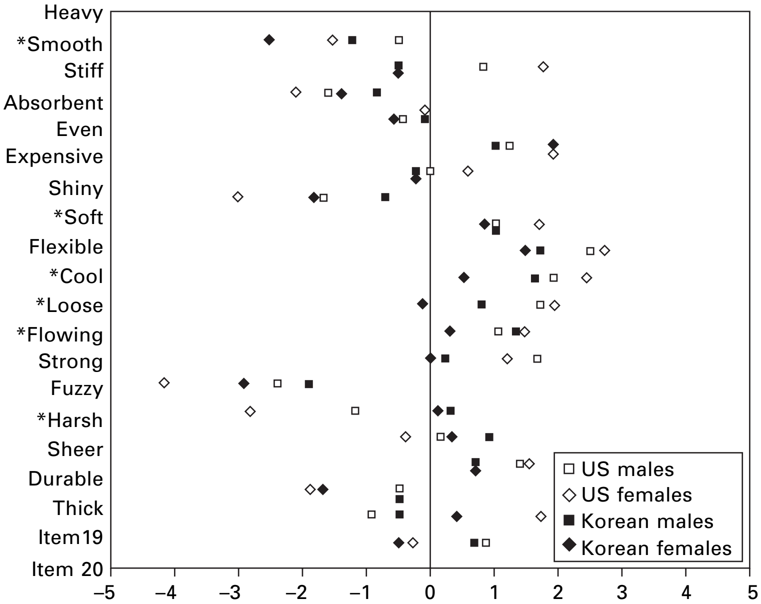


5.2 Means for US and Korean judges for 20 items for both genders across all fabrics. *Source:* 'Fabric hand as perceived by US and Korean males and females,' by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

and thick, Korean and US males agreed, as did Korean and US females. According to Fig. 5.3, nobody was very certain that the fabrics were expensive; the only respondents who described them as even somewhat expensive were US females.

The main effect of country, but not of gender nor their interaction, is significant for flexible, strong, and durable. US judges were more certain that these words described the fabrics than were Korean judges. For all three adjectives, Fig. 5.3 shows that males and females within the same culture nearly agreed in their responses.

For three adjectives, country and gender by country are significant, but not the main effect of gender. These are soft, cool, and loose. For soft, US females were more certain than the rest of the judges; the country effect seemed to result from the distance between their responses and those of all other judges. US judges were more certain that cool and loose described the seven fabrics. For cool, the country effect is also rather misleading: Korean and US males differed a little, while Korean females were least certain and US females most certain that this adjective described the fabrics. Figure 5.3 reveals that the country effect is most meaningful for loose. Korean judges



5.3 Means for judges by gender and country for 20 items across all fabrics (asterisks indicate adjectives for which the gender by country interaction is significant at the 1% or 5% level). *Source:* 'Fabric hand as perceived by US and Korean males and females,' by H. Kim and G. Winakor, from *Clothing and Textiles Research Journal*, vol. 14, no. 2, p. 133, 1996. Copyright Sage Publications.

were considerably less certain than US judges about the appropriateness of this word. For flowing, only the gender by country interaction is significant. Korean females were least certain that flowing described these fabrics; all other judges agreed fairly closely.

5.2.3 Effects of fabric and its interactions

Selected examples of two- and three-way interactions involving fabric are discussed briefly, as they may clarify gender and country effects. Although fabrics were limited to shirtings in variations of white, the main effect for fabric is highly significant for every adjective (Table 5.2).

For six adjectives – heavy, stiff, absorbent, expensive, harsh, and sheer – both two-way interactions and the three-way interaction of gender by country by fabric are significant. Sheer and stiff have the highest F-values of any adjectives for the three-way interaction. Stiff also has the highest F-value for fabric. For two fabrics (C, flat crêpe, judged sheer; and F, oxford cloth, judged not sheer), Korean and USA male judges differed little in their responses, while US females were most certain. For fabrics B (linen crash), E (taffeta), and G (polyester–rayon crash), US judges agreed and Korean judges agreed, regardless of gender, but in all cases Korean judges were more certain of their responses – particularly in the case of *B*, which they judged to be sheer while US judges were uncertain. Fabric *E* was judged not sheer by Korean speakers, while US judges were divided – females, not sheer; males, sheer. All judges rated *G* as sheer. Fabric *A*, a twill, was judged not sheer by all, but females were more certain. Only Korean males thought that *D* (moss crêpe) was sheer; all others were uncertain.

5.2.4 Verification of the three developed hypotheses

Hypothesis 1

As mentioned earlier, the first hypothesis states that US and Korean consumers do not differ in their responses to fabric hand. A critical issue in investigating cultural differences in evaluation of fabric hand is differentiating whether the adjectives are equivalent in meaning in the two languages from whether fabric hand perceptions differ in the US and Korean cultures.

From the results obtained and illustrated in Table 5.2 and Fig. 5.3, this hypothesis was rejected. The significance of the main effect of country in Table 5.2 implies that a majority of the 18 adjectives may have a different central meaning in English and Korean. Also, cultural differences are implied in the main effect of country, as well as in the interactions of country by fabric.

Hypothesis 2

The second hypothesis states that male and female consumers do not differ in their responses to fabric hand. There is evidence to reject Hypothesis 2 for native English speakers. Females in both cultures were more certain of their responses, but the female–male difference was less consistent among Korean judges. Cultural differences were greater for females than for males, as shown by the gender by country interaction. Moreover, US judges of both genders were more certain of their responses than were Korean judges of the corresponding gender. Responses during the focus group sessions suggested that in Korea, more than in the US, fabric hand is seen as the female's topic, part of the female role; however, quantitative results offer little support for this supposition.

Hypothesis 3

The third hypothesis states that, for a specific end use, consumers prefer the same fabrics for their own gender and for the other gender. This hypothesis is rejected in part. For six of the seven fabrics, judges from the two cultures agreed in direction, although not in degree, about which fabrics were more appropriate for males and for females. Gender and cultural differences were evident, but there remained substantial agreement among respondents about preferences for these shirting fabrics for wearers of a specific gender.

5.2.5 Conclusions on the study of the effect of culture, language and male vs female on fabric hand evaluation and their interaction in USA and Korea

The results of this study suggested practical problems in international trade of apparel and textiles because of cultural differences among countries, as well as differences of meaning among languages. Information about cultural and semantic differences for fabric hand and subtle differences in perceptions between males and females in different countries should interest manufacturers and retailers in the international market. These differences in response to fabric hand also suggested a need to explore differences in subjective response to other properties of fabrics and clothing.

Parallel lists of descriptors in Korean and other languages could be used by textile manufacturers for evaluating textiles targeted for export markets. Standardized lists of textile hand descriptors in the languages of exporting and importing countries would be useful for manufacturers, consumers, and researchers. Given the continuing globalization of trade in fabrics and apparel, efforts to improve verbal communication are essential.

5.3 International comparison of fabric hand (Australia, China, Hong Kong, India, Japan, Korea, New Zealand, Taiwan, UK and USA)

Studies were conducted [6, 7] to investigate the levels of commonality and agreements between panels of judges from the different countries mentioned above in assessing fabric hand for both summer and winter men's suiting materials. The aims of the study were as follows:

- Establishing whether a panel of individuals assesses the hand of a series of men's outerwear fabrics in a consistent manner
- Ascertaining whether panels of expert judges from the different countries mentioned above ranked fabric hand in a similar manner
- Finding out the relationships between the experts' assessments of fabric hand and the primary hand characteristics outlined by Kawabata and Niwa [8].

5.3.1 Experimental design and procedure

Fabrics

A total of 214 winter-weight and 156 summer-weight outerwear suiting fabrics, produced from wool, wool-blend and synthetic fibers were used in the study. The fabrics were all commercially produced, and the details are given in Table 5.3.

Table 5.3 Commercially produced fabrics used in hand survey

Fabric weight range	No. of samples	
	Winter fabrics, 220–320 g/m^2	Summer fabrics, 160–220 g/m^2
Composition of sample		
100% wool worsted	157	76
Worsted synthetic blends	36	74
100% synthetic	15	6
Other[a]	6	0
	214	156
Fabric construction		
Plain weave	30	156
Twill	163	0
Hopsack	19	0
Other[b]	2	0
	214	156
Surface finish		
Clear surface	149	–
Semi-clear surface	61	–
Unclear surface	4	–

[a] Includes pure wool, pure cashmere, cashmere/wool, and cashmere/synthetic blends.
[b] Barathea and knitted constructions.

Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

Assessment of fabric hand

The panel of judges was given the following instructions when asked to assess the 370 fabrics:

1. Judge the fabrics following your country's base and following your own definition of 'good hand', but the effects of fashion, color and pattern must be excluded so that only fabric hand is judged.
2. The grading of 'good hand' is as shown in Table 5.4.

Table 5.4 Grading of good hand

Grade	Rating
Excellent	5
Good	4
Average	3
Below average	2
Poor	1
Not in use	0

Judging final panels

Independent sets of expert judges were selected from a variety of areas within the textile and clothing industries to represent each of the seven nominated countries. The 17 expert Australian judges were drawn from the following areas of these industries: fabric design (seven judges, including two with marketing and two with quality control responsibilities), finishing (two judges), clothing manufacture (three judges, including one with retaining responsibilities), merchandising (two judges), marketing (one judge) and fabric research and development (two judges). The six other sets of expert judges had a similar mix of background and experience, with the following total numbers: 123 from Japan, 13 from New Zealand, 15 from India, 15 from the USA, 16 from China (PRC), and 12 from Hong Kong/Taiwan. In the study, another set of judges were used, consisting of eight Australians with no particular experience in these industries (consumer judges) to establish how close to their ultimate consumers the expert judges were in their assessments of fabric hand.

The selection of a final panel of judges to represent the hand preferences of a particular country was made on the basis of the correlation of each judge's hand assessments with those of the mean assessments of his or her national panel. In this manner, seven national panels were assembled, each consisting of the eight judges whose hand preferences most closely matched the mean assessments of their national groups.

5.3.2 Results of comparison between the different countries and consumers

Within-group analysis

The level of agreement on fabric hand assessment within each of the eight (seven experts and one consumer) panels of judges was established using the following three-step procedure:

1. The mean fabric hand assessment was calculated within each panel for each fabric.

2. Correlation coefficients were obtained for the relationship between the hand assessments of each judge and the mean assessment of his or her national panel.
3. The mean of these correlation coefficients was calculated for each national panel.

The average correlation coefficients of all fabrics within a group are quoted in Table 5.5, which shows that each of the panels of judges had very good within-group agreement for winter-weight fabrics. Similarly, good but slightly lower within-group agreement was obtained for each panel for the summer-weight fabrics (Table 5.6). The Chinese expert judges showed similar within-group agreement to the other national panels for both men's winter and summer materials.

One reason that the within-group correlation coefficients for the New Zealand panel were lower than for the other panels might have been associated

Table 5.5 Correlations between mean hand assessments of national panels for 214 winter fabrics

	Australia	New Zealand	India	USA	PRC	Hong Kong/ Taiwan
Japan	0.85	0.76	0.82	0.80	0.62	0.84
Australia		0.86	0.91	0.87	0.58	0.87
New Zealand			0.83	0.83	0.71	0.83
India				0.86	0.82	0.85
USA					0.56	0.83
PRC						0.65

Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

Table 5.6 Correlations between mean hand assessments of national panels for 156 summer fabrics

	Australia	New Zealand	India	USA	PRC	Hong Kong/ Taiwan
Japan	–0.34	–0.30	–0.40	–0.33	0.75	–0.03
Australia		0.82	0.78	0.81	–0.15	0.72
New Zealand			0.76	0.74	–0.20	0.55
India				0.76	–0.26	0.55
USA					–0.13	0.63
PRC						0.13

Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

with the relatively strong (large fiber diameter) wool that is grown and processed in the New Zealand textile industry.

The high within-group correlation coefficients for the winter-weight fabrics indicated that judges with experience in the textile and/or clothing industries definitely agreed, within each national group, on the hand rating of these fabrics. The slightly lower correlations for the summer-weight materials signified that the judges had more difficulty in rating these samples.

Between-group analysis

The situation is quite different when comparing the between-group correlation coefficients for the summer-weight fabric hand assessments. In this case, there were high correlation coefficient values (0.74 to 0.82) for comparison between the Australian, New Zealand, Indian, and US judges. If the Hong Kong/Taiwan panel of judges were added to this group, there are moderate correlation values for this panel and with other panels (from 0.55 to 0.72).

However, the three between-group correlation coefficients involving the Japanese panels all have small negative values, indicating very little correlation between the Japanese panel of judges and any of the other three panels in the case of the summer fabrics. It is to be expected that these differences may be explained in terms of the different weightings given to the primary hand characteristics in the assessment of fabric hand by the different national panels of judges.

The between-group correlation coefficients involving the Japanese and Chinese panels on the one hand, and each of the other national panels on the other, averaged –0.28 and –0.1 for the Japanese and Chinese panels, respectively. Values of these correlations ranged from a low 0.13 to negative values as high as –0.40. The between-group correlation for the Japanese and Chinese panels was 0.75.

The analysis of summer fabric hand assessments indicates that at least two different, and somewhat opposite, assessments were made of the hand of men's summer fabrics as indicated by the size and signs of the correlation coefficients in Table 5.7. One consistent hand assessment was made in Australia, New Zealand, India, the USA and, to a slightly lesser extent, in Hong Kong and Taiwan. A second different, but again consistent, hand assessment was made in Japan and the PRC. There was also a significant level of direct disagreement between the Japanese/Chinese assessments and those of the other five national panels.

It is unclear whether these two different types of fabric hand preference are based on cultural or climatic differences or some combination of both. Certainly, Japan and parts of China experience annual periods of hot (>30 °C) and very humid (>90% relative humidity) weather. Similar conditions also apply in some coastal areas of Australia, India, the USA, and Taiwan, as

Table 5.7 Mean values[a] of the between-group correlation coefficients for the hand assessments of each national panel with the other six panels for the winter and summer fabrics

National panels	Winter fabrics (A)	Summer fabrics (B)
Japan	0.78	–0.28
Australia	0.82	0.78
New Zealand	0.80	0.74
India	0.80	0.71
USA	0.79	0.74
PRC	0.61	–0.19
Hong Kong/Taiwan	0.81	0.53

[a] Mean values taken only for the cases where the sign is constant.

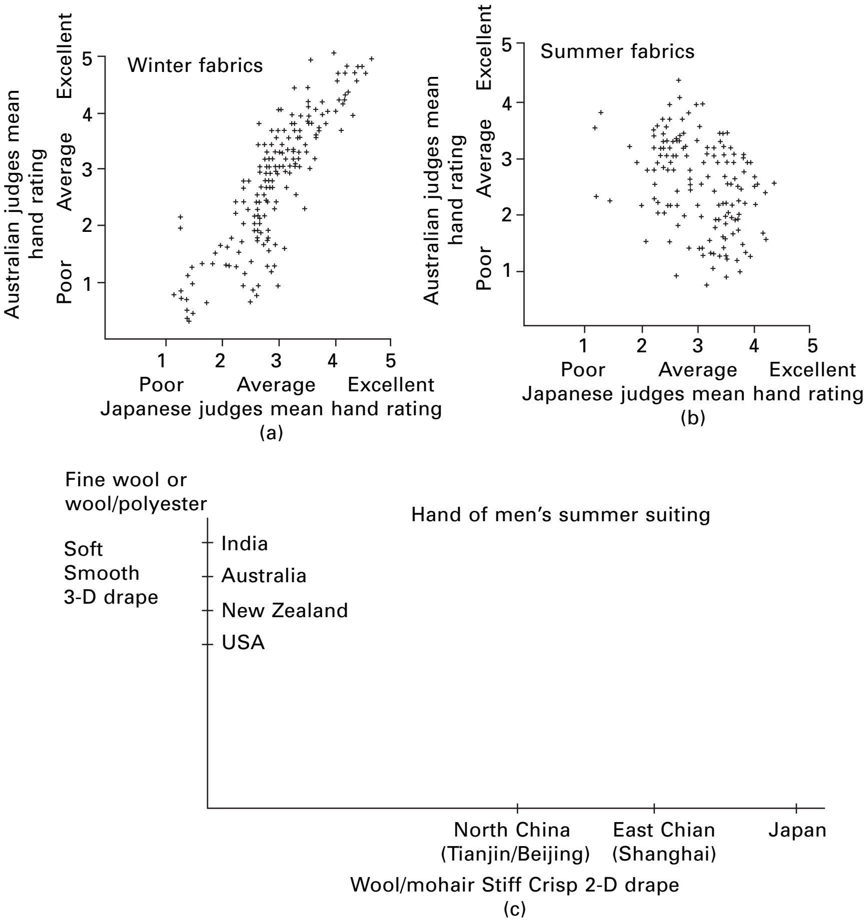
Source: 'Measuring and interpreting low stress fabric mechanical and surface properties. Part IV: Subjective evaluation of fabric hand', by T.J. Mahar and R. Postle from *Textile Research Journal*, vol. 59, no. 12, p. 721, 1989. Copyright Sage Publications.

well as Hong Kong. One might also argue that of the seven countries investigated, Japan, the PRC, Hong Kong/Taiwan, and India have maintained their strong cultural identities, despite the obvious influence of Western culture, e.g. the wearing of Western-style suits.

Concerning between-group agreement for winter suiting materials (Table 5.7A), the two Chinese panels show slightly lower but still significant between-group agreement with the other national panels of expert judges for men's winter suiting materials. Between-group agreement is generally higher for the North China panel (Tianjin/Beijing) than for the East China panel (Shanghai).

Concerning between-group agreement for summer fabrics (Table 5.7B), the two Chinese panels show good between-group agreement only with the Japanese panel for the hand of men's summer suiting materials. The agreement with the Japanese panel is slightly stronger for the Shanghai panel than for the Tianjin/Beijing panel. There is no statistically significant between-group agreement for the two Chinese panels with the other national panels.

The hand of men's summer suiting materials may be represented on a two-dimensional chart according to market preference, as shown in Fig. 5.4(c). In Japan and to a slightly lesser extent China, the market preference is clearly for very lightweight, relatively stiff, crisp suiting materials having some relatively coarse fabrics, usually mohair, in the weft yarns. These fabrics tend to spread or bend in only two dimensions, thus giving a characteristic drape whereby the contact between the fabric and the skin is relatively small. These draping properties are particularly suited for hot tropical climatic conditions. In the other countries surveyed – Australia,



5.4 Graphical representation of the agreement between the mean hand ratings of eight Japanese judges and eight Australian judges for (a) 214 winter fabrics and (b) 156 summer fabrics. (c) Schematic representation of two axes for the hand for men's summer suiting material. *Source:* 'Fabric handle a comparison of Australian and Japanese assessments of suiting materials', by T.J. Mahar and R. Postle, from *Australian Textiles*, Jan–Feb. 1982. Reproduced with permission from *Australian Textiles*.

New Zealand, India, and the USA – the market preferences were for relatively smooth, fine, soft components of fabric hand for these summer suiting materials and appear to be very similar to those for the winter suiting materials, i.e. smoothness and softness. These fabrics would normally be made from fine wool or wool/polyester blend.

Correlation with subjectively assessed primary hand values

Besides the hand ratings previously discussed, each of these fabrics has been rated by the Japanese panel for the various subjective fabric characteristics previously noted as being the important primary components of fabric hand, namely *koshi* (stiffness), *numeri* (smoothness) and *fukurami* (fullness and softness) for the winter fabrics; and *koshi* (stiffness) and *shari* (crispness) for the summer fabrics. Average stiffness, smoothness, and fullness and softness ratings were calculated for each winter fabric, and similarly, stiffness and crispness ratings were calculated for each summer fabric. The average ratings of these subjective fabric characteristics (made by the Japanese panel of judges) were correlated with the mean total hand rating of each of the four panels of judges.

The results for the winter-weight fabrics are given in Table 5.8(a). From inspection it is clear that, in the hand assessment for the winter-weight

Table 5.8 Correlation between fabric hand ratings and subjectively assessed fabric characteristics
(a) Winter weight fabrics

Panel of judges	Smoothness (*numeri*)	Softness/fullness (*fukurami*)	Stiffness (*koshi*)
Japanese	0.87	0.84	–0.22
Australian	0.93	0.81	–0.40
New Zealand	0.79	0.72	–0.19
Indian	0.87	0.74	–0.39
United States	0.82	0.69	–0.39
Chinese			
Shanghai	0.54	0.62	0.31
Tianjin/Beijing	0.65	0.69	0.06
Consumers	0.67	0.64	0.01

(b) Summer weight fabrics

Panel of judges	Stiffness (*koshi*)	Crispness (*shari*)	Anti-drape stiffness (*hari*)	Softness/fullness (*fukurami*)
Japanese	0.51	0.74	0.43	0.25
Australian	–0.70	–0.74	–0.63	0.12
New Zealand	–0.60	–0.69	–0.52	0.32
Indian	–0.73	–0.75	–0.71	0.11
United States	–0.61	–0.65	–0.55	–0.02
Chinese				
Shanghai	0.32	0.53	0.27	0.15
Tianjin/Beijing	0.20	0.30	0.17	0.19
Consumers	–0.69	–0.68	–0.58	0.02

Source: International Fabric Hand Survey, by T.J. Mahar and R. Postle. Reproduced with permission from the Textile Machinery Society of Japan.

fabrics, each panel of judges rates fabric surface smoothness (*numeri*) as the most important of the three primary characteristics. Indeed, the high correlation coefficients (*ranging* from 0.79 for the New Zealand panel to 0.93 for the Australian panel) indicate that fabric smoothness has a very strong influence on the determination of overall fabric hand. Fabric fullness and softness (*fukurami*) is only slightly less important for each panel of judges, as evidenced by the slightly lower positive correlations (from 0.72 for the New Zealand panel to 0.84 for the Japanese panel).

The low negative correlation coefficients between winter fabric hand and fabric stiffness (from –0.40 for the Australian panel to –0.19 for the New Zealand panel) indicate that each panel of judges tends to prefer fabrics of lower stiffness (*koshi*), with the Australian and Indian judges showing a slightly stronger preference in this respect. Because the absolute value of the fabric stiffness correlations is much less than the fabric smoothness and fabric fullness and softness values, fabric stiffness appears to be by far the least important (though still a significant) factor in the assessment of winter fabric hand.

When considering the summer fabrics, the difference between the fabric hand assessments of the Japanese panel on the one hand, and the Australian, New Zealand, Indian and US panels on the other, are shown quite clearly by the correlation coefficients in Table 5.8(b). The Japanese panel shows a clear preference for summer fabrics of relatively high stiffness and crispness when rating overall fabric hand, as evidenced by the positive correlation coefficients, 0.51 and 0.74, with fabric stiffness and fabric crispness respectively. Conversely, the Australian, New Zealand and Indian panels have clearly rated fabric stiffness and fabric crispness as undesirable characteristics when assessing summer fabric hand, as evidenced by the relevant correlation coefficients (ranging from –0.74 for the Australian and Indian panels' correlation with fabric crispness to –0.60 for the New Zealand panel's correlation with fabric stiffness).

The correlation coefficients for the two Chinese panels between overall fabric hand assessments and the subjectively assessed primary components of fabric hand for both the winter and summer suiting materials are quoted in Table 5.8(a) and (b). The two Chinese panels are in agreement with the other national panels in placing most emphasis on the primary characteristics of fabric smoothness and fabric fullness when assessing the hand of men's winter suiting materials. For the summer fabrics, however, the correlation coefficients given in Table 5.8(b) show that the two Chinese panels assess the hand of men's suiting materials by weighting the primary hand components of stiffness, crispness, and fullness in a manner similar to the Japanese panel. The positive correlation coefficients for both the Chinese panels and the Japanese panel of judges indicate that fabric springy-stiffness, crispness and anti-drape stiffness are regarded as desirable characteristics in their summer fabric hand assessments. The opposite is true for the four other national panels.

5.3.3 Conclusions of the study of comparison of fabric hand assessments

A number of conclusions relevant to the overall concept of fabric hand and its measurement can be drawn from the results of this study.

1. It could be concluded with a high degree of confidence that a panel of judges from the textile and/or clothing industries of any one of the countries selected can produce a large measure of agreement when asked to assess the fabric hand of a very wide range of men's suiting materials. The agreement is better for winter-weight fabrics than for summer-weight fabrics.
2. As far as winter-weight fabrics are concerned, there is a very large measure of agreement for hand ratings between panels of Australian, Japanese, New Zealand, and Indian judges drawn from the textile and related industries in each of the four countries. Furthermore, it is scientifically possible to relate these judges' ratings of fabric hand to subjectively assessed measurements of fabric smoothness (*numeri*), fabric softness and fullness (*fukurami*) and, to a very much lesser extent, fabric stiffness (*koshi*). All judges placed a very high emphasis on fabric smoothness and to a slightly lesser extent on fabric softness and fullness, when assessing the hand of winter-weight materials. The same judges exhibited a slight tendency to prefer winter fabrics of lower stiffness in their assessments of hand, but much less emphasis was placed on fabric stiffness for winter fabrics than in the case of hand assessments for summer-weight fabrics. The judges seem to accept fairly readily that winter materials, being relatively thick, are fairly stiff, and accordingly, high levels of fabric stiffness were not severely penalized in their assessments of fabric hand for winter materials.
3. The situation is, however, very different for the summer-weight materials. Firstly, it is in this area that the Japanese panel of judges shows a marked difference in its assessment of fabric hand when compared to any of the other panels. The Japanese judges clearly prefer relatively stiff (*koshi*) and/or crisp (*shari*) fabrics in their assessments of lightweight fabric hand, but the exact opposite applied for the Australian, New Zealand, and Indian judges who showed a very clear preference for fabrics of relatively low stiffness and/or crispness when assessing lightweight fabric hand. The extension of the hand survey to include other Asian countries (e.g. Philippines, Taiwan, Hong Kong), as well as European countries (e.g. Germany, Italy, UK) may help to explain this apparently culturally based

difference in hand expectations between the Japanese judges and the other national panels of judges surveyed so far in this study.

4. The judges from both Chinese panels, in common with the judging panels from the other countries surveyed, placed high emphasis on fabric smoothness and fabric fullness when assessing the hand of winter-weight materials. For the summer suiting materials, the two Chinese judging panels were in reasonable agreement with the Japanese judging panel in their clear preference for relatively stiff and/or crisp fabrics in their assessments of lightweight fabric hand for men's summer suiting.

The differences in fabric hand preferences noted in this work may be traced to differences in cultural background and different fashion preferences between Eastern and Western nations.

5.4 Fabric hand equations for Australia, New Zealand, India and USA

A series of 10 equations for the translation of the Primary Hands (PHs) of men's suiting fabrics into Total Hand Values (THVs) is presented according to the model used by Kawabata [11]. These equations relate subjectively assessed PHs to fabric hand assessments (THVs) of expert judges drawn from the textile and clothing industries of Australia, New Zealand, India and the USA for both winter-weight and summer-weight suiting fabrics. Results based on the hand preferences of a group of consumers drawn from the Australian marketplace are also included.

An international survey [7] was undertaken involving fabric hand assessment of the same sets of fabrics as were studied before (Section 5.3.1), by similar panels of expert judges. The survey also included a panel of consumers or people with no textile expertise drawn from the Australian marketplace.

5.4.1 Experimental design and procedure

Each of the expert judges was asked to assess for fabric hand small (20 cm ¥ 10 cm) samples of the 214 winter and 156 summer fabrics. In their assessments, the judges were requested to ignore the effect of fabric color and pattern. The judges were asked to assess subjectively, without reference to standard samples, the hand of each fabric according to the rating scale given before. Approximately 15 judges from each country completed the survey. The individual hand ratings of each judge were used to calculate the average hand assessment for each of the national panels of judges.

Each judge's individual rating was then correlated to the mean hand rating of his or her national group. The subgroup of eight judges from each country who showed the highest correlation with their group mean rating was then selected as the panel of expert judges who best represent the fabric hand preferences of their country. Besides the fabric hand ratings previously discussed, each of these fabrics was subjectively rated by the Japanese panel for the various primary hand expressions, or fabric characteristics, quoted by Kawabata [11] as being the important primary components of fabric hand. These primary components, which are given in Table 5.9, are *koshi* (stiffness), *numeri* (smoothness), *fukurami* (softness and fullness) for the winter fabrics; and *koshi* (stiffness), *shari* (crispness), *hari* (anti-drape stiffness), and *fukurami* (softness and fullness) for the summer fabrics.

Table 5.9 Fabric primary hand values

Winter	*Koshi*
	Numeri
	Fukurami
Summer	*Koshi*
	Shari
	Hari
	Fukurami

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

5.4.2 Results of fabric hand equations for Australia, New Zealand, India and USA

The primary hand ratings of the Japanese panel of judges have been used to predict the group mean hand ratings of each of the national panels of expert judges. The calculations followed the procedure adopted in the model proposed by Kawabata [11] to predict the hand preferences or total hand values of the Japanese panel of expert judges.

The general form of the mathematical model used to predict Japanese preferences for fabric hand is:

$$\text{Hand rating (or Total Hand Value, THV)} = C_0 + \sum_{i=1}^{k} Z_i \tag{5.2}$$

$$\text{where} \quad Z_i = C_{i1}\left(\frac{Y_i - M_{i1}}{\sigma_{i1}}\right) + C_{i2}\left(\frac{Y_i^2 - M_{i2}}{\sigma_{i2}}\right) \tag{5.3}$$

Y_i are the handle characteristics given in Table 5.8; M_{i1}, M_{i2}, σ_{i1} and σ_{i2} are the mean values of Y and Y^2 and the standard deviations of Y and Y^2 respectively (see Table 5.10 for values); and C_0, C_{i1} and C_{i2} are constants.

Table 5.10 Values of the means and standard deviations for each of the PH and PH^2 defined by Kawabata as being necessary for the objective specification of fabric hand for 214 winter and 156 summer fabrics

	M_{i1}	M_{i2}	s_{i1}	s_{i2}
(a) Winter fabrics				
i = 1: *Koshi*	5.7093	33.9032	1.1434	12.1127
i = 2: *Numeri*	4.7537	25.0295	1.5594	15.5621
i = 3: *Fukurami*	4.9798	26.9720	1.4741	15.2341
(b) Summer fabrics				
i = 1: *Koshi*	4.6089	22.4220	1.0860	11.1468
i = 2: *Shari*	4.7480	24.8412	1.5156	14.9493
i = 3: *Fukurami*	4.9217	25.2704	1.0230	10.1442
i = 4: *Hari*	5.3929	30.7671	1.2975	14.1273

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The values for the constants used in the model to determine the contribution to total hand value of the primary hand expressions have been published by Kawabata [11] for the case of the Japanese panel of expert judges. These values and the corresponding values for the non-Japanese expert and consumer sub-group panels of eight judges are given in Tables 5.11 and 5.12 for the winter and summer fabrics, respectively. The values of these constants were calculated with the aid of a standard multiple linear regression technique using the fabric hand ratings obtained in the international survey.

The values of the multiple correlation coefficients in Tables 5.11 and 5.12 with the exception of the US summer fabric assessments are high, ranging from 0.79 for the consumer summer fabric ratings to 0.94 for the Australian winter fabric ratings. High multiple correlation coefficients indicate that the model based on Japanese subjective assessments of the primary hand expressions can be used to predict the fabric hand preferences of the non-Japanese panels of expert and consumer judges to the level of accuracy applicable to the Japanese expert panel. In the case of the US summer fabric assessments the lower value of the multiple correlation coefficient (0.70) indicates less reliability when the Japanese model is applied. This effect may be related to the dominance of synthetic and cellulosic fibers in the men's suit market in the USA, particularly for summer fabrics. For the present international survey of fabric hand, the fabrics had been collected in Japan and are predominantly pure wool and wool/synthetic materials. The results shown in Table 5.12 indicate that, in order to achieve a higher level of reliability of prediction for US summer fabric hand, another primary hand expression (derived from lightweight synthetic and cellulosic materials) may be required.

Table 5.11 Constants and multiple correlation coefficients for the winter fabric HV-THV translation equations for each national judging panel

Constants for each judging panel	Winter Primary Hand (PH) expressions Stiffness (*koshi*)	Smoothness (*numeri*)	Softness and fullness (*fukurami*)	Multiple correlation coefficient	C_0
Japanese					
C_1 (PH)	0.6750	–0.1887	0.9312	0.90	3.1466
C_2 $(PH)^2$	–0.5341	0.8041	–0.7703		
Australian					
C_1 (PH)	0.3810	1.2622	–0.0376	0.94	2.7768
C_2 $(PH)^2$	–0.3282	–0.1429	–0.0282		
New Zealand					
C_1 (PH)	0.4620	1.3449	–0.1562	0.86	3.1449
C_2 $(PH)^2$	–0.3644	–0.7663	0.2011		
Indian					
C_1 (PH)	0.7091	1.2617	–0.4972	0.88	3.0380
C_2 $(PH)^2$	–0.6818	–0.2446	0.3467		
United States					
C_1 (PH)	0.4146	1.4450	–0.2489	0.85	3.1351
C_2 $(PH)^2$	–0.4842	–0.6288	0.1343		
Consumers					
C_1 (PH)	1.2271	1.1203	0.4430	0.83	3.1483
C_2 $(PH)^2$	–0.9793	–0.4196	–0.3986		

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The average hand rating for each national panel of the fullest of 214 winter fabrics, given by the value of the constant C_0, falls within a relatively narrow band, ranging from 2.78 for the Australian expert panel to 3.15 for the Japanese expert and Australian consumer panels. This result indicates that all panels had a similar average level of appreciation for the hand of the winter fabrics.

For the summer fabrics, it has been shown that although there is a good level of agreement among the non-Japanese panels of judges, there is a marked tendency for disagreement between the Japanese and each of the other national panels of judges. The Japanese judges show significant positive correlation coefficients with *koshi* (0.51), *shari* (0.74) and *hari* (0.43), whereas all the other judging panels show significant negative values for the correlation coefficients with these three summer fabric primary hand expressions, ranging from –0.52 to –0.75. Although there is a strong interaction between the three

Table 5.12 Constants and multiple correlation coefficients for the summer fabric HV-THV translation equations for each national judging panel

	Primary Hand (PH) expressions					
Constants for each judging panel	Stiffness (*koshi*)	Crispness (*shari*)	Anti-drape Stiffness (*hari*)	Softness and Fullness (*fukurami*)	Multiple correlation coefficient	C_0
Japanese						
C_1 (PH)	–0.0004	1.1368	0.3316	0.5309	0.85	3.2146
C_2 $(PH)^2$	0.0066	–0.5395	–0.4977	–0.3741		
Australian						
C_1 (PH)	–1.0332	–0.0542	1.0779	0.7032	0.83	2.5073
C_2 $(PH)^2$	0.8994	–0.3176	–1.2219	–0.6992		
New Zealand						
C_1 (PH)	–0.7082	0.2432	0.9902	0.4482	0.83	3.0825
C_2 $(PH)^2$	0.7945	–0.6296	–1.1357	–0.3373		
Indian						
C_1 (PH)	–0.3644	0.1152	0.1585	–0.0560	0.81	2.6489
C_2 $(PH)^2$	0.3135	–0.4730	–0.4308	–0.0982		
United States						
C_1 (PH)	–0.2250	–0.0460	0.5740	0.3452	0.70	2.8281
C_2 $(PH)^2$	0.2471	–0.3679	–0.7720	–0.4494		
Consumers						
C_1 (PH)	–0.9173	0.8220	0.6741	0.5958	0.79	3.1482
C_2 $(PH)^2$	0.7430	–1.1430	–0.8095	–0.6638		

Source: 'Fabric handle equations for Australia, New Zealand, India and USA', by T.J. Mahar and R. Postle, from *Journal of The Textile Machinery Society of Japan*, vol. 31, no. 2, p. 35, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

Japanese summer primary hand expressions of *koshi*, *shari* and *hari*, the negative correlation coefficients for the non-Japanese judging panels is greatest for the case of *shari*. The difference in summer fabric hand expressions can be seen by inspection of Table 5.12, where the Japanese preference for a crisp summer fabric hand shows in the positive net contribution (i.e., the sum of the contribution to THV of the linear and squared terms for each of the primary hand expressions) of the PH and PH^2 constants for *shari*. The dislike shown for a very crisp fabric hand by each of the non-Japanese panels of judges is evidenced by the negative net contribution to summer fabric THV of the PH and PH^2 constants for *shari*. For the summer fabrics, the average hand ratings for each of the panels of judges ranged from 2.51 for the Australian expert panel to 3.21 for the Japanese panel. This result indicates a wider spread in the judges' overall appreciation of the summer fabrics than for the winter fabrics.

5.4.3 Conclusion of the study of the fabric hand equations for Australia, New Zealand, India and USA

It could be concluded that the international survey of the fabric hand preferences of judges drawn from the textile and clothing industries of Australia, New Zealand, India and the USA has provided the necessary data for a similar system of fabric hand specification in these countries. The separate specification of fabric hand on a national basis is necessary because, though there is broad overall agreement amongst the international panels of judges about winter fabric hand, there are subtle differences in hand preferences amongst the various national judging panels. These differences suggest that users of Kawabata's system for the objective measurement of fabric hand should consider the market for which a fabric is manufactured when evaluating the hand of winter-weight suiting fabrics.

Because of the much more readily defined differences in hand expectations between the Japanese and non-Japanese panels of judges when assessing summer fabric hand, it is imperative that users of this fabric hand specification system relate their measurements to the relevant national market when assessing the hand of summer-weight suiting fabric.

The values for the constants of the Kawabata hand specification equations given in Tables 5.10–5.12 for the Australian, New Zealand, Indian and US markets will enable users of these equations to specify fabric hand for these markets in a more confident manner.

5.5 Comparison between KES-FB and FAST systems in discrimination of characteristics of fabric hand

The differences in basic concept and application between the Kawabata system (KES) and fabric assurance by simple testing system (FAST) were discussed in Chapter 2.

In order to be able to compare the KES-FB and FAST systems in discrimination of fabric characteristics, Sang-Song *et al.* [12] applied discriminant analysis and neural network principles to the physical properties of fabrics measured by the KES-FB system and the FAST system. They established discriminant models for fabric characteristics. The KES-FB discriminant model, which applied fabric mechanical properties, appeared to have better classification ability than the FAST discriminant model. On the other hand, the discrimination model established by applying neural network principles appeared to have a better classification ability than that by applying discriminant analysis.

5.5.1 Experimental design and study methodology

The study included woven fabrics of cotton, linen, wool, and silk. Their basic properties are shown in Table 5.13. These fabrics are used mainly for summer outer garments, such as women's dresses and men's suiting. All samples were commercial fabrics that had not been processed through special finishes.

Table 5.13 The experimental fabrics

Fabric group	Yarn construction	Number of samples	Thickness (mm)	Weight (g/m^2)
Cotton	Spun	13	0.4–0.65	86–165
Linen	Spun	15	0.4–0.78	102–184
Wool	Spun	17	0.36–0.82	112–212
Silk	Filament	15	0.21–0.42	36–56

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

5.5.2 Fabric physical properties

KES-FB system

Using Kawabata's system (KES-FB), 16 mechanical properties of fabrics were tested under standard conditions. These were given earlier (see page 22).

FAST system

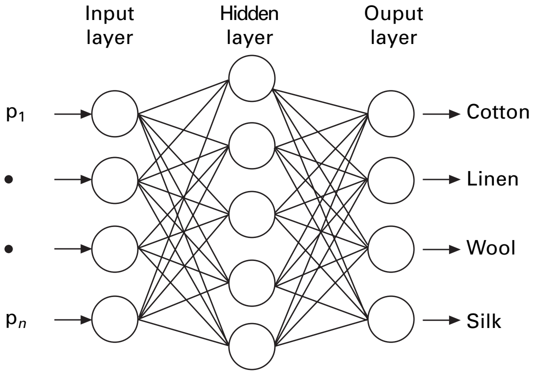
Only 10 independent variables of the fabric physical properties were measured by the FAST system. These were given earlier [13] and were selected to form the discrimination model.

5.5.3 Discrimination analysis

Based upon the presupposition of known group data, discrimination analysis can be applied to derive the 'Discrimination Function' for clear discrimination of group data. Then, discrimination of new group data can be carried out in accordance with the function. Using 60 fabrics of known fiber type and physical properties, discrimination analysis was applied to establish the discrimination function for fabric characteristics and types. The detailed step-by-step derivation of the effective discrimination is given in reference 12.

5.5.4 Neural network

Artificial neural networks are often applied to solve prediction and classification problems, especially in the prediction of nonlinear structural systems [14]. A back-propagation artificial neural network with an input layer, an output layer, and a hidden layer, was used by Sang-Song *et al.* [12]. Its configuration is shown in Fig. 5.5. Input variables included 16 mechanical properties measured by the KES-FB system (Method A), nine mechanical properties selected by applying the stepwise method (Method B), 10 physical properties measured by the FAST system (Method C), and five physical properties



5.5 Adopted neural network structure. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

selected by applying the stepwise method (Method D). Characteristic discriminances of cotton, linen, wool and silk are used as the network target values in neural network training. The entire computation procedure is hidden. For nonlinear transformation, the sigmoid function, $f(x) = \dfrac{1}{1 + e^{-x}}$ was used, with a range of (0, 1). The related network conditions are presented in Table 5.14. For computation of the weight value variation between the hidden layer and the output layer, generalized delta learning rules were employed.

Table 5.14 Parameters of neural network

	Item	Parameter
Input layer	Normalization	Standard
	Number of units	16, 9, 10, or 5
Hidden layer	Transfer function	Sigmoid
	Number of units	5
Output layer	Normalization	Standard
	Number of units	4
Weights	Distribution	Uniform
	Range	0.1–1
Learning rule	Algorithm	Steepest descent
Training stages	Learning coefficient	0.5
	Momentum coefficient	0.3
	Maximum records	105
	Maximum updates	10000

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

The learning network was aimed at reducing the margin between the target value and prediction output. The quality of learning was evaluated by the energy function $E = \frac{1}{2}$ Â $(T_j - Y_j)^2$, where T_j is the output layer target value and Y_j is the output layer prediction value. In order to minimize the value of the energy function, the steepest gradient descent entry method was implied. The optimal data convergence after network training was obtained under these conditions (see Table 5.14). In the supervised network learning process, the degree of convergence can be expressed as root-mean-square error:

$$\mathrm{RMSE} = \left[\frac{1}{n}\,\mathrm{S}\,(T_j - Y_j)^2\right]^{\frac{1}{2}} \tag{5.4}$$

where n is the number of units processed by the output layer. The RMSE values were in the range 0–1.0. If the RMSE converges to less than 0.1, a good result is obtained. Root-mean-square error, the confusion matrix, and the percentage of correct classification were used to evaluate the learning results of a supervised network [12].

5.5.5 Factor analysis

Factor analysis summarizes multiple variables into fewer groups of new factors, a kind of multiple analysis, and can be represented by vectors and matrices: $\mathbf{X} = \mathbf{Af} + \boldsymbol{\varepsilon}$, where $\mathbf{X} = [\mathbf{X}_1, \mathbf{X}_2, \ldots, X_p]$ is a $(p \times 1)$ observable random vector, $\mathbf{A} = [r_{ij}]$ is a $(p \times q)$ unknown matrix of factor loading where r_{ij} is the unknown parameter to represent the loading of the ith variable on the jth factor, $\mathbf{f} = [f_2, f_2, \ldots, f_q]$ is a $(q \times 1)$ unobservable error or so-called 'common factor', and $e = [e_1, e_2, \ldots, e_p]$ is a $(p \times 1)$ unobservable error or so-called 'specific factor' [15]. It is found after many tests that the principal component method provides a better reduction effect on the dimension of the variance–covariance matrix and, therefore, is used to estimate the model variance.

5.5.6 Results of the different analyses

Correlation analysis

As shown in Table 5.15, a significant correlation exists between every two of the fabric mechanical properties measured by the KES-FB system. This implies that they can be inter-replaced. Hence, the stepwise method was applied to select the mechanical properties that could affect discrimination of fabric characteristics most significantly. As shown in Table 5.16 a significant correlation also exists between every two of the fabric physical properties measured by the FAST system. Therefore, it was necessary to select those key variables that are non-collinear and can affect discriminating results most significantly before a simple, convenient and effective method for discrimination of fabric characteristics could be established.

Discriminant analysis

This section aims to use fabric physical properties measured by the KES-FB and FAST systems to establish a discriminant function for the characteristics of cotton, linen, wool, and silk. Correct percentages of the discriminant function obtained from discriminant analysis are shown in Table 5.17. In the KES-FB system, 100% correct discriminant percentage could be obtained when either the enter or the stepwise method was applied to measure fabric mechanical properties. When enter was applied in the FAST system, one piece of thin cotton twill fabric was wrongly discriminated as silk, three

Table 5.15 Mechanical properties and correlations for the KES-FB system

Property	Correlations
LT	WT*, 2HB*, G**, 2HG*, 2HG5**, MIU*, MMD*, T WW**
WT	RT*, SMD*, LC**, WC**, RC*, T***, W***
RT	2HB***, 2HG5*, MIU*, MMD***, SMD***, LC*, WC**, RC***, T**
B	2HB***, G**, 2HG**, 2HG5*, WC*, T**, W**
2HB	G**, 2HG***, 2HG5***, SMD**, WC***, RC**, T***, W***
G	2HG***, 2HG5***
2HG	2HG5***, WC*
2HG5	RC*
MIU	WC***
MMD	SMD***, RC**
SMD	LC*, RC***, T*
LC	RC***, T*, W*
WC	T***, W***
T	W***

*:$p < 0.05$
**:$p < 0.01$
***:$p < 0.001$

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

Table 5.16 Physical properties and correlations for the FAST system

Property	Correlations
W	T2***, STR*, E100*, F***, RS*
T2	ST***, STR***, B**, E100***, F***
ST	STR***, B**, E100*
STR	B***, E100*
B	F*, G***, HE*
E100	F***
F	HE*

*:$p < 0.05$
**:$p < 0.01$
***:$p < 0.001$

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

Table 5.17 Classification results and percentages discriminated for each system and method

Fabric	Predicted fabrics group of enter method				Predicted fabrics group of stepwise method			
	Cotton	Linen	Wool	Silk	Cotton	Linen	Wool	Silk
(a) KES-FB system								
Cotton	13	0	0	0	13	0	0	0
Linen	0	15	0	0	0	15	0	0
Wool	0	0	17	0	0	0	17	0
Silk	0	0	0	15	0	0	0	15
Correct % discriminated	100				100			
(b) FAST system								
Cotton	12	0	0	1	8	3	1	1
Linen	2	12	1	0	3	9	2	1
Wool	0	1	16	0	0	0	17	0
Silk	0	0	0	15	0	0	0	15
Correct % discriminated	91.67				81.67			

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

pieces of linen were wrongly discriminated as two cotton and one wool piece, and one piece of wool was wrongly discriminated as linen, to give a correct discriminant percentage of 91.67%. When the stepwise method was applied, five pieces of cotton were wrongly discriminated as linen (three), wool and silk, and six pieces of linen were wrongly discriminated as cotton (three), wool (two) and silk. Therefore, it is feasible to use fabric physical properties measured by the KES-FB or the FAST system to establish a discriminant function for the characterization of cotton, linen, wool and silk, but the KES-FB discriminant function gives much more reliable discrimination than the FAST discriminant function.

The KES-FB (stepwise) or FAST (enter) canonical discriminant function formed by the fabric physical properties can be expressed as:

$$D_{n(\text{K or F})} = \mathrm{b}_{n0} + \mathrm{b}_{n1}X_{i1} + \mathrm{b}_{n2}X_{i2} + \mathrm{b}_{n3}X_{i3} + \ldots + \mathrm{b}_{np}X_{ip} \tag{5.5}$$

where $D_{n\text{K}}$ is the KES-FB canonical discriminant function and $D_{n\text{F}}$ is the FAST canonical discriminant function. Function coefficients are shown in Table 5.18. Both $D_{n\text{K}}$ and $D_{n\text{F}}$ have good discrimination ability but $D_{n\text{K}}$ has fewer variables than $D_{n\text{F}}$.

Table 5.18 Canonical discrimination function coefficients

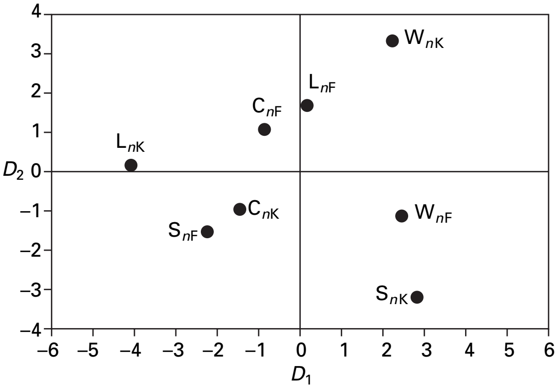
Coefficients	$D_{n\text{K}}$			$D_{n\text{F}}$		
	X	*n* = 1	*n* = 2	*X*	*n* = 1	*n* = 2
b_0	–	–5.2550	–1.7013	–	–4.4500	–1.6000
b_1	LT	–9.5944	1.1271	W	0.0201	–0.0029
b_2	RT	0.1187	–0.0284	T2	2.6658	2.9972
b_3	2HB	1.9286	–33.7060	ST	51.1094	15.3248
b_4	2HG	0.0420	0.6208	STR	–51.2280	–20.5250
b_5	SMD	–0.2927	–0.1012	B	–0.0813	0.1922
b_6	WC	–3.6143	–17.1370	E100	0.2514	0.5218
b_7	RC	0.1306	–0.0369	F	0.1658	–3.8234
b_8	T	3.6741	8.7783	G	0.0315	–0.0690
b_9	W	–0.1328	0.2824	RS	–0.0347	–0.0061
b_{10}	–	–	–	HE	0.2713	–0.1239

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

The results of significance tests on $D_{n\text{K}}$ and $D_{n\text{F}}$ discriminant functions were as follows. Respectively, for KES-FB canonical discriminant functions D_1 and D_2, eigenvalues were 8.55 and 6.25, canonical correlation coefficients were 0.9462 and 0.9284, and Wilks' Lambda values were 0.0075 and 0.0718. Their cumulative variance percentages were more than 94.15% and their *p* values were <0.001. Respectively, for FAST canonical discriminant functions

D_1 and D_2, eigenvalues were 3.34 and 1.92, canonical correlation coefficients were 0.8771 and 0.8108, and Wilks' Lambda values were 0.0503 and 0.2178. Their cumulative variance percentages were more than 90.17% and their p values were <0.001. Therefore, it is necessary only to find the two functions D_1 and D_2 to achieve good interpretation ability. Also, finding the two functions will help visual observation when a two-dimensional scatter diagram is used to indicate fabric characteristics.

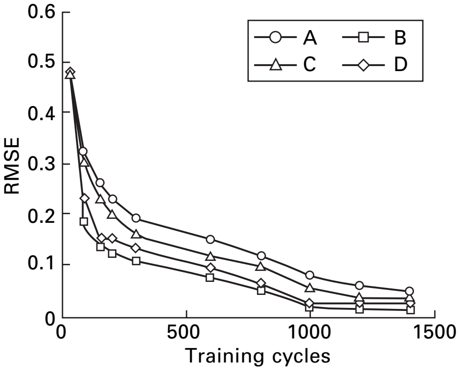
Figure 5.6 is the scatter diagram of D_{nK} and D_{nF}. For D_{nK}, coordinates of centurions for the characteristics of linen, cotton, silk and wool are (–1.46, –0.94), (–4.07, 0.19), (2.23, 3.33) and (2.80, –3.16), respectively. For D_{nF}, coordinates of centurions for the characteristics of linen, cotton, silk and wool are (0.18, 1.67) (in the first quadrant), (–0.84, 1.09) (in the second quadrant), (–2.23, –1.48) (in the third quadrant) and (2.45, –1.09) (in the fourth quadrant), respectively. For both D_{nK} and $D_{nF,}$ centurions for the characteristics of the four fabrics can be classified in different quadrants of a two-dimensional plane. D_{nK} consists of nine mechanical properties of fabric and has 100% correct discriminant percentage. Variables in the discriminant function established by using FAST fabric physical properties and applying the stepwise method include W, E100, B, F and G. The correct discriminant percentage is 81.67%. Indeed, the stepwise method possesses the characteristics of simplicity, convenience and effectiveness for discrimination.



5.6 Centurions of cotton (c), linen (L), wool (W) and silk (S) fabrics (nK: D_{nK}, nF: D_{nF}). *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

Neural network

In Fig. 5.7, the RMSE of method A decreases along with the increase in the number of network training cycles. When the number of training cycles



5.7 Convergence of RMSE. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

reaches 950, the RMSE become 0.028, indicating that convergence has been reached. Methods B, C and D all have the same tendency of convergence as method A. The number of cycles for convergence and the RMSE are 1150 and 0.014 respectively for method B, 1250 and 0.037 for method C, and 1325 and 0.051 for method D. These results indicate that all four neural network models established in this study have a good training effect. Table 5.19 shows the confusion matrices for the four neural network models. Factors on the diagonals of the matrices are larger than the other values, indicating that the models have good training and discrimination effects. Confusion coefficients of methods A and B were both 0, indicating that the four natural fiber fabrics had been correctly discriminated. The confusion coefficient of method C was 0.017, because one piece of linen was wrongly discriminated as cotton. The confusion coefficient of method D was 0.60, because one piece of cotton was wrongly discriminated as wool, four pieces of linen were wrongly discriminated as cotton, and one piece of silk was wrongly discriminated as wool.

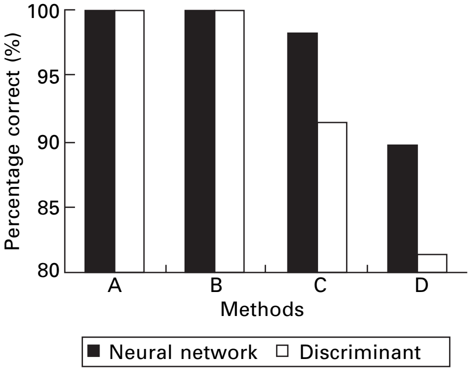
Figure 5.8 compares the KES-FB and FAST systems in characteristic discrimination of natural fiber fabrics. Regardless of whether discriminant analysis or neural network is applied, all the discriminant models established by the KES-FB system give 100% correct discrimination. Although the discriminant models established by the FAST system can also discriminate cotton, linen, wool and silk, they give a slightly lower correct percentage than those established by the KES-FB system. In terms of discrimination ability, discriminant models established by applying neural networks are better than those established by applying discriminant analysis, and method C is better than method D.

In other words, a discriminant model could also be established by the

Table 5.19 Confusion matrices for neural network output (60 samples)

True		Predicted of method A		
	1	1.6	2.6	3.4
1	13	0	0	0
1.6	0	15	0	0
2.6	0	0	17	0
3.4	0	0	0	15
True		Predicted of method B		
	1	1.6	2.6	3.4
1	13	0	0	0
1.6	0	15	0	0
2.6	0	0	17	0
3.4	0	0	0	15
True		Predicted of method C		
	1	1.6	2.6	3.4
1	13	0	0	0
1.6	1	14	0	0
2.6	0	0	17	0
3.4	0	0	0	15
True		Predicted of method D		
	1	1.6	2.6	3.4
1	12	0	1	0
1.6	4	11	0	0
2.6	0	0	17	0
3.4	0	0	1	14

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.



5.8 Comparison between the KES-FB system and the FAST system in percentage correct. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

parameters in the FAST system. For either statistical method used (method A or B), the discriminant percentage of the model established by the KES-FB system's variables is 100%. In addition, the discriminant percentage under method B (only using nine variables in the KES-FB system) is higher than that under method C (using 10 variables in the FAST system). The study showed that the higher number of model variables did not imply higher discriminant percentage. Only through finding the key variables that affect the characteristics of the four kinds of fabrics would the discriminant percentage be improved.

Factor analysis

Factor analysis indicated that the four natural fiber fabrics possessed their own characteristics when correctly discriminated in accordance with their physical properties as described in the previous section. In order to know the characteristic combinations of the four fabrics, the principal component method of factor analysis was applied. Under the condition that the eigenvalue is greater than 1, physical properties measured by the KES-FB and FAST systems were transformed into four new factors. Cumulative variance percentages of the factors in the KES-FB and FAST systems were 75.09% and 79.34% respectively, as shown in Table 5.20.

Table 5.20 Eigenvalues and cumulative variances

Factor	KES-FB system			FAST system		
	Eigenvalue	Variance (%)	Cum. variance (%)	Eigenvalue	Variance (%)	Cum. variance (%)
1	5.09	31.81	31.81	2.91	29.13	29.13
2	3.28	20.53	52.34	2.22	22.19	51.32
3	2.39	14.91	67.25	1.60	16.02	67.34
4	1.26	7.84	75.09	1.20	12.0	79.34

Source: Comparison between KES-FB and FAST in discrimination of fabric characterization, by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of the Textile Machinery Society of Japan*, vol. 55, no. 7, p. 49, 2002. Reproduced with permission from the Textile Machinery Society of Japan.

New combinations of the 16 mechanical properties measured by the KES-FB system were as follows:

- Factor 1: G, 2HG, 2HGS, 2HB, B and LT. Since there are three shear properties having a communality of more than 0.95 when 2HB, B and LT are 0.74, 0.48 and 0.40 respectively, shear properties can affect Factor 1 significantly. Factor 1 is defined as 'shear stiffness'.

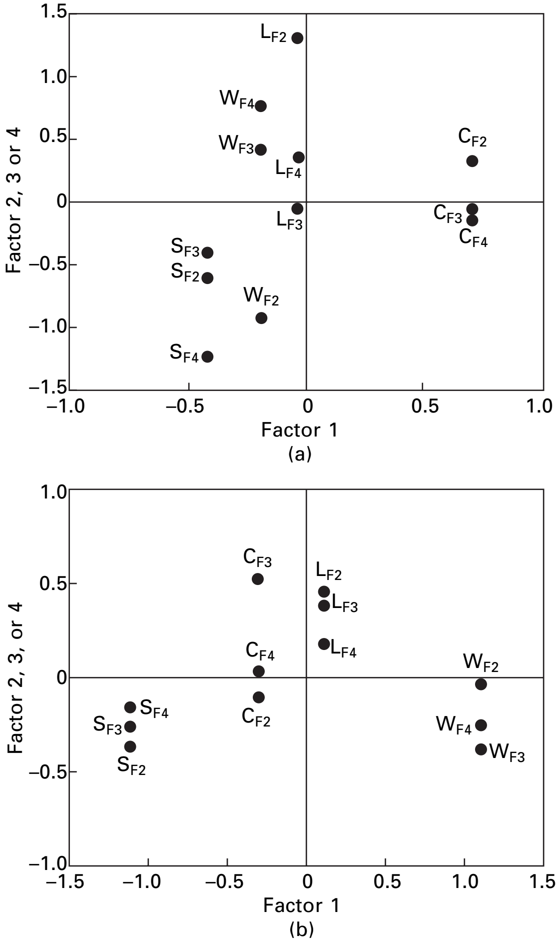
- Factor 2: SMD, MMD, RT and RC. Since surface property has a high communality and is significantly correlated with RT and RC, Factor 2 is defined as 'surface roughness'.
- Factor 3: W, MIU and T. Since WC has a high communality and is significantly correlated with MIU and T, Factor 3 is defined as 'compression energy'.
- Factor 4: WC, LC and WT. Since W is significantly correlated with LC and WT, Factor 4 is defined as 'weight'.

New combinations of the 10 mechanical properties measured by the FAST system were as follows:

- Factor 1: F, T2, W and E100. Since thickness and weight are correlated with fabric formability, Factor 1 is defined as 'formability'.
- Factor 2: ST and STR. Factor 2 is defined as 'thickness'.
- Factor 3: G and B. Factor 3 is defined as 'rigidity'.
- Factor 4: RS and HE. Factor 4 is defined as 'dimensional stability'.

Transforming a large number of variables that can affect discrimination of fabric characteristics into a small number of factors helps to observe the characteristics of the four natural fiber fabrics. Figure 5.9(a) shows the distribution for the average factor scores of cotton, linen, wool and silk samples in the four factor spaces of the KES-FB system. From the characteristic space formed by Factor 1 and Factor 2, the following can be noted. Cotton tends to have extremely high shear stiffness and medium surface roughness. Linen tends to have extremely high surface roughness and medium shear stiffness. Wool tends to have extremely low surface roughness and slightly low shear stiffness. Silk tends to have low shear stiffness and surface roughness. From the characteristic space formed by Factor 1 and Factor 3, the following can be noted. Cotton and linen tend to have medium compression energy. Wool tends to have high compression energy. Silk tends to have slightly low compression energy. From the characteristic space formed by Factor 1 and Factor 4, the following can be noted. Cotton tends to have medium weight. Linen and wool tend to be heavy in weight. Silk tends to be light in weight.

As shown in Fig. 5.9(b), for the FAST system, the characteristics of silk appear to cluster in four factor spaces (F1, F2, F3 and F4). The same applies to wool and linen. Cotton tends to have slightly low formability, low thickness, medium dimensional stability and high rigidity. Linen tends to have slightly high formability, high rigidity and thickness and slightly high dimensional stability. Wool tends to have extremely high formability, medium thickness, and slightly low rigidity and dimensional stability. Silk tends to have extremely low formability, low thickness, and slightly low rigidity and dimensional stability. In the new factor space of either the KES-FB system or the FAST system, the characteristics of the four natural fiber fabrics do not overlap. In



5.9 Distribution of fabric average factor scores in the characteristic spaces: (a) KES-FB; (b) FAST. *Source:* 'Comparison between KES-FB and FAST in discrimination of fabric characterization', by Lai Sang-Song, Shyr Tien-Wei and Lin Jer-Yan, from *Journal of Textile Engineering*, vol. 48, no. 2, 2002.

other words, each of cotton, linen, wool and silk has its own unique characteristics.

5.5.7 Conclusion of the comparison between KES-FB and FAST systems

Discriminant analysis and neural network were used successfully to apply fabric physical properties measured by the KES-FB or the FAST system to establish discriminant models for characteristics of cotton, linen, wool and silk. The discriminant model established by the KES-FB system gave 100% correct discrimination and is apparently a better discriminant model than the one established by the FAST system. Only nine mechanical properties for KES-FB (LT, RT, 2HB, 2HG, SMD, WC, RC, T and W) and five physical properties for FAST (W, E100, B, F and G) needed to be applied in methods B and D, respectively, to effectively discriminate the characteristics of the four natural fiber fabrics. Therefore, for simplicity and convenience, methods B and D are surely better than those discriminant models established previously [16, 17]. Also, discriminant models can help in understanding the characteristic distribution of the four natural fiber fabrics and improving the effectiveness of man-made fabrics in imitating natural fabrics.

5.6 English version (translation) of the Japanese description of primary hand values

The task of providing accurate translations from one language to another of the meaning of words, in particular words which describe abstract concepts, is extremely difficult. Each culture develops words in its language in order to communicate concepts that are considered relevant to that culture. Although, in the case of describing the characteristics of the 'hand' of fabrics in either Japanese or English, the basic cloths themselves are the same, or very similar, each of the two cultural groups represented by the two languages employs different concepts in its description. The Japanese terminology, e.g. *numeri, koshi*, etc., does not equate exactly with any single word in the English language. The use of any 'best', or most appropriate, single word descriptor for one of the Japanese PHVs represents, then, an imperfect substitution which may well be misleading, since this 'best' word really describes a fabric quality attribute which is different from the Japanese PHV.

An international team [18] conducted a study with two objectives:

1. To propose a series of single-word descriptors considered to best characterize each of the five PHVs nominated by the HESC as being necessary to describe the hand of men's suiting fabrics.
2. To describe the concepts identified by these PHVs.

5.6.1 Procedure

For the English-speaking world, the origins of the traditional worsted menswear fabric industry lay in the West Riding area of Yorkshire, England. One of the research team (P. Wheelwright) gained his technical training and early experience of the worsted menswear industry in the region. During his subsequent working experience in the textile industry of other countries, Mr Wheelwright found the vocabulary used in these countries to describe aspects of fabric quality to be in common with that used in the United Kingdom.

An extensive search was undertaken of literature relating to the terminology used traditionally by the worsted manufacturing industry in Yorkshire to characterize fabric hand, quality and finish. The combination of Mr Wheelwright's experience and the literature survey ensured that there was a comprehensive list of fabric descriptors from which to draw in order to assign an English terminology to the Japanese PHVs.

In order to obtain a strong grasp of the concepts identified by the Japanese PHVs, detailed examinations were made of both the fabric samples and the mechanical property data contained in the PHV standards [11] published by the HESC. Discussions were held with English-speaking Japanese (especially S. Sukigara, a member of the research team), who were involved with the textile and/or clothing industries and thus acquainted with the terminology.

5.6.2 Results and discussions

Numeri

Standards were first established for winter suitings. A summary of the fabric quality attributes which characterize the PHV *numeri* is provided in Table 5.21. Of the English expressions used to describe the hand of a fabric with high *numeri*, 'sleekness' is considered to be the most appropriate. 'Smoothness',

Table 5.21 English description of the Japanese primary hand expression, *numeri*

HESC:	Smoothness 'A mixed feeling come from smooth, limber and soft feeling. The fabric woven from cashmere fiber gives this feeling strongly'
Preferred word:	*Numeri* = Sleekness
Other words:	Silkiness Softness Smoothness
Characteristic fabric:	Traditional, fine, high quality velour in very fine wool. (Twill weave, raised, cut both ways)
Opposite characteristics:	Rawness* (underdone) Harshness Wiriness Threadiness
	*Rawness could be due to overtwisting component yarn of underscouring fabric in finishing.

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

'silkiness' and 'slipperiness' are also included as examples of feelings associated with high-*numeri* fabric.

Fukurami

The results for the English description of the PHV *fukurami* are summarized in Table 5.22. *Fukurami* is used to characterize both winter and summer fabric hand. 'Fullness' has been chosen as the preferred descriptor for this PHV. Another word which might be used within the textile and clothing industries to characterize this Japanese concept is 'loftiness'. Examples of fabrics which might be expected to display strong *fukurami* are:

- a half-milled flannel (acid milling in fulling stocks) in a twill weave, weighing approximately 280 g/m^2, resultant count of yarn 37 tex/2, and made from 80s quality wool;
- an all-wool heavyweight, woolen split-pick Crombie (double cloth).

Fabric characteristics of 'thinness', 'sponginess' and 'paperiness' are the opposite of *fukurami*.

Table 5.22 English description of the Japanese primary hand expression *fukurami*

HESC:	Fullness and softness 'A feeling come from bulky, rich and well formed feeling. Springy property in compression and thickness accompanied by warm feeling are closely related with this feeling (Fukurami means swelling)'
Preferred word:	*Fukurami* = Fullness
Other word:	Loftiness
Characteristic fabric:	Traditionally achieved by acid milling a cloth made from 'fine' wool in fulling stocks 2/48^s w.c. yarn, lightweight (12 oz/yd), halfmilled flannel in 80^s quality wool twill; all wool heavyweight, woolen split-pick Crombie (double cloth)
Opposite characteristics:	Thinness Sponginess* Paperiness *Sponginess may be the result of overworking a gaberdine repp or fresco in the wet processing – or by refinishing (including rescouring) any firmly set cloth.

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

Koshi

As in the case of *fukurami*, *koshi* is a PHV which is used by the HESC to assess the hand of both winter and summer suiting fabrics. The preferred single-word translation of this fabric characteristic, which is described in Table 5.23, is 'firmness'. The complexity of the concept which the Japanese describe as *koshi* can be gauged by the list of 'other (descriptor) words', including 'resilience', 'springiness' and 'solidarity'.

Table 5.23 English description of the Japanese primary hand expression *koshi*

HESC:	*Stiffness* 'A feeling related with bending stiffness. Spring property promotes this feeling. The fabric having compact weaving density and woven by springy and elastic yarn makes this feeling strong'
Preferred word:	*Koshi* = Firmness
Other words:	Resilience Springiness Solidity
Characteristic fabric:	Typified by plain weave, worsted warp $2/40^s$ w.c. yarn of 64^s, $1/18^s$ w.c. mohair weft yarn, overset in loom weft way, and tensioned in finishing to bring weft on to fabric face, singed
Opposite characteristics:	Limpness Slackness Underset Sleaziness

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

A fabric which displays the *koshi* PHV strongly is a plain weave; worsted warp yarn-resultant yarn count 44 tex/2 in 21.5 mwool; mohair weft yarn, single 49 tex/1 overset in loom weft way, tensioned during finishing to bring the weft yarns to the fabric face. The fabric would be singed during finishing.

'Limpness', 'slackness' and 'sleaziness' are fabric characteristics which are opposite to *koshi*. An 'underset' fabric would behave in a manner opposite to a fabric with a strong *koshi* feeling.

Shari

Shari is a PHV which is considered by the HESC to be extremely important to the characterization of the hand of summer suitings in Japan. Neither *shari* nor the final PHV to be considered, *hari*, is considered necessary for the description of the fabric hand of winter suitings. Both are uniquely (for menswear) required to characterize summer fabric hand. As indicated in Table 5.24, the preferred translation of *shari* is 'crispness'.

Table 5.24 English description of the Japanese primary hand expression *shari*

HESC:	*Crispness* 'A feeling that comes from crisp and rough surface of fabric. This feeling is brought by hard and strongly twisted yarn. This feeling brings us a cool feeling (this word means a crisp dry and sharp sound arisen by that the fabric is rubbed with itself'
Preferred word:	*Shari* = Crispness
Characteristic fabric:	A characteristic of the traditional 'Frescoe' as patented by Ganier (pre-WWII) or heavier 'thornproof' Border Tweeds (Reid and Taylor, Kynoch, Scotland)
Opposite characteristic:	Softness

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The traditional 'frescoe' fabrics and the heavier 'thornproof' Scottish Border Tweeds are examples of fabrics whose hand is characterized by strong *shari*. 'Softness' is the opposite fabric attribute to shari.

Hari

The final PHV for men's suiting fabrics is *hari*, described in Table 5.25. The most appropriate single word for *hari* is 'boardiness'.

The traditional Bradford (UK) 'hair' cloths, e.g. 'Orleans', 'Brilliantines' and 'Sicilians', typify a strong *hari*. These fabrics are generally made with a worsted warp yarn and a coarser hair or blended wool coarse hair weft, and are firmly set. Similar strong *hari* hand can be obtained in fabrics by using coarse crossbred wools. A 'soft', 'clothy' fabric hand is the opposite of a strong *hari*.

5.6.3 Conclusion

The dedication and skill of the HESC in publishing standards for fabric hand have provided an opportunity to improve the level of communication about the aesthetic qualities of fabrics on an international basis, both within and between the textile and clothing industries.

Table 5.25 English description of the Japanese primary hand expression *hari*

HESC:	*Anti-drape stiffness* 'Anti-drape stiffness, no matter whether the fabric is springy or not'
Preferred word:	*Hari* = Hardness
Other word:	Boardiness
Characteristic fabric	Traditional Bradford (UK) 'hair' cloths (i.e. worsted warp, single, coarser hair or blended weft), firm sett, such as 'Orleans', 'Brilliantines', 'Sicilians', etc. Currently produced by oversett crossbred cloths with various proofing treatments
Opposite characteristics:	Softness Clothiness

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

The English versions of the Japanese primary hand expressions presented in this study are, of course, not unique. Indeed, in most cases, the word considered as the single most appropriate descriptor of a given primary hand expression has been nominated together with a group of words that have similar, but not the same, meaning.

The translations and descriptions presented here represent an educated attempt to build upon the work of the HESC in order to establish a sounder international basis for the assessment of the aesthetic qualities of fabrics both within and between the textile, clothing and fabric and garment merchandising and retailing industries. If agreement can be reached on acceptable English translations of the Japanese terminology with respect to the primary hand values, the English-speaking world will be better placed to take advantage of the unique opportunity provided by the HESC. A Japanese translation of English words is given in Table 5.26.

5.7 Measurement of fabric hand by different methods

In this comparison between the USA and Japan, a comprehensive study was designed to obtain results showing the effect of the following different procedures used [2]:

- commercial fabric from both countries
- type of yarns in the fabric and the raw material
- evaluation of primary hand value
- physical and mechanical properties and their relation to fabric hand

Table 5.26 Japanese translations of English words

List I	
Silkiness:	Kinu no youna hyoomen no utsukushisa
Softness:	Yawarakasa (Nuno o osaeta tokino)
Smoothness:	Namerakasa
Rawness:	Shiage no fujuubunsa
Harshness:	Araku, zarazara shita kankaku
Wiriness:	Harigane de kousei sareta you na nuno
Threadiness:	Fujuunun na shiage no tame, ito ga yoku wakaru (e.g. kibata)
List II	
Loftiness:	Koushyo, kedakai
Thinness:	Ususa
Sponginess:	Yawaraka ku pan o yaku mae no kigi o netta you na danryoku sei
Paperiness:	Kami no you
List III	
Resilience:	Danryoku sei
Springiness:	Hanekaeru chikara
Solidity:	Kataku mitsu de aru
Limpness:	Shinayakasa
Slackness:	Shimari ga nai
Undersett:	Shiage ga fujuubun de orikozo ga so de aru
Sleaziness:	Usuppera de orikouzou ga yowai
List IV	
Boardiness:	Ita no youna danryoku sei
Clothiness:	Yawarakaku, drape ga aru nuno. Ita no you dewa nai

Source: 'Quality attributes and primary hand expressions for wool fabric – English versions of the Japanese descriptions', by P. Wheelwright, T.J. Mahar, R. Postle and S. Sukigara, from *Proc. Third Japan–Australia Joint Symposium on Objective Measurement: Applications to Product Design and Process Control*, 1985. Reproduced with permission from the Textile Machinery Society of Japan.

- nozzle measurement or engineering evaluation of fabric hand
- subjective assessments by panels of judges from the two countries.

The 145 fabrics evaluated in the study were commercially available and mainly used for career uniforms. Woven fabric constructions of 100% polyester, 100% wool, and five polyester/wool blends were analyzed. Fabric weights ranged from 270 to 478 g/m on a 142.2 cm width basis. Polyester yarn types included 100% spun staple, 100% texturized continuous filament, and a combination of staple and texturized filament yarns.

5.7.1 Primary hand values

The fabrics were judged with standard samples for men's winter suits and also with standards for men's summer suits by Kawabata and Niwa. Primary hand values of *koshi*, *numeri*, and *fukurami* were obtained when fabrics were compared with the men's winter suiting assessments, and *koshi*, *shari*, *fukurami*, and *hari* were determined for the fabric samples from a comparison with men's summer suit standards.

5.7.2 Mechanical properties and total hand values

Measurements for selected mechanical properties of the fabrics were conducted by Kawabata and Niwa on the KES system. These tests are described in Appendix A and include tensile linearity, tensile energy, tensile resilience, bending rigidity, bending hysteresis, shear stiffness, shear at q = 0.5°, shear hysteresis at q = 5.0°, compression linearity, compression energy, compression resilience, coefficient of friction, mean deviation of coefficient of friction, geometrical roughness, fabric weight, and fabric thickness. Kawabata and Niwa calculated total hand values for summer and winter men's suit fabrics as given in detail in references 11, 19 and 20.

5.7.3 Nozzle measurements

Fabric samples were tested by the nozzle quantitative measure of hand developed by Alley and McHatton [21]. Hand modulus was calculated using the revised theory [22].

5.7.4 Subjective assessment

A panel of four experts from the textile industry [20, 23, 24] made a qualitative assessment of the fabrics. The end use of the materials was established as career uniforms. Fabric samples were judged in reference to a standard fabric. Ratings of the fabrics were established according to the scale given earlier (Table 5.4).

5.7.5 Physical tests related to fabric hand

Physical tests considered relevant to fabric hand were performed on the fabrics, including (a) cantilever bending: (1) bending length and (2) flexural rigidity; (b) compressibility; (c) cyclic bending: (1) coercive couple and (2) elastic flexural rigidity; (d) initial tensile; and (e) percent drape coefficient.

5.8 Results of fabric hand evaluation by different methods

5.8.1 Primary hand value

Statistical analyses were made by calculating the Spearman rank correlation coefficients to compare the various means of assessing fabric hand. Significance tests were conducted on these correlation coefficients at the 0.01 and 0.05 levels. The results of the significance tests of Kawabata's primary hand values compared with other tests are shown in Table 5.27.

Table 5.27 Results of significance tests of the correlation coefficients for primary hand values versus results of tests conducted

Tests conducted	*Koshi* (winter)	*Numeri* (winter)	*Fukurami* (winter)	*Koshi* (summer)	*Shari* (summer)
1. Subjective hand	*				
2. Hand modulus	**	**	**	**	**
3. Cantilever bending length	**	**	*	**	**
4. Cantilever flexural rigidity	**	*		**	**
5. Compressibility	**	*	**	**	
6. Cyclic bending – coercive couple	**			**	
7. Cyclic bending – elastic flexural rigidity	**			**	*
8. Initial tensile modulus	*			*	
9. Percent drape coefficient	**	**	**	**	**
10. Fabric weight	**	**	**	**	
11. Fabric thickness	*	**	**		*
12. Tensile linearity	**	**	*	**	**
13. Tensile energy	**				
14. Tensile resilience		**	**		
15. Bending rigidity	**	**		**	**
16. Bending hysteresis	**			**	**
17. Coefficient of friction	**			**	
18. Mean div. of coeff. of friction		**	**		**
19. Geometric roughness		**	*		**
20. Shear stiffness	**	**	**	**	**
21. Shear hysteresis, 0.5°	**	**	**	**	**
22. Shear hysteresis, 5.0°	**	**	**	**	**
23. Compression linearity					
24. Compression energy	**	**	**	**	*
25. Compression resilience		*			*
26. Thickness	**	**	**	**	**
27. Fabric weight	**	**	**	**	
28. Total hand value – winter	**	**	**		
29. Total hand value – summer				**	**

*Significant at 0.5 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

5.8.2 Subjective hand assessment

Subjective hand assessment conducted in the previous study [24] was significantly correlated at the 0.01 level to the primary hand value *hari* (summer) and *koshi* (winter) at the 0.05 level. This indicated that stiffness properties as measured by the primary hand values in both *hari* (summer) and *koshi* (winter) were reflected in the other subjective evaluation, which shows a consistency in the US panel in response to the fabric stiffness.

5.8.3 Nozzle measurement or engineering evaluations of fabric hand

Hand modulus calculated from the nozzle measurement correlated significantly at the 0.01 level to all of the primary hand values with the exception of *fukurami*-summer (fullness and softness). This could be because most of the fabrics used tend toward the stiffer side. Also, the mechanics of flow through the nozzle might be influenced by fabric stiffness. The hand modulus also correlated significantly to *fukurami*-winter, perhaps because of the effect of the fabric weight. The negative correlations found between hand modulus and *numeri*-winter, as well as *fukurami*-winter, indicated that as the hand modulus increased, the primary hand values for both *numeri* and *fukurami*-winter decreased.

5.8.4 Effect of physical and mechanical properties on primary hand value

Table 5.28 sums up the correlation between primary hand value and physical properties 3–11 in Table 5.27 tested in the study by Behery [24]. The table shows the five physical properties with the highest significant correlations to each primary hand value. The percent drape coefficient and cantilever bending length were among the top five physical measurements correlated to every primary hand value. Cantilever flexural rigidity was correlated to all the primary hand values with the exception of *fukurami*-winter. A significant correlation between compressibility and each primary hand value was observed except for *shari*-summer. The cyclic bending measurement of the coercive couple was significantly correlated to *koshi*-winter, *koshi*-summer, and *shari*-summer, indicating the test detects stiffness. Significant correlations were noted between cyclic bending–elastic flexural rigidity and primary hand values, with the exception of *numeri*-winter and *fukurami*-winter.

Table 5.29 shows the mechanical properties that were most highly correlated to the primary hand values as measured by Kawabata's system (KES). Shearing and bending properties were reflected in the *koshi*-winter values, which

Table 5.28 The five most highly correlated physical test values for each primary hand value

Primary hand value	Physical test	Correlation
Koshi-winter	Percent drape coefficient	0.699
	Cantilever flexural rigidity	0.674
	Cantilever bending length	0.599
	Coercive couple	0.395
	Elastic flexural rigidity	0.371
Numeri-winter	Fabric thickness	0.418
	Percent drape coefficient	–0.368
	Cantilever bending length	–0.341
	Fabric weight	0.254
	Cantilever flexural rigidity	0.234
Fukurami-winter	Fabric thickness	0.554
	Compressibility	0.375
	Fabric weight	0.306
	Percent drape coefficient	–0.303
	Cantilever bending length	–0.234
Koshi-summer	Cantilever flexural rigidity	0.772
	Percent drape coefficient	0.756
	Cantilever bending length	0.737
	Elastic flexural rigidity	0.470
	Coercive couple	0.418
Shari-summer	Percent drape coefficient	0.444
	Cantilever bending length	0.404
	Cantilever flexural rigidity	0.361
	Fabric thickness	–0.193
	Elastic flexural rigidity	0.180
Fukurami-summer	Cantilever bending length	–0.526
	Fabric weight	0.418
	Percent drape coefficient	–0.320
	Elastic flexural rigidity	–0.319
	Cantilever flexural rigidity	–0.314
Hari-summer	Percent drape coefficient	0.723
	Cantilever flexural rigidity	0.699
	Cantilever bending length	0.658
	Coercive couple	0.496
	Elastic flexural rigidity	0.355

Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

represent fabric stiffness. Figure 5.10 shows the correlation between *koshi*-winter and the shear hysteresis at $q = 5.0^\circ$.

Numeri-winter, which represents the fabric smoothness, was most highly correlated to surface properties. Fullness and softness as judged in the *fukurami*-

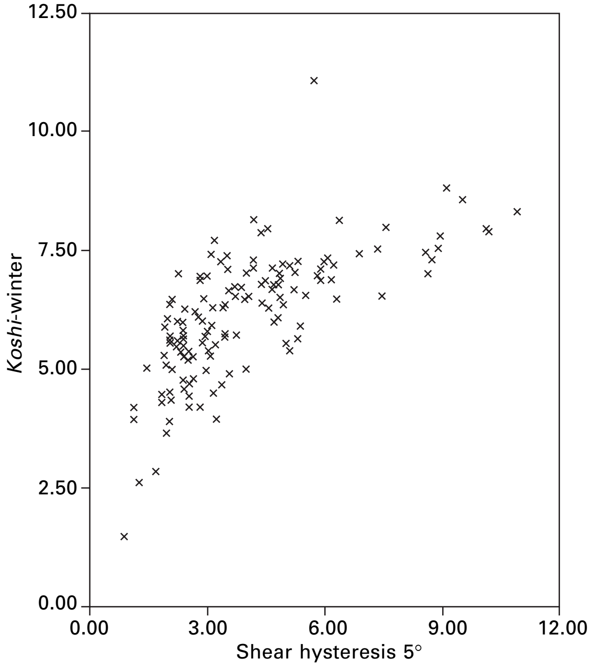
Table 5.29 The five most highly correlated mechanical tests of Kawabata for each primary hand value

Primary hand value	Kawabata's mechanical test	Correlation
Koshi-winter	Shear hysteresis, 5.0°	0.759
	Shear stiffness	0.747
	Shear hysteresis, 0.5°	0.684
	Bending rigidity	0.681
	Bending hysteresis	0.615
Numeri-winter	Mean deviation coefficient of friction	–0.786
	Fabric thickness	0.568
	Compression energy	0.502
	Geometric roughness	–0.465
	Shear hysteresis, 5.0°	–0.422
Fukurami-winter	Fabric thickness	0.835
	Compression energy	0.797
	Mean deviation coefficient of friction	–0.561
	Shear hysteresis, 5.0°	–0.369
	Tensile resilience	–0.357
Koshi-summer	Bending rigidity	0.770
	Shear hysteresis, 5.0°	0.744
	Shear hysteresis, 0.5°	0.721
	Bending hysteresis	0.698
	Shear stiffness	0.689
Shari-summer	Geometric roughness	0.732
	Mean deviation coefficient of friction	0.628
	Bending rigidity	0.370
	Tensile linearity	0.346
	Shear stiffness	0.338
Fukurami-summer	Tensile linearity	0.534
	Tensile energy	–0.510
	Fabric weight	0.426
	Compression resilience	0.410
	Bending rigidity	–0.374
Hari-summer	Shear hysteresis, 5.0°	0.792
	Bending hysteresis	0.751
	Shear stiffness	0.735
	Shear hysteresis, 0.5°	0.723
	Bending rigidity	0.647

Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

winter values were correlated to a variety of mechanical properties, including thickness and compression, reflecting the fullness and softness of fabrics.

The correlation between *fukurami*-winter and fabric thickness is shown in Fig. 5.11. *Koshi*-summer was correlated most highly to bending and shear characteristics in magnitudes similar to that of *koshi*-winter.



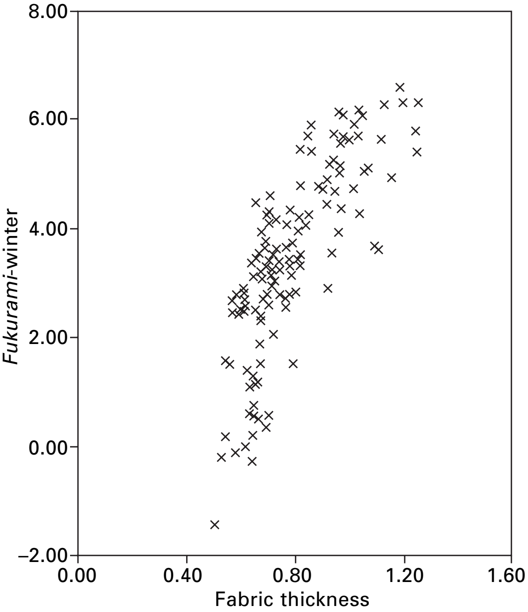
5.10 Correlation between *koshi*-winter and shear hysteresis at q = 5.0°. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Crispness properties of *shari*-summer were related most to the surface qualities of geometric roughness and mean deviation of the coefficient of friction, as shown in Fig. 5.12.

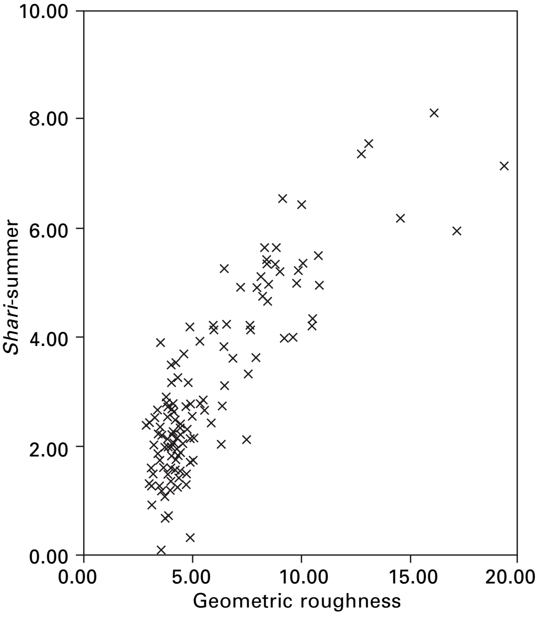
Significant correlations were noted between *fukurami*-summer and tensile properties as given in Fig. 5.13. *Hari*-summer was best represented by shearing and bending properties.

Figure 5.14 shows the correlation between *hari*-summer and the shear hysteresis at q = 5.0°. There are great similarities between both correlations shown in Figs 5.10 and 5.14.

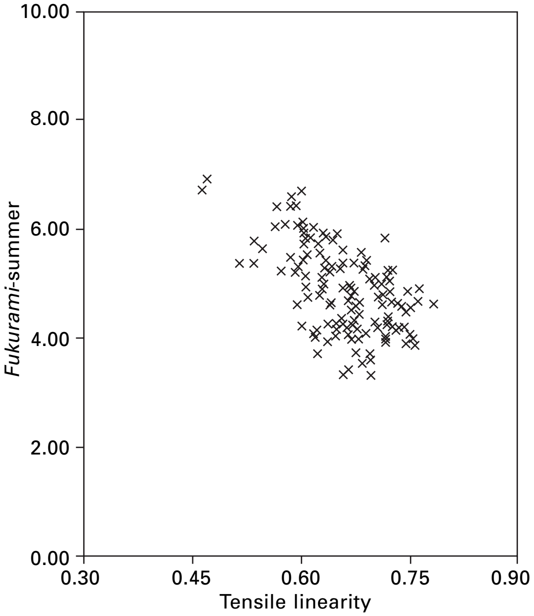
Correlations between the primary hand values were studied in the same fashion as Kawabata and Niwa [8] and are given in Table 5.30. High correlations were observed for *koshi*-winter versus *koshi*-summer, *koshi*-summer versus *hari*-summer, *koshi*-winter versus *hari*-summer, and *numeri*-winter versus *fukurami*-winter. Stiffness properties of a fabric were judged to be similar when compared to standards of *koshi* for summer or winter suits. Anti-drape stiffness as characterized in *hari* ratings was related to *koshi* (stiffness) for both winter and summer suiting. Properties of softness and fullness for men's



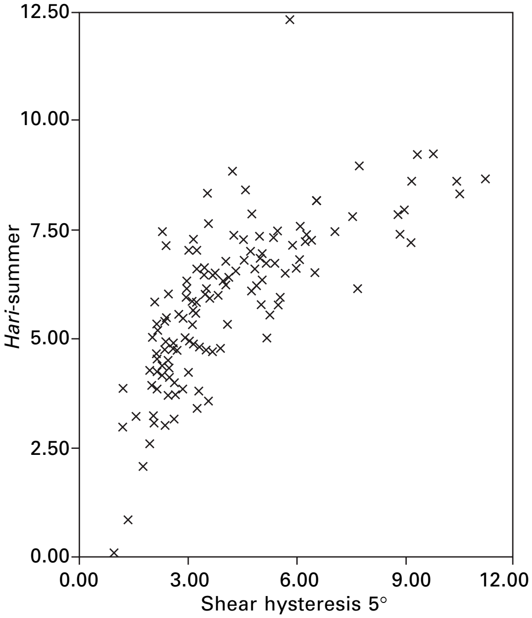
5.11 Correlation between *fukurami*-winter and fabric thickness. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.12 Correlation between *shari*-summer and geometric roughness. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.13 Correlation between *fukurami*-summer and tensile linearity. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.14 Correlation between *hari*-summar and shear hysteresis at q = 5.0°. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Table 5.30 Correlation between primary hand values

	Koshi (winter)	*Numeri* (winter)	*Fukurami* (winter)	*Koshi* (summer)	*Shari* (summer)	*Fukurami* (summer)	*Hari* (summer)
Koshi-winter		–0.494**	–0.482**	0.944**	0.467**	–0.198*	0.921**
Numeri-winter			0.867**	–0.504**	–0.755**	0.476**	–0.426**
Fukurami-winter				–0.414**	–0.537**	0.394**	–0.372**
Koshi-summer					0.584**	–0.367**	0.927**
Shari-summer						–0.442**	0.497**
Fukurami-summer							–0.142
Hari-summer							

*Significant at 0.05 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

suits were found in many fabrics that had a smoothness desirable for winter suiting.

No correlation at the 0.05 level existed for the relationship of anti-drape stiffness to fullness and softness. Kawabata's study of fabrics [19] reported a positive correlation for the relation between *fukurami*-summer and *hari*-summer, but this correlation was found to be negative for fabrics in Behery's study [24]. Positive correlations were observed in Kawabata's work, as well as our investigation, for *numeri*-winter versus *fukurami*-winter, *koshi*-summer versus *shari*-summer, *koshi*-summer versus *hari*-summer, and *shari*-summer versus *hari*-summer.

5.8.5 Total hand value and its interaction with other factors

Total hand values for winter suiting were most highly correlated to the primary hand values of *numeri* and *fukurami* as shown in Table 5.30. This indicated that smoothness, fullness, and softness were the fabric properties best represented by the total hand values. All three primary hand values were significantly correlated at the 0.01 level to the total hand value for winter suits. A negative correlation existed for the *koshi* (stiffness) primary hand value.

According to Kawabata's hand evaluation and standardization committee, koshi was more important than *fukurami* in the judgment of hand for winter suiting; however, in the study, a high correlation to total hand value was found with *fukurami* than *koshi*.

Summer suit total hand values were significantly correlated to primary hand values and expressions of *koshi*, *shari*, and *fukurami* at the 0.01 level. Significant correlations were found at the 0.05 level between the summer total hand values and *hari* (anti-drape stiffness). *Fukurami* (fullness and softness) was negatively correlated to the summer total hand value. Kawabata's work [19] found positive correlations for all the primary hand values as related to total hand value for summer. Total hand value for summer suiting was most highly correlated to *shari* (crispness).

A negative correlation was observed between THV-winter and THV-summer in Table 5.31, which shows correlations for the total hand values versus the subjective hand and hand modulus. Hand modulus was significantly correlated to the total hand value for men's winter suiting at the 0.05 level.

5.8.6 Comparison between conventional physical and mechanical properties and those measured by Kawabata's system

Correlations were examined between conventional physical tests conducted on the fabrics and similar tests performed by Kawabata's system; the results

Table 5.31 Correlation coefficients for total hand values versus subjective hand and hand modulus

	Total hand value: winter	Total hand value: summer
Subjective hand	–0.071	0.011
Hand modulus	–0.234*	0.089
Total hand value: winter		–0.420**

*Significant at 0.05 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

are shown in Table 5.32). Significant correlations at the 0.01 level were observed for all these comparisons. A negative correlation occurred between the coefficient of friction values. The coefficient of friction measurements by Behery and Monson [23] used the inclined plane method under the fabric's own weight. Kawabata's method of determining the coefficient of friction was more representative of the surface roughness under a standard weight, so this method gives a higher value for rough surfaces and a lower value for smooth surfaces. The coefficient of friction as measured by the inclined plane method gives higher values for a smooth surface and vice versa for a rough surface. This is in agreement with previous findings by Bradbury and

Table 5.32 Correlation coefficients for Kawabata's KES measurements versus physical tests

Kawabata's KES measurements		Physical tests	Coefficient
Bending hysteresis	vs.	cyclic bending coercive couple	0.696**
Bending rigidity	vs.	cyclic bending elastic flexural rigidity	0.786**
Compression energy	vs.	compressibility	0.584**
Coefficient of friction	vs.	coefficient of friction	–0.342**
Fabric weight	vs.	fabric weight	0.991**
Fabric thickness	vs.	fabric thickness	0.759**
Tensile work recovery – W	vs.	tensile work recovery – W	0.615**
Tensile work recovery – F	vs.	tensile work recovery – F	0.543**

** Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Reicher [25], in which they indicated that the yarn coefficient of friction is associated with the true area of contact.

Hand modulus values are significantly correlated at the 0.01 level to several of Kawabata's mechanical tests as indicated in Table 5.33. The highest significant correlations were noted between hand modulus and bending and shearing properties. Tensile linearity, tensile energy, coefficient of friction, and fabric weight were also significantly correlated at the 0.01 level. This indicates that the mechanics of the flow of the fabric through the nozzle are affected by most of the properties measured by Kawabata.

Table 5.33 Results of significance tests of the correlation coefficients for Kawabata's mechanical tests versus hand modulus and subjective hand values

Kawabata's KES measurements	Hand modulus	Subjective hand
Tensile linearity	**	*
Tensile energy	**	**
Tensile resilience		**
Bending rigidity	**	
Bending hysteresis	**	*
Coefficient of friction	**	**
Mean deviation of the coefficient of friction		
Geometric roughness		
Shear stiffness	**	**
Shear hysteresis at q = 0.5°	**	**
Shear hysteresis at q = 5.0°	**	**
Compression linearity		**
Compression energy	*	
Compression resilience		**
Thickness	*	*
Weight	**	*

* Significant at 0.05 level.
**Significant at 0.01 level.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

The tensile resilience was not significantly related to the hand modulus, as this property relates to the recovery of the material, which is a post-action to the passage of the fabric through the nozzle. The same explanation could also be provided for the non-significance of the correlation between the hand modulus and the compression resilience property.

The non-significance of the correlation between the geometric roughness, the coefficient of friction mean deviation, and the hand modulus could be explained as being due to the difference between the action of the material rubbing against the nozzle and the principle of the measurement of both the friction coefficient and surface roughness in the Kawabata system.

Correlations between the subjective assessment as measured by the US panel and Kawabata's (KES) measurements are also reported in Table 5.33. Subjective hand values were correlated most highly to shear properties, compression linearity, and tensile energy. Properties of tensile resilience and compression resilience were also noted to be significantly correlated at the 0.01 level. These properties seem to reflect the action of the hands and the responses to the tactile qualities of the fabrics.

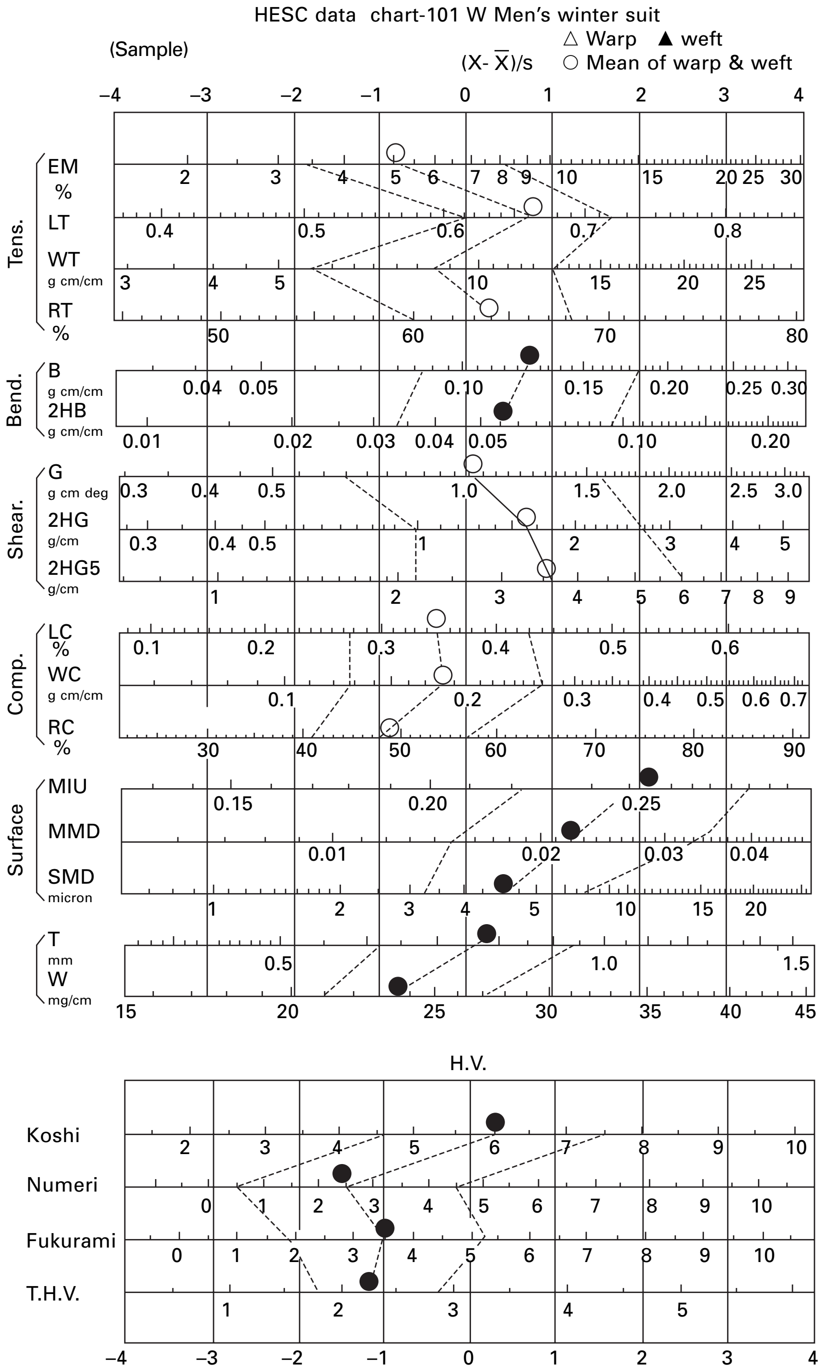
5.8.7 Comparison between US and Japanese fabrics

The study was further extended and a comparison made between fabrics produced in Japan similar to those used in the study. This analysis was done by Kawabata and Niwa [8] using a total of 214 samples for Japanese men's suiting versus the 145 US fabrics used in this study. The Japanese fabrics also included different types of fiber blends, yarns, and fabric constructions. For the summer men's suiting, the comparisons were made with 186 Japanese fabrics.

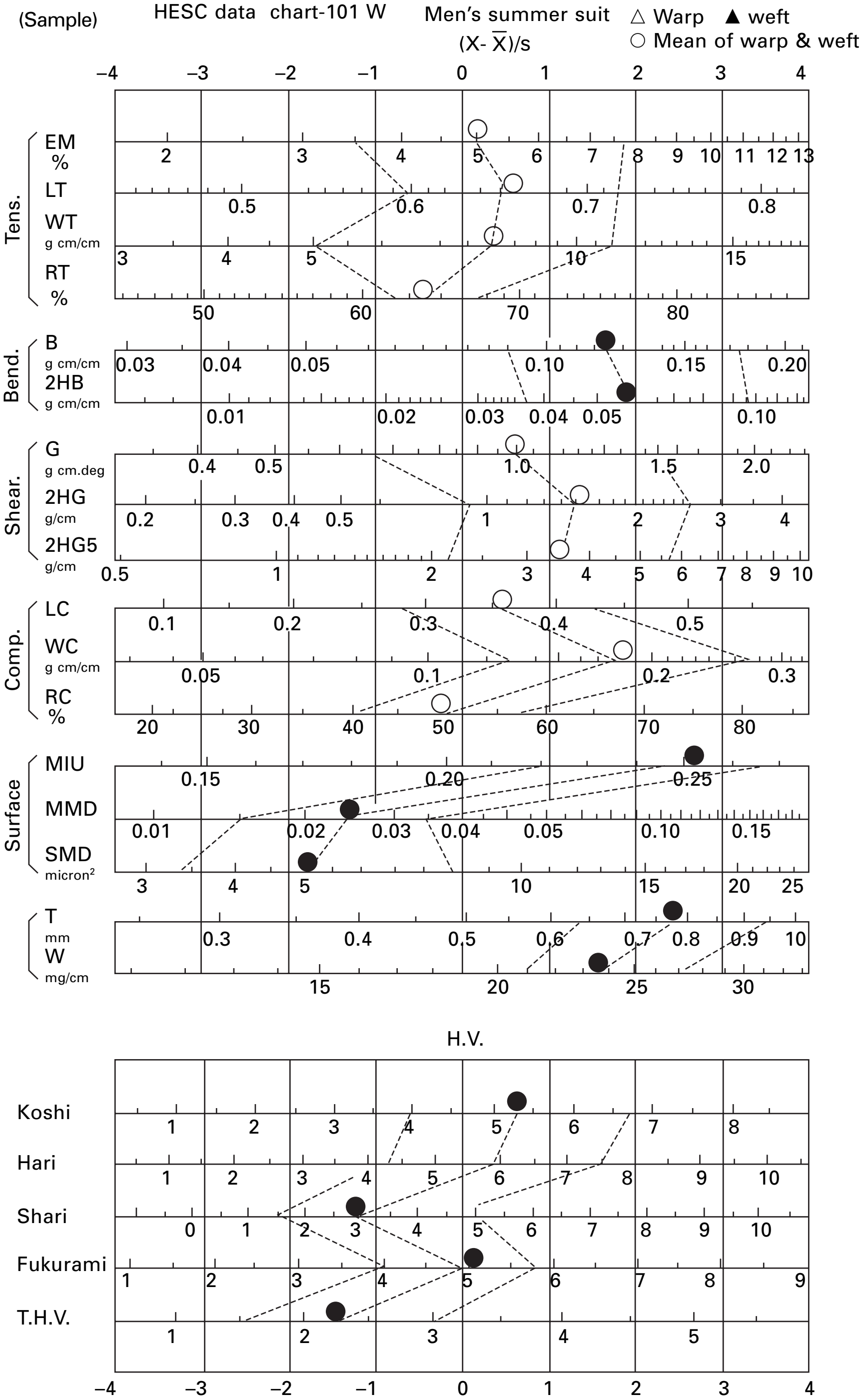
The HESC chart shown in Fig. 5.15 illustrates the deviation of the mean values of the different properties of the US winter suiting fabrics from the Japanese winter fabrics. The center line of value zero used as the reference value for the comparison represented the average of the properties of the Japanese fabrics. It is quite clear that the US fabrics had higher values in tensile, bending, and shear properties, as well as higher values of surface characteristics. The compression properties of the US fabrics were lower than the values for the Japanese fabrics except for the compressional energy, which was equal. This explains the difference of the hand values. Because of the higher tensile properties, the *koshi* value (stiffness) of the US fabrics was higher than that of the Japanese fabrics. On the other hand, the higher surface friction and roughness of the US fabrics showed lower hand values of *numeri* (smoothness) and *fukurami* (fullness and softness) for these fabrics. Also the total hand value for the US fabrics was lower than for the Japanese fabrics.

Figure 5.16 shows a similar comparison of US and Japanese summer suitings. Similar findings were obtained as in the case of winter men's suiting of Japanese fabrics. Note that the 145 US fabrics had weights ranging from 190 to 360 g/m, even though all the fabrics were chosen from those commercially available for career uniforms.

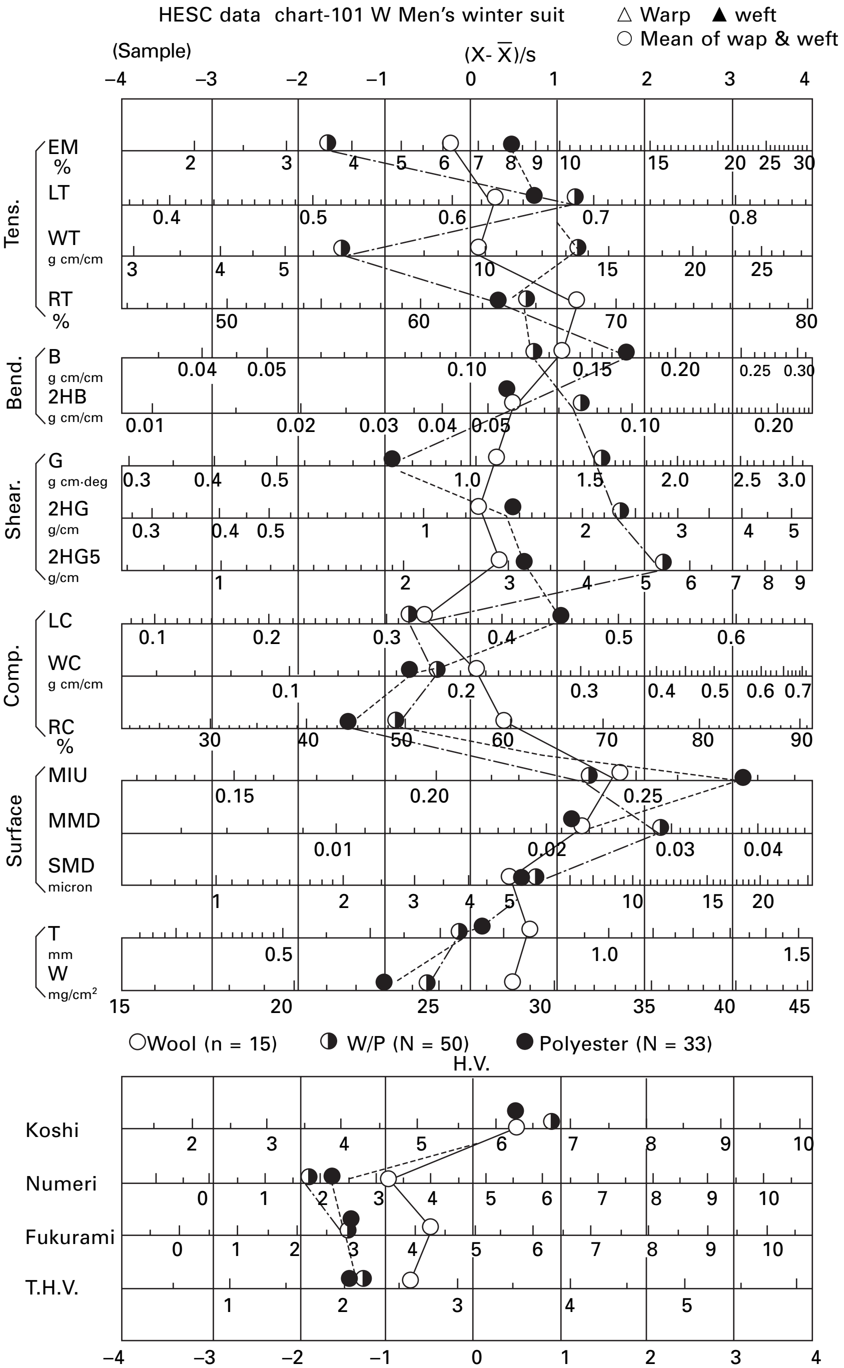
Three groups were chosen from the US fabrics and compared with similar fabrics from Japan: (a) 100% wool – 15 fabrics, (b) polyester/wool blends – 50 fabrics, and (c) textured polyester – 33 fabrics. The results of the comparison are shown in Fig. 5.17. One striking feature is that all the groups show the same trend: the US fabric properties are higher than those of the Japanese fabrics, resulting in lower hand values for *numeri*, *fukurami*, and total hand value, but higher hand value for *koshi*. This is also in full agreement with the



5.15 Comparison of properties measured by KES system and hand values between US and Japanese fabrics (men's winter suiting). *Source*: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



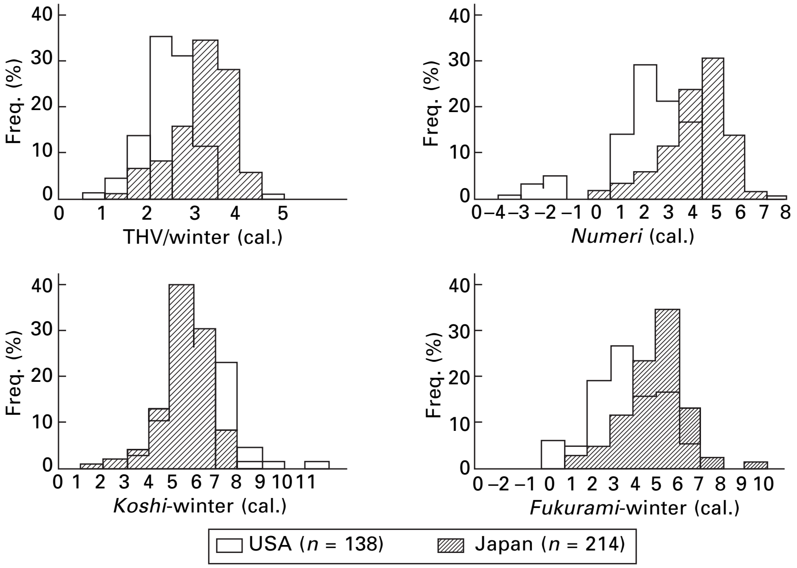
5.16 Comparison of properties measured by KES system and hand values between US and Japanese fabrics (men's summer suiting). *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.17 Comparison between 100% wool/polyester blends and 100% polyester fabrics made in USA and Japan. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

comparison made when all the samples were taken together regardless of fiber type.

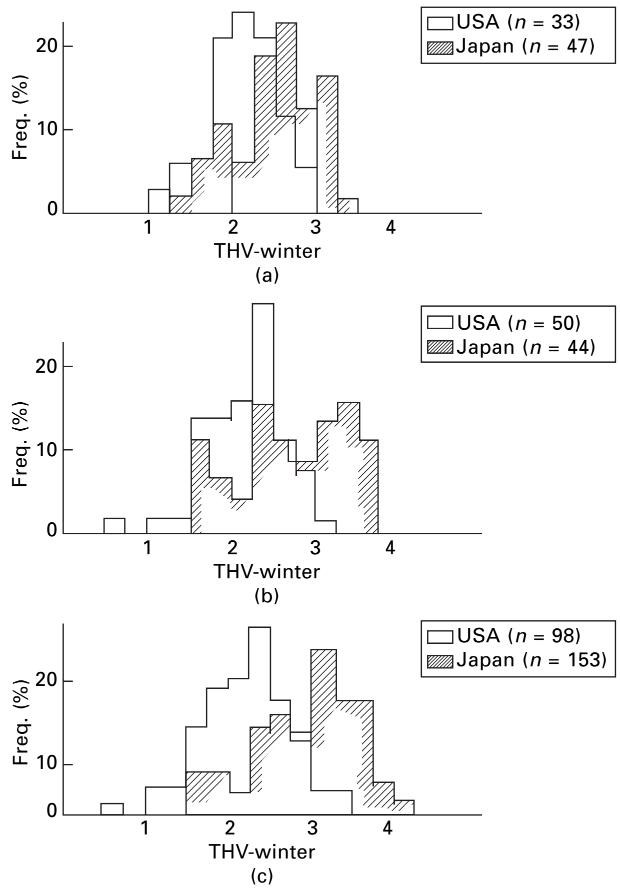
Figure 5.18 shows the distribution of primary hand values as calculated for *koshi*, *numeri*, and *fukurami*, as well as the distribution of total hand values for fabrics from the USA and Japan. These were calculated for winter men's suiting. The distribution indicated that there was good agreement in the fabrics evaluated with *koshi* (stiffness) for both US and Japanese fabrics, probably because the feel of stiffness was more or less consistent. For the other two primary hand values, *numeri* and *fukurami*, the Japanese fabrics tended to have more hand values in these categories than the US fabrics. For total hand value, the Japanese fabrics were distinctly different from and higher than the US fabrics.



5.18 Distribution of primary and total hand values for US and Japanese fabrics. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

The distribution of total hand values for the fabrics, when divided into the three groups indicated previously, is shown in Fig. 5.19. The differences in the total hand values (winter) for fabrics made of textured polyester and wool/polyester blends were relatively small between US fabrics and Japanese fabrics. The Japanese fabrics tended to have higher total hand values than the US fabrics (Fig. 5.19(a) and b)).

When studying the fabrics of the three groups as a whole, the distribution

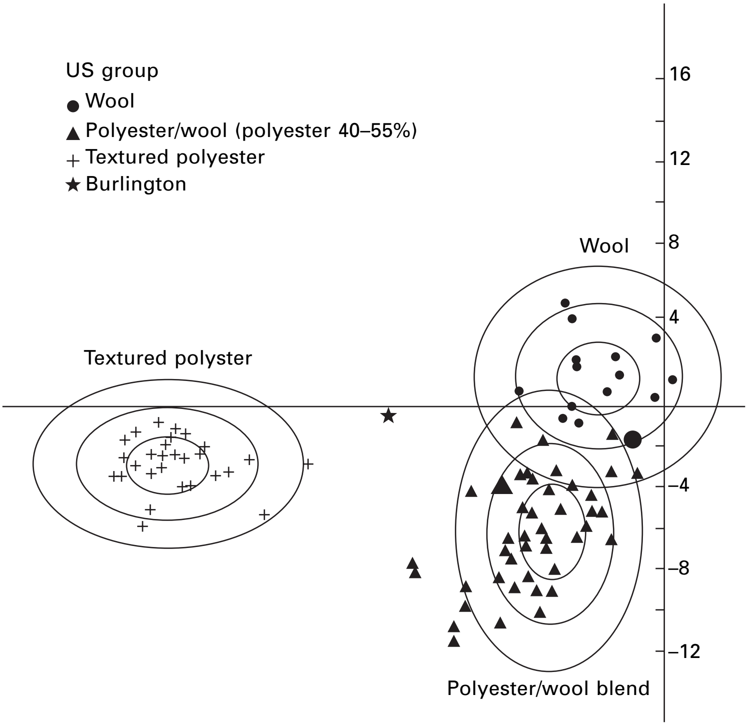


5.19 Distribution of total hand values (THV-winter) of (a) textured polyester; (b) polyester/wool; and (c) wool + polyester/wool + polyester. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

of the total hand values is shown in Fig. 5.19(c). The difference between US fabrics and Japanese fabrics is very distinct, with the Japanese fabrics showing higher total hand values.

A discrimination analysis was conducted following the same procedure adopted by Kawabata and Niwa [20]. The results are shown in Figs 5.20 through 5.23. The fabrics used in the analysis were those identified by the three groups mentioned before: wool, wool/polyester blends, and textured polyester. The values of Z_1 and Z_2 were calculated from the following equations:

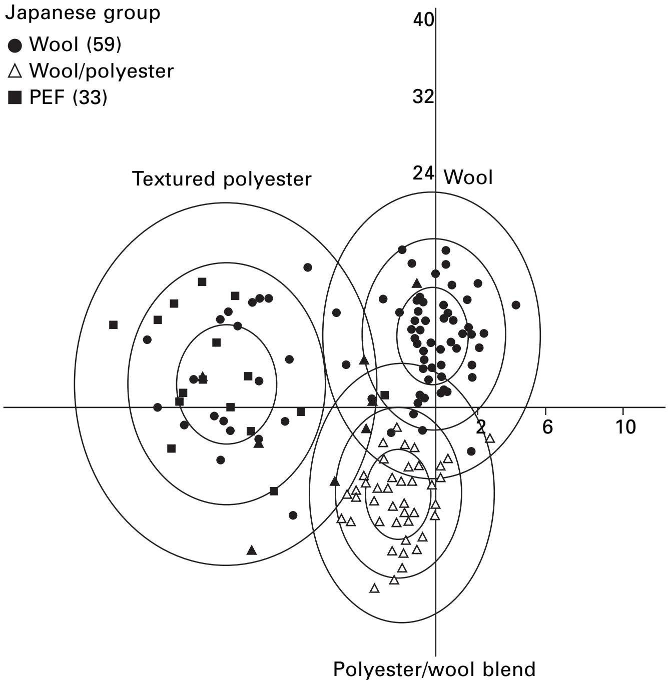
$$Z_1 = \sum_{i=1}^{16} \lambda_{1i} \left(\frac{X_i - \overline{X}_i}{\sigma_i} \right) \qquad (5.6)$$



5.20 Two-dimensional discrimination mapping of three US fabrics. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

$$Z_2 = \sum_{i=1}^{16} \lambda_{2i} \left(\frac{X_i - \overline{X}_i}{\sigma_i} \right) \qquad (5.7)$$

where X_i represents the 16 different parameters measured by the KES system. The values for the discrimination analysis shown in Fig. 5.20 are given in Table 5.34. The graphs in Fig. 5.20 show a two-dimensional discrimination mapping of the three types of material. The values of Z_1 and Z_2 from equations (5.6) and (5.7) can separate the generic hands of the different materials. The graphs show the overlap between the wool and wool/polyester hands, while the textured polyester fabrics have a separate sort of hand that seems to be characteristic of these fabrics. The center point of each graph is shown in Table 5.35.

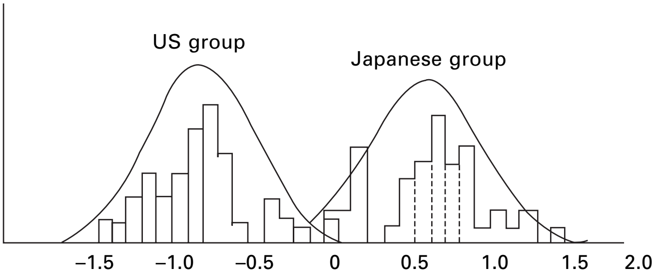


5.21 Two-dimensional discrimination mapping of three Japanese fabrics. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

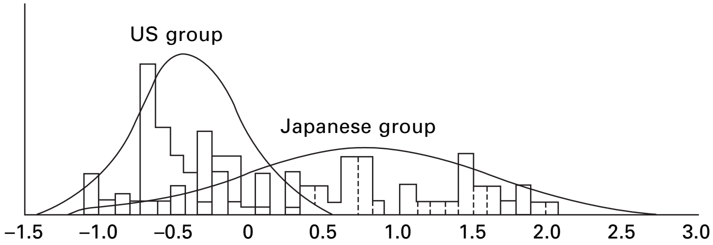
5.9 Conclusions from the comparison of fabric hand assessments between the USA and Japan measured by different methods

This study included the following five different methods and/or data by which the fabric hand could be assessed: hand modulus (by the nozzle method), subjective evaluation by a US panel of experts, testing of several mechanical properties (Behery [24], Kawabata's (KES) system (primary hand value), and Kawabata's (KES) system (total hand value)). It was concluded that there was a fairly good agreement between the quantitative approaches used in this study. There were few overlaps between the data obtained from these methods as shown by this discrimination analysis. This resulted in some differences in the hand evaluation.

The other conclusion worth pointing out is the difference in the hand of fabrics in the USA and Japan. The striking feature is the consistency and the degree of the differences, though the fabrics were obtained from various producers in the two countries. The mechanical properties of the fabrics were also different and this resulted in different assessments of



5.22 Comparison of discrimination analysis of textured polyester fabrics from US and Japanese groups. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.



5.23 Comparison of discrimination analysis of US and Japanese fabrics for properties relating to bending only. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

tailorability, with the USA fabrics showing better tailorability than the Japanese fabrics.

5.10 Fabric hand globalization interaction in the textile industry

5.10.1 Standards for fabric hand

The question arises as to whether it is feasible to construct an internationally acceptable scale of fabric hand standards development. Clearly, in view of the results summarized before, this task is more difficult for lightweight summer fabrics than for winter-weight fabric where the level of agreement is very good for all countries considered so far in the international hand survey. Such fabric hand standards could then be specified in objective terms through the 16 fabric mechanical parameters quoted in Table 5.33. This procedure could prove a scientific basis for an objective system of measuring overall fabric quality as shown in Fig. 5.19.

Table 5.34 Values of I_{1i} and I_{2i} for determination of Z_1 and Z_2 for wool, polyester/wool blend, and polyester textured fabrics for the 16 parameters

X_i^a	I_{1i}	I_{2i}
1. LT	–0.0645	–0.6482
2. log WT	–0.2054	1.4229
3. RT	0.0484	–0.2881
4. log B	–1.0524	2.5218
5. log 2HB	0.5424	–2.0117
6. log G	1.2462	1.9681
7. log 2HG	0.1557	1.5406
8. log 2HG5	–1.4999	–3.5823
9. LC	–0.2823	–1.5067
10. log WC	–0.2628	0.3235
11. RC	–0.0858	0.7927
12. MIU	–0.4003	0.0687
13. log MMD	–0.0043	–0.3112
14. log SMD	0.3144	0.2236
15. log T	–0.1846	–1.5543
16. log W	1.0000	1.0000

[a] The key to these abbreviations is given in Appendix A.
Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

Table 5.35 Center points of discrimination charts for wool, wool/polyester, and textured fabric

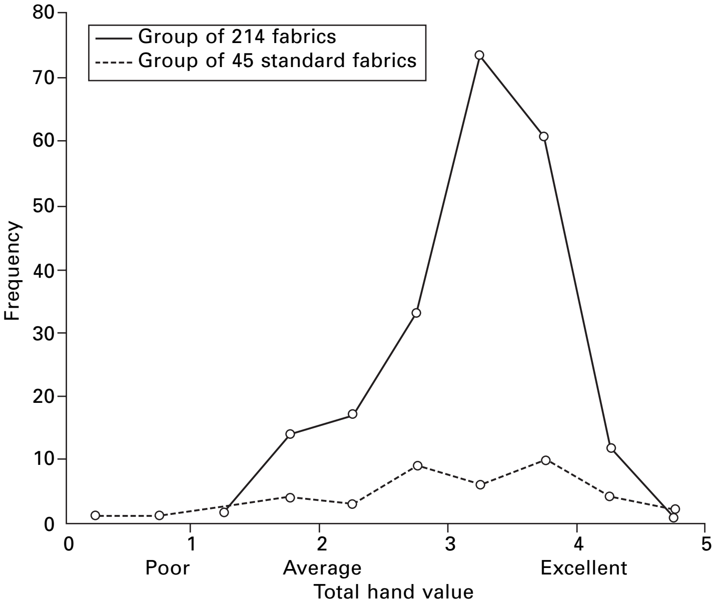
Center point for discrimination graphs	Z_1		Z_2	
	$\breve{Z}_1$	s_1	$\breve{Z}_2$	s_2
Wool	–0.8153	0.5022	1.4355	1.8214
Wool/polyester blend	–1.4250	0.3723	–6.1878	2.3432
Textured polyester	–6.1017	0.5520	–2.8378	1.3756

Source: 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

A frequency distribution for a series of 40 winter fabric hand standards, prepared jointly from Japanese and Australian fabric hand assessments, is shown by the dashed line in Fig. 5.24. The full line shows the frequency distribution for the population of 214 men's winter suiting fabrics from which the hand standards were derived.

5.10.2 Management of fabric hand property

It is significant to realize that substantial technological developments have been achieved in past years by chemical and physical modification of both



5.24 Frequency distribution for a series of forty winter fabric hand standards from Japanese and Australian fabric hand assessments. *Source:* 'Comparison of fabric hand assessment in the United States and Japan', by H.M. Behery, from *Textile Research Journal*, vol. 56, p. 227, 1986. Copyright Sage Publications.

natural and synthetic fibers in order to improve specific performance characteristics of the resultant fabrics. Relatively little emphasis has been placed until now on the fabric engineering approach whereby the use of different fiber qualities or varieties is combined with the optimization of yarn and fabric construction in order to produce superior fabrics and garments for specific end uses and with the hand that renders the product appealing, attractive and marketable.

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Part II

Effect of fibre yarn and fabric factors on fabric hand

6

Effect of fiber factors on fabric hand

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6.1 Introduction

The understanding and measurement of fabric hand has been described in the previous chapters of this book. Testing of the fabrics is performed to determine the hand value of these products; however, to enable design of new products, we must gain an understanding of how the component properties lead to the hand of the fabric. All of the fabrics discussed in this book are made of fibers. It is therefore logical to gain an appreciation for the way that fiber properties and behavior influence fabric hand. In this chapter, the fiber properties that can affect fabric hand will be discussed. These include fiber type, fineness, cross-sectional shape, length, friction, crimp, moisture properties and molecular orientation. The response of the fibers to deformation will impact the fabric hand properties significantly. Some of the standard testing procedures will be described and the relationship between the measured values and the fabric hand will be presented. Finally, the future trends in fiber development and testing will be proposed along with the identification of sources of information for further study.

6.2 Describing fibers

The Complete Textile Glossary (Celanese Acetate LCC 2001) defines fiber as ‘a unit of matter, either natural or man-made, which forms the basic element of fabrics and other textile structures. A fiber is characterized by having a length at least 100 times its diameter or width.’ Fibers are the building block for fabrics and their behavior influences the way that the fabrics respond to various modes of deformation.

As stated in the definition of fiber given above, the fiber can be natural or man-made and this is usually the first classification used to identify fibers. Table 6.1 lists the most commonly used fibers using this type of classification. The commonly used name of the fiber along with the polymer name is given. Other properties that help describe a fiber are its shape, color, luster, specific

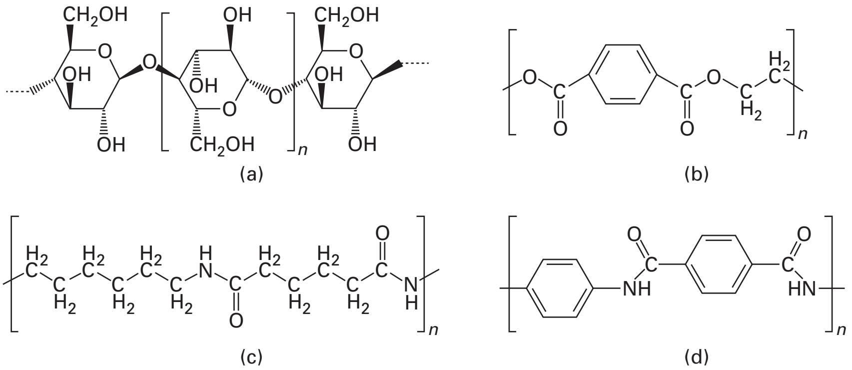
Table 6.1 Commonly used fibers and the polymers associated with them

Source	Fiber name	Polymer
Natural	Cotton	Cellulose
	Linen	Cellulose
	Silk	Polypeptide
	Wool	Polypeptide
Man-made	Acetate	Modified cellulose
	Acrylic	Polyacrylonitrile
	Kevlar	Poly-paraphenylene terephthalamide
	Modacrylic	Polyacrylonitrile
	Nomex	Polyamide
	Nylon	Polyamide
	Olefin	Polyethylene, polypropylene or other
	PBI	Polybenzimidazole
	Polyester	Polyester
	Rayon	Modified cellulose
	Spandex	Polyurethane

gravity, linear density, crimp and length. Before we discuss these properties, it is necessary to understand the building blocks of the fibers, polymers.

6.2.1 Polymers

A polymer is a long-chain macromolecule that is made up of many ‘mers’ or units. For example, cotton fiber is composed of cellulose (Fig. 6.1(a)), while polyester (a man-made fiber) is made of units that contain the ester linkage (Fig. 6.1(b)). Nylon (Fig. 6.1(c)) and aramids such as Kevlar (Fig. 6.1(d)) contain the amide linkage. Other polymers such as polypropylene have relatively simple chemical structures. The *n* in Fig. 6.1 indicates the number



(a) (b)

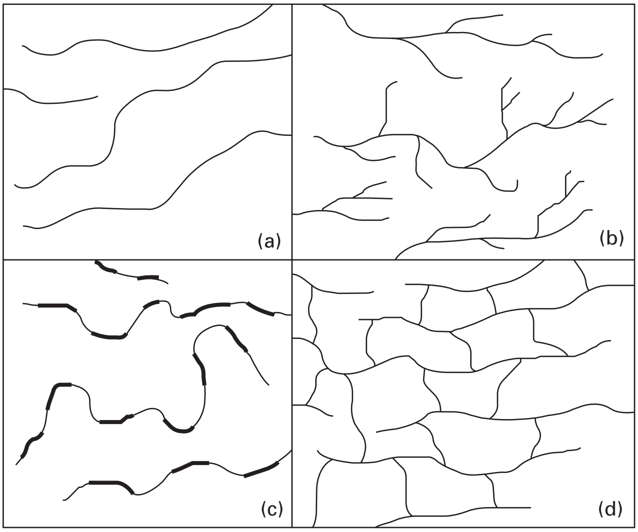
(c) (d)

6.1 Polymer repeat units for (a) cellulose, (b) PET, (c) nylon 6-6, and (d) Kevlar.

of polymer units in the polymer chain and is also called the degree of polymerization.

The types of elements and the way they are bonded together greatly influence the behavior of the polymer and its processability. For example, polypropylene was discovered in the 1950s but was not processed into fibers until the 1980s because of a small change in the way that the polymer units were put together.

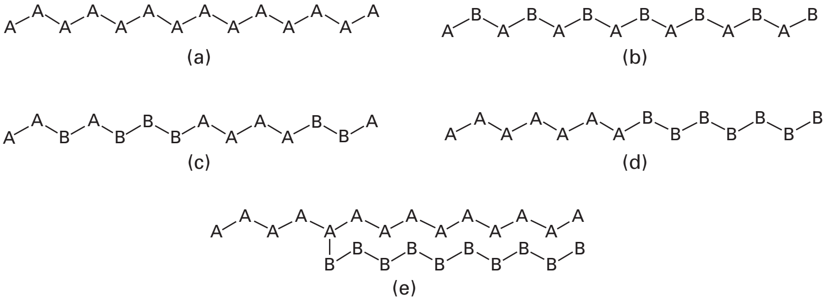
Some of the terms used to describe the different polymer structures are linear, branched, or cross-linked. They can also be classified as homopolymers (made of only one type of mer) or copolymers, which are made of more than one type of unit. This is usually done to gain the characteristics of both types of polymer units. Figure 6.2 shows all of these structures in schematic representation. The structure can also be described as flexible, such as Nylon 6-6, or stiff, such as Kevlar. This type of flexibility refers to how easily the molecular chain can change its configuration. The bonds in the Nylon 6-6 are very flexible, but the aromatic rings of the Kevlar polymer are quite rigid. This stiffness will be related to the stiffness of the fibers made from the polymer. Hence, the Kevlar fibers are more resistant to bending as compared to the nylon fibers. Polyurethanes are made up of units that contain highly extensible sections held together by stiffer sections. This structure leads to the highly extensible fibers such as Spandex.



6.2 Schematic representation of (a) linear, (b) branched, (c) copolymer and (d) cross-linked polymers.

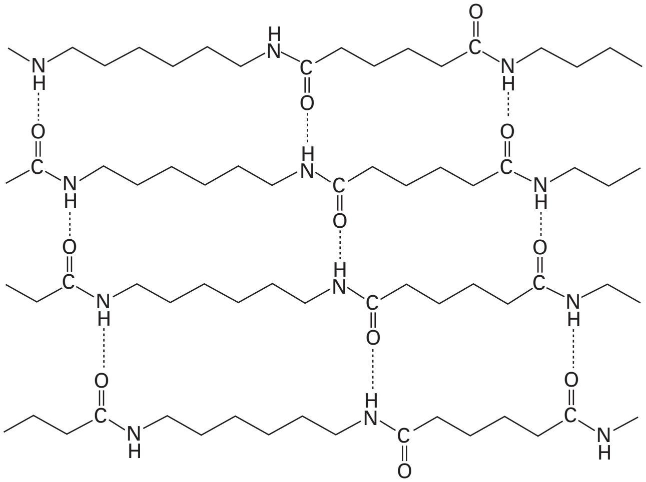
Other than changing the overall polymer structures such as linear, branched, or cross-linked, copolymers can be used to alter factors such as flexibility.

Figure 6.3 shows the variations that are possible in copolymer systems in which A is one monomer unit and B is a different monomer unit. In this way, a combination of the behavior of the two units is achieved. By adjusting where and how many times the monomer units in the copolymer repeat, it is possible to create a polymer that meets a precise specification. In Fig. 6.3, only two monomers are used, through copolymers can be made with more monomers.



6.3 Copolymer variations: (a) homopolymer, (b) alternating, (c) random, (d) alternating, and (e) graft.

The chemical structure of the polymer chain also determines the way that they can interact with each other. For example, the amide linkage in the nylon 6-6 polymer can form a hydrogen bond with the amide linkage on other chains. In this way, the bulk polymer, which contains many polymer molecules, will have a crystalline structure (Fig. 6.4). The crystalline structure

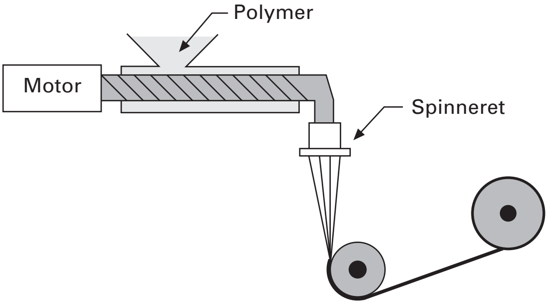


6.4 Hydrogen bonding in nylon 6-6.

will change during processing and it is important to note that all Nylon 6-6 fibers will not have the same crystallinity and, therefore, will not have the same response to deformation. There are many books and journal articles reporting the ways to measure crystallinity of polymeric fibers and explaining how the crystallinity affects the fiber properties. A list of some of these references for further reading is given at the end of this chapter.

6.2.2 Fiber spinning

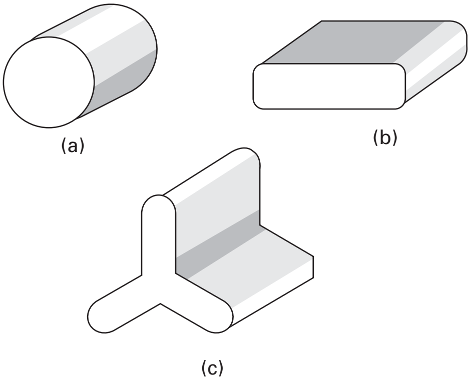
There are many ways to process the polymers into fibers. Melt spinning is done by melting the polymer and extruding it through a die called a spinneret (Fig. 6.5). In cases where the polymer cannot be melted or when melt spinning does not yield the desired molecular orientation, other spinning methods must be used. For example, acetate fibers are formed via dry spinning. In this type of spinning the polymer is put into a volatile solvent and then is pushed out of a spinneret. The solvent is driven off by an air flow and the fiber is wound onto a package. Rayon and acrylic fibers are also formed by making a polymer-solvent solution; however, the solution is pushed out of a spinneret into a bath containing a second solvent. The first solvent remains in the bath and the polymer fiber is removed. This type of fiber spinning is called wet spinning. Gel spinning is a special type of wet spinning with the polymer-solvent being a very dilute solution, i.e. a small concentration of polymer. Gel spinning produces a fiber with the molecular chains of the polymer highly oriented or organized. The fibers that are produced by all of these methods are termed ‘as spun’ fibers. In most cases the fibers will be further processed to obtain the desired fiber properties.



6.5 Schematic of melt spinning.

6.2.3 Fiber properties

It is useful to describe the geometry of the fibers and to note how different geometries lead to fiber mechanical responses. Some measures of fiber geometry are fiber cross-sectional area, diameter or nominal diameter, and fiber length. Additionally, if the fiber is not circular in cross-section, the shape of the cross-section is usually specified and other measures such as the minor and major axis for an oval cross-section or minimum and maximum diameter for a trilobal cross-section are used (Fig. 6.6). The diameter of the fiber is also a measure of fineness.

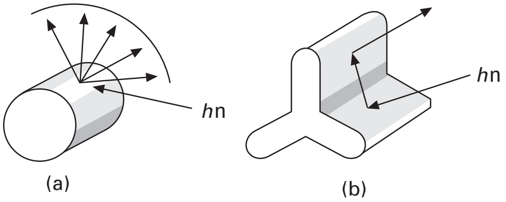


6.6 Fibers with (a) circular, (b) oval and (c) trilobal cross-sections.

Cross-sectional shape

Fibers come in many shapes and sizes. Natural fibers such as cotton vary greatly in cross-sectional size and shape, even for fibers from the same plant. The cross-section also varies along the length of a fiber. Other natural fibers such as wool have a near-circular cross-section. However, wool fibers will also vary in length and cross-sectional area. Man-made fibers will also have variations in the cross-section. The cross-section is determined by the fiber spinning method, the shape of the holes in the spinneret and the way that the fiber is processed after it is spun. For example, dry and wet spun fibers are usually made with spinnerets that have a circular cross-section; however, the fiber produced has a serrated cross-section. This is caused by the removal of the solvent during the spinning process. A melt spun fiber, on the other hand, has a cross-sectional shape very similar to the spinneret hole used to produce it. *Textile World* has produced the ‘Textile World 2003 Man-Made Fiber Chart’ (*Textile World* 2003), which contains typical photomicrographs of fibers used for textile materials.

The cross-sectional shape of a fiber will determine how light interacts with the fiber. For example, a round fiber will appear more lustrous than a trilobal fiber made of the same polymer. This is explained by looking at the way light bounces off of surfaces. Figure 6.7 shows a schematic representation of this concept. As light or hn hits the surface of the fiber it is scattered in multiple directions. Due to the shape of the round fibers, no light being



(a) (b)

6.7 Schematic representation of how light (*hn*) bounces off a fiber surface.

reflected is blocked from view as with the trilobal fiber. The trilobal geometry also has other benefits. Because of its larger surface area per length of fiber as compared to a round fiber with the same volume, the fiber may have more desirable moisture properties. For example, Nike Dri-FIT (Nike 2005) garments are made from fibers that have a high surface to volume ratio and/or have striations along their length to channel moisture, similar to that shown in Fig. 6.7(b). The multilobal fibers are also more efficient at 'hiding dirt' because of their light-scattering properties. Because of their ability to scatter light, they are frequently used in carpets and other applications.

As discussed above, the cross-section of a fiber changes along its length and may vary greatly in natural fibers and in man-made fibers that are spun out of a solution of polymer and solvent. Since the fibers are small, the cross-section may be non-circular and varies along the fiber length; the diameter is not an accurate measure of size of the fiber. Therefore, another measure is used. This measure is the linear density and is a measure of the mass of a given length of fiber. For fibers made from the same polymer, the larger the linear density the larger the fiber cross-sectional area. The linear density can be expressed in grams per meter or by two other units, which are commonly used. These two units are *denier* and *tex*. A denier is the mass of 9000 meters of fiber and a tex is the mass of 1000 meters of fiber. It is useful to note that for a fiber with a circular cross-section, the diameter of the fiber can be calculated if linear density, h, and density, r, are known (Equation (6.1)).

$$\text{Diameter} = \sqrt{\frac{4h}{pr}} \tag{6.1}$$

This equation can also be used to calculate the nominal diameter for a fiber with a non-circular cross-section.

Moisture properties

The way that the fiber interacts with moisture will impact its processability as well as its comfort. The ability of a fiber to take moisture into the fiber is called absorption. Adsorption is the ability of moisture to travel along the surface of the fiber. Adsorption is also described as wicking or wicking ability. As discussed previously, the surface area of the fiber has been increased by changing the cross-sectional area and/or shape to gain more desirable moisture properties.

Fiber size

We have already discussed how fiber size can affect the moisture properties of the fiber bundle. The fiber bending properties will also be governed by the shape and size of the fiber. For example, the bending resistance is proportional to the diameter to the fourth power as will be shown later in Equation (6.3). To see the effect of this, let us look at a given volume of polymer. For this volume of polymer, one can make any number of fibers. The surface area of these fibers is related to the square root of the number of fibers. This means that if the number of fibers is increased from one to four, the surface area doubles; and if the number of fibers is multiplied by 100, the surface area increases by 10 times. As pointed out, the fiber's resistance to bending is proportional to the fiber radius to the fourth power. Therefore, if the radius is decreased by a factor of 2, the bending resistance decreases by a factor of 16. Gone are the days of polyester fabrics that are uncomfortable to wear and have a harsh hand. The development of polyester microfibers has enabled the development of fabrics with desirable flexibility and moisture transport properties. These microfibers are fibers that have linear density less than 1 denier (9 tex). Fabrics made from these microfibers are soft and have good wicking ability because of the low bending resistance and the high surface area.

Fiber length

The length of fiber will also influence the way that the fiber properties translate to fabric hand. Short fibers having a length in the 2 to 3 cm range are called short staple fibers, while longer fibers such as wool have a staple length of 7 to 10 cm and are called long staple fibers. Continuous filament or filament yarns are ones that have very long lengths. Silk fibers are naturally occurring filament fibers, while man-made fibers are produced as filaments as described in section 6.2.2. The man-made filaments that will later be made into staple yarns (those made from staple fibers) will require that the filaments be cut before they are made into yarns. Fibers used to make non-woven fabrics, which do not require yarns to be formed, may be continuous filament or staple fibers.

Crimp

Fibers are characterized by the level of crimp in them. Crimp is a measure of the comparison of the actual length of fiber and the length of the fiber in its resting state. Crimp may be naturally occurring as in cotton or wool, or can be imparted on a man-made fiber through a process called texturing. Texturing adds bulk to the fibers, causing them to take up more volume than in their untextured state. This leads to the ability of the fiber to cover more space, as is desirable in carpets, or to allow air to be trapped in the fiber, which will change the thermal properties of the yarns and fabrics made from the fibers. Texturing will also change the way that light interacts with the fibers. Man-made fibers that are combined (blended) with fibers that have natural crimp are usually textured before blending with the natural fiber.

Fiber friction

Another property that is important to fabric hand is the fiber friction. The fiber–fiber friction influences the way that the fibers interact with each other. The fiber–fiber friction is reported as a friction coefficient. The friction properties will affect the flexibility of the yarns that are made from the fibers as well as how the yarns interact with each other. As the fiber–fiber friction increases, the ability of the fibers to slide past each other during yarn and fabric deformation decreases. This leads to a higher resistance to the deformation as compared with a fabric made from yarns with fibers that have a lower fiber–fiber friction coefficient.

6.2.4 Properties of common fibers

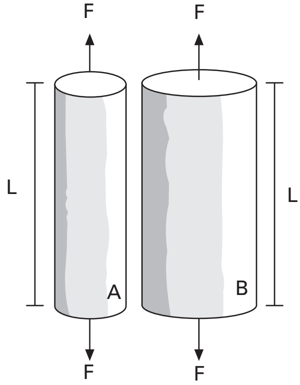
Table 6.2 contains some of the properties for some common fibers. These were taken from the Textile World 2003 Man-made Fiber Chart (*Textile World* 2003) and *Textiles* (Kadolph and Langford 2002). The chart contains properties of many other fibers; however, we have concentrated on the most widely used fibers.

6.3 Mechanical properties

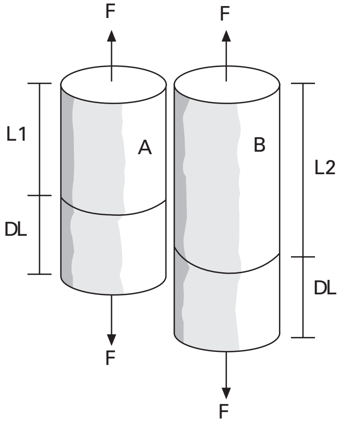
The mechanical properties of the fibers are important to the mechanical behavior of the fibrous structure in which they are incorporated. As discussed in Chapter 2, the tests used to determine the hand of a fabric are relatively low deformation tests. Therefore, the tensile modulus, bending or flexural modulus, and torsional modulus are of interest. These properties correspond to three different types of deformation as shown in Figs 6.8, 6.9, 6.10 and 6.11. The tensile modulus is used to describe the response of a fiber to tensile

Table 6.2 Mechanical properties of some common fibers

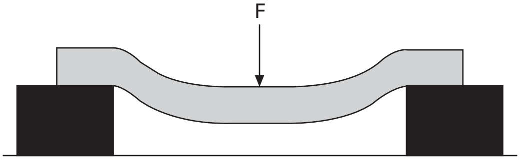
Fiber	Breaking tenacity (gpd)		Tensile strength (psi)	Breaking elongation		Elastic recovery (%)	Average stiffness (gpd)	Specific gravity	Moisture regain 65% rh and 70F
	Standard	Wet		Standard	Wet				
Acetate	1.2–1.4	0.8–1.0	20–24	25–45	35–50	48–65 at 4%	3.5–5.5	1.32	6.3–6.5
Acrylic	2.2–2.3	1.8–2.4	30–40	40–55	40–60	99 at 2%; 89 at 5%	5–7	1.17	1.5
Herculon (olefin)	3.5–4.5	3.5–4.5	41–52	70–100	70–100	96 at 5%; 90 at 10%	20–30	0.9	0.01
Modacrylic	1.7–2.6	1.5–2.4	45–60	45–60	45–65	100 at 1% 95 at 10%	3.5	1.35	2.5
Nylon 6	3.5–7.2	3.7–6.2	62–98	30–90	42–100	100 at 2%	17–20	1.14	2.8–5
Nylon 6,6	2.9–7.2	2.5–6.1	40–106	16–75	20–47	82 at 3%	10–45	1.13–1.14	4.0–4.5
Polyester	2.4–7.0	2.4–7.0	39–106	12–55	12–55	81 at 3%	12–17	1.38	0.4
Polypropylene	2.5–5.5	2.5–5.5	12–60	30–150	30–150	93 at 5%; 85 at 10%		0.91	0.01
Rayon	1.9–2.3	1.0–1.4		20–25	24–29			1.48–1.54	
Spandex	1.0		11–14	400–625		97 at 50%	0.13–0.20	1.21	1.3



6.8 Schematic representations of two fibers with different cross-sectional areas and the same length.

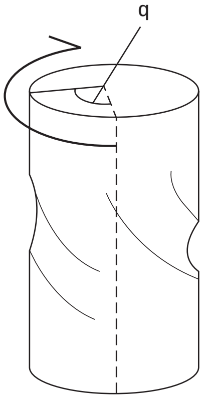


6.9 Schematic representations of two fibers with the same cross-sectional area and different lengths.



6.10 Schematic representation of the bending of a fiber to determine flexural modulus.

loading as indicated by the arrows in Figs 6.8 and 6.9. Bending modulus relates to the response of a fiber to a bending moment that can be imparted by a 'beam bending' type test or a 'loop test' (Fig. 6.10). When a fiber is twisted along its axis, the torsional modulus is used to characterize the response (Fig. 6.11).



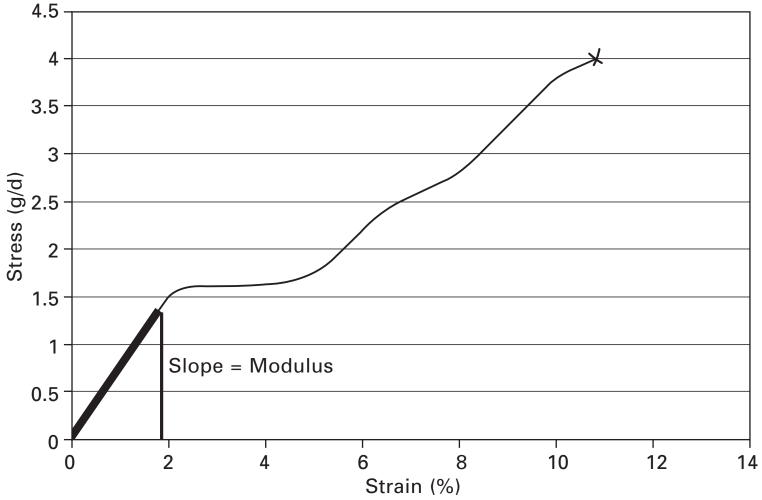
6.11 Schematic of torsional deformation of a fiber.

6.3.1 Tensile modulus

There are standard tests available to measure a fiber's response to tensile loading; ASTM D638–03 (ASTM 2004b) gives a more general testing method for polymers subjected to tensile loading. In ASTM method D2256 (ASTM 2004c), the fiber is held in two places by a set of grips. The grips are then displaced and the resistance to the displacement is monitored using a load cell. The results can then be presented as values of resistance (load) and displacement. Often the load is converted into specific stress (load/linear density) measured in grams per denier or centi-newtons per decitex. The displacement is used along with the original length between the grips (gauge length) to calculate the strain. Specific stress and strain are used to make the comparison of different fibers easier. To illustrate this we show two fibers in Fig. 6.8. These fibers are the same length but fiber A has a smaller cross-sectional area than fiber B. If these fibers are tested as described above and they both fail at the same load, we would say that they have the same strength. However, we would know that the fiber with the smaller cross-sectional area (fiber A) outperformed fiber B. The cross-sectional area is related to the linear density as shown in Equation (4.1), therefore we can divide the load by the linear density to yield the specific stress and then note that fiber A breaks at a higher specific stress than fiber B.

The argument for calculating strain is similar. Figure 6.9 shows two fibers with the same cross sectional area but with different lengths, L1 and L2. These fibers are displaced and are found to fail when they have been stretched the same amount, DL. Again, one fiber has outperformed the other. The strain is given by the displacement divided by the original length (gauge length). When the strain is calculated, the strain to fail for fiber A is greater than that of fiber B. Strain has no units and is presented as a decimal value or as a percentage. Strain is also known as elongation.

A typical specific stress versus strain curve is shown in Fig. 6.12. The initial slope of this curve is termed the tensile modulus or initial modulus. This low deformation response is very important to fabric hand. Another response that can be measured in a tensile test is the fiber's ability to recover from a deformation. This is called the elasticity of the fiber and it can be measured by subjecting the fiber to a tensile load, removing the load and measuring the changes in fiber length. It can also be measured by monitoring the specific stress vs. strain response of the fiber as it is repeatedly subjected to tensile loading and unloading. In many cases, the hysteresis is used as a measurement of recovery or elasticity of the fiber.



6.12 Stress versus strain curve for cotton fiber.

6.3.2 Bending or flexural modulus

Flexural modulus is defined by Dow Chemical Company as the ratio of stress to strain within the elastic limit, when measured in the flexural mode (Dow Chemical Company 2005). This property is used to indicate the bending stiffness of a material. Since fibers are similar in geometry to beams, many researchers have used beam bending models and theory to describe the behavior of fibers. Beam bending has been modeled and discussed for many years. Many mechanical engineering textbooks discuss the models in detail. Figure 6.10 illustrates one of these models where the ends of the beam (fiber) are fixed and a force is applied to the center of the beam. Linear beam theory shows that the force, F, required for fiber bending is given by

$$F = \frac{48EI}{l}h \tag{6.2}$$

where E = Young's modulus, I = geometrical moment of inertia of a fiber, h = half value of the deflection of a fiber, and l = the length of the sample. For a fiber with a circular cross-sectional area, I is related to the diameter of the fiber to the fourth power. The effect of changing the fiber size (fineness) on the flexural modulus is clear. As the fineness decreases, the flexural modulus decreases. This relationship has been exploited in the development of microfibers, which form fabrics with low flexural modulus as compared to fabrics made from larger fibers. As fibers continue to become finer and finer, fabrics with softer hand and lower resistance to bending will be developed. The flexural moduli for some commonly used fibers are given online at MatWeb (MatWeb 2005). Flexural properties of polymers can be measured using ASTM D790-03 (ASTM) 2004a)

6.3.3 Torsional modulus

A third way that fibers are deformed is by being twisted along their axis. Figure 6.11 is a schematic of this type of deformation. In this figure, one end of the cylinder (fiber) is stationary, while the other end is displaced about its axis as indicated by the arrow. The resulting displacement can be described by the angle, theta (q). The magnitude of the couple to cause this deformation is given by

$$C = \frac{pnr^4q}{2l} \tag{6.3}$$

where n is the torsional modulus, r is the fiber radius, and l is the fiber length. As with the bending deformation described above, the microdenier fibers have a low resistance to torsional deformation.

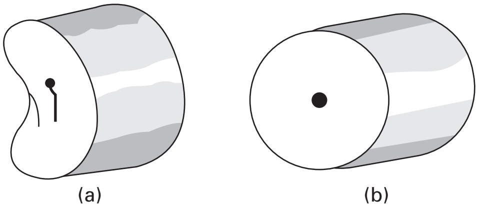
6.3.4 Resiliency

Resiliency is the ability of a fiber to recover or spring back after deformation. This may include bending, twisting, compressing, or a combination of these deformations. All of these properties are subjectively measured when a consumer handles a fabric. For apparel fabrics, resiliency is important in fabrics with a relatively large thickness or where the insulating properties are important. Resiliency of the fabric is directly related to the resiliency of the fibers as well as the fiber–fiber friction properties and the fabric structure. Resiliency is particularly important in applications such as carpets where they are deformed and expected to recover quickly. Recovery from long-term deformation, such as from a heavy object placed on the carpet, is also desired.

6.4 Chemical modification of fibers for improved fabric hand

Other than the typical mechanical methods to alter the hand of fabrics/fibers, hand can be improved by chemically treating the fiber. Two ways to chemically treat a fiber will be discussed: one way is to treat the surface and the other is to change the chemical make-up of the fiber. In treating the fiber surface, chemicals called ‘softeners’ are usually used. Softeners work by lubricating the surface of the fiber. This reduces the fiber–fiber friction, which makes the fabric move and flow more easily. Softeners are a type of textile auxiliary called surfactants that have the basic shape of a long hydrophobic carbon chain with a hydrophilic cationic end. By having a softener on the surface of the fiber, the fiber will not wear down or pill as fast as it would without the softener, thus maintaining good hand.

Another method of changing fiber hand is to alter the chemical nature of the fibers themselves. A very common method used is the mercerization of cellulose. Mercerization is the chemical treatment of cellulose with a caustic alkali such as sodium hydroxide. In this process the fiber swells, becomes stronger and more susceptible to dye, and has an increased luster. The pretreated cellulose fiber has a cross-section similar to that of a bean, as seen in Fig. 6.13. As cellulose is mercerized the overall shape of the fiber becomes more circular and more uniform than its irregular predecessor, thus becoming smoother to touch. With its round shape, this new cellulose or mercerized cellulose becomes more lustrous as demonstrated by the round fiber in Fig. 6.7. In addition to luster, the fibers are now able to absorb a larger amount of dye into the substrate, leading to richer shades of color. This is due to the solid-state structures being reformed. In this case there is a decrease in fiber crystallinity. For fibers that can form crystallites, the molecular orientation in the fiber can be classified as either crystalline or amorphous. In the crystalline areas, the fiber molecules are orientated to form crystallites. These crystalline areas are nearly impermeable to moisture or chemicals. The amorphous areas, on the other hand, are not orientated and are disordered. The chemicals and moisture can penetrate these areas. After mercerization, there is a decrease in the crystalline regions in the cellulose. Therefore, there are more amorphous

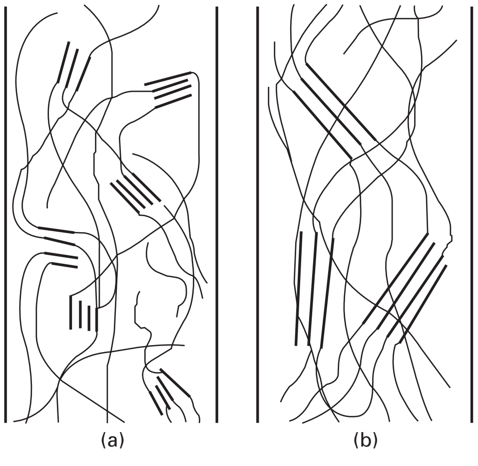


6.13 Fiber cross-section of (a) cellulose and (b) mercerized cellulose.

regions for the dyes to penetrate, which leads to better coloration of the fibers. Finally, the mercerization process also relieves some residual stresses. The result is a stronger fiber. In general, higher order of the molecules in the fiber leads to higher strength; however in the case of mercerization, the increase in strength from stress relaxation outweighs the loss in strength due to fewer crystalline regions.

6.5 Crystallinity in fibers

In general, the strength of a fiber increases with increasing degree of order of the molecules that make up the fiber. In other words, if the molecules in a fiber are aligned along the fiber axis, the fiber will be strong in uniaxial tension along the fiber axis. The orientation of the molecules in the fibers can be classified in two general classes or regions: the amorphous or unordered region and the crystalline or ordered region. Crystalline regions are areas in a fiber or material in which the molecules line up in a single direction, and amorphous regions are areas in which the molecules have no common direction. Crystallinity of a fiber can be expressed as a percentage of the volume that is crystalline. Although crystallinity can be used to get a general idea of the strength of a fiber, it is not all that is necessary to understand how the fiber behaves. We must also understand how the areas or regions are arranged in the fiber, the size of each region and the number of regions in a given volume of fiber. For example, Fig. 6.14 shows two fibers that have the same crystallinity. That shown in Fig. 6.14(a) is made up of smaller crystals, while Fig. 6.14(b) shows a fiber made of large crystals. Although the crystals in Fig. 6.14(b) are much larger, the volume of crystalline regions is the same in both fibers, thus

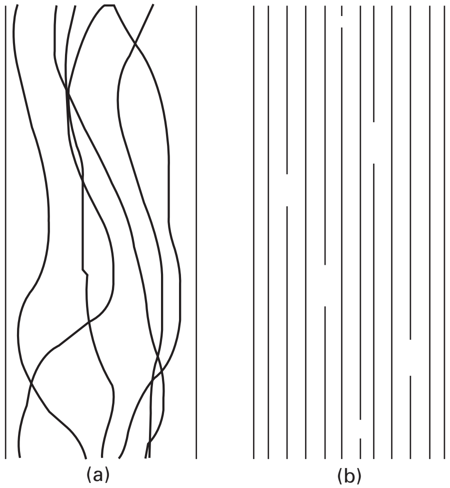


6.14 Fiber with (a) small crystals and (b) large crystals.

they have the same crystallinity. The differences in the size and number of crystalline regions lead to different levels of mobility of the molecules in the fibers. What this means is that with smaller crystals, the fiber shown in Fig. 6.14(a) can move with more freedom and less restriction than that in Fig. 6.14(b) with its large crystals.

The size and number of crystalline regions can be controlled by processing the fibers after they are spun. Typically this is done through drawing (stretching) the fiber in a heated state and setting the new structure. The process of setting the structure with heat is termed 'heat setting'. During heat setting, the fiber is heated to a temperature near its melt temperature. At this temperature small crystals in the fiber become amorphous while larger ones are maintained. The molecules from the newly melted small crystallites can then become part of the larger crystals. This will lead to a more crystalline fiber that is also stronger. Heat setting the fiber in a moist environment also affects the size and number of crystalline regions.

The drawing process involves the elongation of fibers by means of stretching. The stretching is achieved through the use of sets of heated rollers with varying speeds. As the fibers are stretched, so are the molecules in the fibers. With the stretching, the molecules become more ordered in the direction of drawing (see Fig. 6.15). With this higher orientation the fiber becomes stronger.



6.15 Fibers that are (a) unoriented and (b) oriented.

Crystallinity will also affect the hand of the fabrics made with the fibers by influencing the way that the fibers move and respond to bending. A more crystalline fiber like that in Fig. 6.15 is more resistant to bending. If an article of clothing were made from a highly crystalline fiber, it would feel stiffer as compared to a fabric made of fibers with a lower crystallinity. The desire to have a strong (highly crystalline) fiber which is also flexible is achieved by manipulating the size of the fiber. As shown in Equation (6.2), the flexibility of a fiber varies with its moment of inertia and its initial modulus. We have already discussed how the flexibility varies with fiber diameter. The crystallinity and fiber size and cross-section can be manipulated to obtain a fiber with the strength and bending behavior that is desired. Although the modulus increases with crystallinity (in most cases), the fiber size can be decreased to obtain a strong flexible fiber. As with many other materials, the design of a fiber requires tradeoffs.

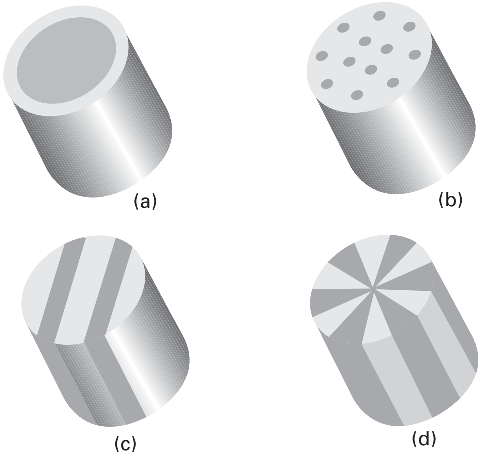
6.6 Future trends

In the field of polymers there is a great deal of research being done. Fibers that can carry electricity and sensors are being developed in clothing for medical, recreational, military and other purposes. The challenge will be in designing these new structures such that they have good fabric hand, while providing a robust system that can withstand normal washing conditions.

We have seen how the fiber size can be manipulated to yield fibers that are strong and flexible and have good moisture properties. The future will see the further miniaturization of fibers. Already, electrospun fibers with very small diameters are being produced in laboratories. A search of the compendex (2005) database using the search term 'electrospinning' yields over 150 journal articles published in 2004. In this spinning process, fibers are spun from a syringe that has an electrical current applied to it. The resulting fibers have diameters in the order of 1/10 to 1 microns. Yarns made from these fibers would have very high surface area to volume ratios. Researchers have been able to form electrospun fibers with a porous structure, thus increasing the surface area even more. The use of these fibers will be in applications such as filters, protective garments and biomedical applications, as well as in apparel.

Still other small structures are being developed (Fig. 6.16). For example, the 'island in the sea' fiber structure is shown in Fig. 6.16(b). In these fibers, two or more types of polymers are combined to obtain fibers that have the desired properties. In some cases the supporting 'sea' is removed after fiber extrusion to yield very small fibers, while in other cases the entire fiber is used. Researchers are currently working to develop these fibers with carbon nano tubes as the 'islands' in a 'sea' of another polymer (Kumar 2005). Through this type of technology, they will be able to form very small conducting fibers.

Currently, several research laboratories and companies are developing electronic textiles. These structures will become available to consumers in the next few years. In these products, thin conducting wires are incorporated into the garment to enable information to be passed from one part of the



6.16 Bicomponent fibers with (a) sheath-core structure, (b) island in the sea structure, (c) layer-by-layer structure, and (d) segmented pie structure (Kumar 2005).

garment to the other. The combination of the ‘island in the sea’ nano fibers and the idea of a garment that can act to enable input and output will lead to structures that can support many different electronic devices, all in a person’s clothing.

Carbon nano tubes have also been used to try to obtain fibers with much higher strengths. The nano tubes are incorporated into the fiber to reinforce the polymer. The further development of this technology will lead to fibers that are flexible yet have incredible strength.

Fibers are being developed that are made from polymers that change color with a stimulus such as light or an electrical charge. Still other fabrics are being developed from liquid crystal polymers to be used for flexible displays. In this application, the flexibility of the fabric is important as well as its ability to act as a display device. One of the challenges is to obtain fabrics with good hand that also display the desired optical properties.

The progress that has been made and that will be made in the future in materials development will lead to yet other fibers and fiber structures. Most of the applications, whether it be apparel, medical, composites or others, will require specific material properties, and therefore the hand of the fabrics formed from the fibers made from these new materials will be of great interest.

Here we have discussed only a few of the fiber developments being made at this time. For more current information, we suggest that you refer to the many polymer journals available online or through your local college or company library.

6.7 Sources of further information and advice

In this chapter the basic properties of fibers that are important to understanding fabric hand are discussed. Various dictionaries and glossaries are available online and in print. Three of these are Beech *et al.* (1988), Celanese Acetate LLC (2001), and Dow Chemical Company (2005). There is active research in the area of development of polymers for fiber forming, development of fiber processing methods and results from various testing of fibers. Additionally, there is an entire body of work investigating the mechanical response of fibers and modeling their behavior. Most of the work has been presented in the form of technical papers, journal articles and conference proceedings. The *Textile Research Journal* is a good technical source of research results concerning the modeling of fibers, yarns and fabrics. Listed here are examples of the types of research being reported in the literature concerning the mechanical properties of fibers, yarns and fabrics: Cheng *et al.* (2004), Gong and Mukhopadhyay (1993), Hoffman and Beste (1951), Honald and Grant (1961), Hunter *et al.* (1982), Kawabata *et al.* (2002), Ko and Jovicic (2004), Matsudaira *et al.* (1984, 1993), Sen *et al.* (2003), Sujica *et al.* (2003), Taylor (1972), Vasanthan (2004), Yamaura *et al.* (2004), Yu *et al.* (2003), Yusheng and Matsudaira (1993) and Zhang and Qiu (2003). A paper by Huang *et al.* (2005) contains many useful references concerning fiber properties and fabric hand.

There are also various books that can be used as reference materials. *Understanding Extrusion* (Rauwendaal 1998) includes an interactive training disk and teaches about the extrusion of polymers. For more details about fiber properties, the *Textile World* 2003 Man-Made Fiber Chart has already been mentioned. This chart is poster sized and contains fiber identification properties such as chemical reactivity and burning characteristics as well as mechanical properties for over 50 fibers. It includes sample stress versus strain curves for these fibers as well as numerical values for the mechanical properties. *Textiles*, 9th edition (Kadolph and Langford 2002) contains a table in the third chapter that summarizes the translation of certain fiber properties to fabric properties and is a good reference to use in understanding how fabric hand is influenced by fiber properties. Additionally, *Understanding Textiles* (Collier and Tortora 2001) contains information about fibers and their properties as well as a discussion of the basics of polymers. For a more in-depth discussion of fiber sciences, readers can go to *Fiber Science* (Warner 1995) and *Advances in Fibre Science* (Mukhopadhyay 1992).

The ASTM standards should be consulted for more information on the standard methods used to test fibers. These are readily available online or from your local college or company library. Other papers concerning the measurement of fiber properties include Collier and Epps (1998), Peykamian and Rust (1999), and Shao and Filteau (2004).

For more reading on electrospinning and if you have an interest in nano fibers and/or nano tubes as part of a composite fiber, a quick search of an engineering database such as Compendex or Web of Science (Web of Science 2005) will yield a list of the most recent research results available. Compendex is a very comprehensive engineering database that has almost 7.5 million records referencing engineering journals as well as conference materials. Compendex is available through universities that offer engineering degrees as well as by online access.

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7

Effect of yarn factors on fabric hand

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7.1 Introduction

According to the ASTM (American Society for Testing and Materials), yarns have been defined as 'a generic term for continuous strand of textile fibers, filament, or material in a form suitable for knitting, weaving, or otherwise inter-twining to form a textile fabric'.

Yarns constitute the major elements upon which the characteristics of the end products (fabrics or otherwise) are determined. In the course of this chapter the emphasis will be directed towards the effect of yarn properties – physical, mechanical, or both – on fabric hand.

Commercially, there is a huge variety of yarns. It would appear that there could be no limit to the number of distinctly different yarns.

7.2 Yarn types

Yarns have been classified into different types according to the methods of characterization and specification. In order to have full comprehension of these methods, and of the variety of possible yarns, it could be shown that any of the yarns available in the market will fall within one or more of the following categories.

7.2.1 Major categories of yarn types

The four major categories are:

- Types of fibers
- Yarn structure
- Yarn twist
- Method of manufacturing

If there are 10 possibilities in each of these categories, by simple probability there will be 10^4 different types of yarns. The following is an overview of the above categories.

Classification according to types of fibers and their length

Yarns are produced from two main types of fibers according to their lengths:

1. Staple-fiber yarn. In this type, the fiber length is of a staple type, either short, medium, or long staple, such as cotton and/or wool and worsted fiber, or any kind of man-made fibers or silk.
2. Continuous filament yarn. These are mostly man-made filaments which are of continuous length or of natural type, like silk.

Of the above fibers, yarns are produced in different types according to the different constituents. These could be:

- Entirely of one kind of fiber (natural or man-made)
- A blend of two or more fibers to obtain the desired yarn properties according to the percentages of the different fibers in the blend. In addition, in continuous filament yarns, there are two more special types of yarns:
- Bi-constituent yarns, in which each filament in the yarn is composed of two or more different polymers
- Bi-component yarns have filaments made from one type of polymer that are combined to form the yarn.

Classification according to yarn structure

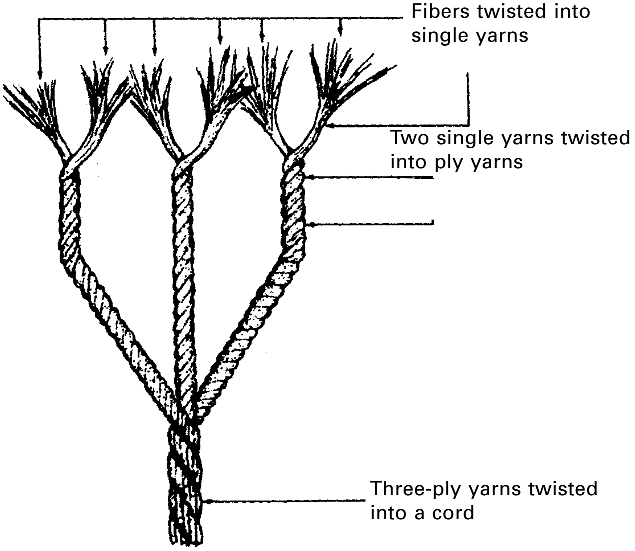
Yarn structure is another highly significant factor, which plays a major role in the physical and mechanical properties of the yarn. This, in turn, may affect the fabric properties which may reflect among other things on the fabric hand, as presented and discussed throughout this book. Six yarn structures are well known in the textile industry and are used according to their physical and mechanical properties, as well as the performance characteristics of the yarn. The different yarn structures are:

- Single yarns
- Plied yarns
- Cabled or cord yarns
- Complex yarns (core-spun)
- Fancy yarns
- Modified continuous-filament yarns.

Single yarns are made from a group of staple fibers or filaments twisted together.

Plied yarns are made by twisting together two or more single yarns. Each single yarn twisted into the plied yarn is called a ply.

Cabled or cord yarns are made by twisting together two or more ply yarns. Cord yarns are used in making ropes, sewing thread and cordage, and are woven as decorative yarns in novelty fabrics. Figure 7.1 shows an illustration of single, ply, and cord yarns.



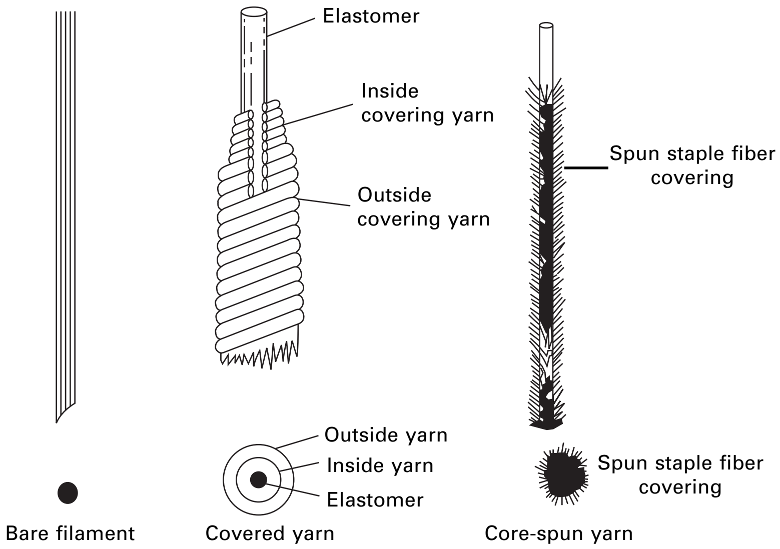
7.1 Single, ply, and cord yarns. *Source: Understanding Textiles*, 5th edn, by P.G. Tortora and B.J. Collier, 1997, Prentice Hall.

Core-spun yarns are yarns made with a central core of one fiber around which is wrapped or twisted an exterior layer of another fiber. Core-spun yarns could be made with an elastomeric core, such as Spandex, covered by another fiber to produce a stretch yarn. Figure 7.2 shows an illustration of types of elastomeric yarns (lengthwise and cross-section).

Fancy yarns are usually made by the irregular plying of staple or continuous-filament yarns and are characterized by abrupt and/or periodic effects. The periodicity of such 'effect' yarns is preferred to be random. Figure 7.3 illustrates different types of fancy yarn (sometimes referred to as novelty yarns or specialty yarns).

Continuous-filament yarns are mostly produced as man-made materials, such as nylon, polyester, or acetate and rayons. The filaments produced are joined to form multi-filament yarns by twisting them together either loosely or more tightly. The amount of twist, together with the characteristics of the fibers (luster, hand, cross-sectional shape, etc.), will determine the appearance and feel of the yarn.

In order to change the smooth surface feel of fabrics made from continuous-filament yarns and to be able to simulate the feel of fabrics made from staple



7.2 Covered and core-spun yarns. *Source: Understanding Textiles*, 5th edn, by P.G. Tortora and B.J. Collier, 1997, Prentice Hall.

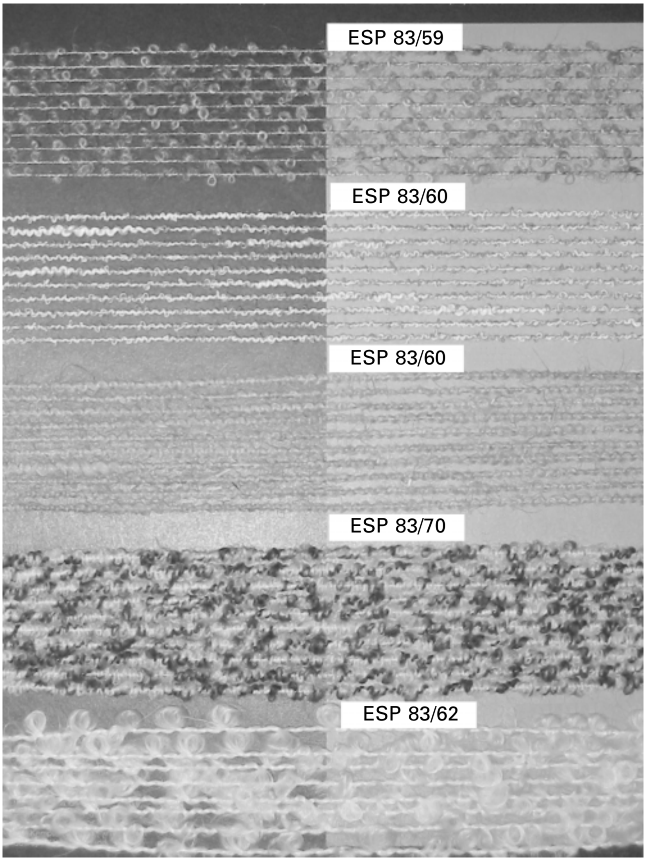
fiber yarns with the hairy surface condition, filament yarns are sometimes put through an additional process known as texturizing. The process modifies the feel of the filament yarns by adding bulk and/or stretch to the filaments: the yarns produced are known as **modified continuous-filament yarns**. The different processes used will be presented later in the chapter.

Classification according to yarn twist

Yarn twist is one of the most important parameters in determining the major properties of the yarn. Mostly, yarns are twisted at some level or another. The degree of twist given to a yarn affects a number of aspects of its appearance, behavior, and durability. As a general rule, increasing twist decreases apparent yarn size.

Yarn tensile strength increases in staple fiber yarns as twist increases up a certain twist level known as ‘optimum twist’. Beyond this point, the strength of the yarn begins to decrease. On the other hand, filament yarns are stronger untwisted, and the strength decreases as twist increases.

The appearance and hand of fabric are affected to a large extent by the twist of the yarn. For example, if filament yarns of higher luster are given only very low twists, they will reflect greater quantities of light in mirror-like fashion and, therefore, appear brighter and of smoother hand than the same yarns when they are more highly twisted. Loosely twisted worsted yarns produce a smooth, more even surface.



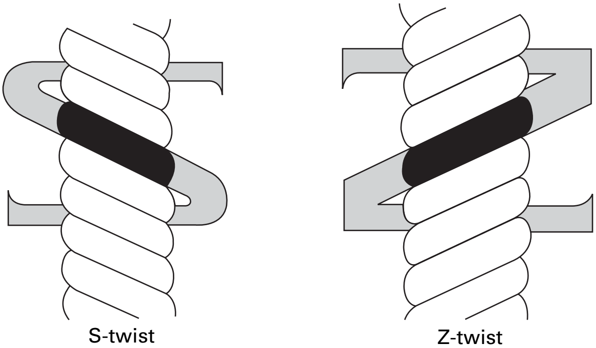
7.3 Different types of fancy yarn.

Direction of twist

In the textile industry, the terminology describing the direction of twist in yarns is called S or Z twist (Fig. 7.4). Z-twisted yarns are twisted so that the direction of the fibers or the filaments follows the center bar of the letter Z. In S-twisted yarns, the yarn twist direction follows the center bar of the letter S. The adoption of these terminologies is simply to facilitate the description of the direction of twist in the yarns, instead of right or left twist. Most single yarns are produced with Z-twist and are twisted in the S-direction when plying two single yarns together.

Methods of yarn manufacture

Yarns are also classified according to the method of manufacture since these methods adopt different technologies and, hence, produce different types of



7.4 Direction of twist. *Source: Understanding Textiles*, 5th edn, by P.G. Tortora and B.J. Collier, 1997, Prentice Hall.

yarns. The different methods of manufacturing yarns are summarized as follows:

- Short staple spinning
- Modified short staple spinning
- Worsted yarn spinning system
- Woolen yarn spinning system
- Tow-to-top conversion system (by either cutting or stretch breaking)
- Texturizing.

The most popular systems to process staple fiber yarns of short, medium or sometimes long staple fibers are:

- Ring spun yarns, either carded or combed
- Open-end spinning
- Air-jet spinning
- Friction spinning.

As the technological details of yarn manufacture are outside the scope of this book, the reader is advised to refer to the suggested reading list at the end of this chapter.

7.3 Effect of yarn structure on fabric hand

An overview of the relationship of yarn structure and fabric hand has been outlined by Scardino [1]. He has pointed out that in the case of visual aesthetics, the contribution of yarn structure to the tactile qualities of fabrics is transmitted through the surface geometry of the constituent yarns. Exceptions to this tendency, once again, can be found in the case of heavily napped, brushed, or felt-finished fabrics and in the case of apparel fabrics that have been given heavy coatings or chemical treatments.

However, the tactile qualities of a fabric are also dependent on the compressive behavior of the fabric. The dimensional stability of the cross-section of the constituent yarns plays a major role in fabric compression. Thus, the behavior of yarn cross-section during fabric compression is quite fundamental to the hand of fabrics.

The role of yarn structure in tactile aesthetics of fabrics is somewhat dominated by yarn twist. For example, fabrics composed of yarns with higher levels of twist are known to have higher bending stiffness, less compressibility, less fiber mobility, lower surface friction, less bulkiness, and less potential contact with a contiguous surface than similar fabrics composed of yarns with less twist. Increased yarn twist leads to greater internal (fiber-to-fiber) friction within the yarn structure. The constituent fibers or filaments tend to bend as a group rather than individually, thereby increasing the bending stiffness of the yarn. The increased fiber entanglement and internal friction caused by yarn twist also provide for a more dimensionally stable yarn structure that does not deform as much under compressive loads. On the yarn surface, the segment of fiber length between points of entanglement is reduced with increased yarn twist. This effect severely restricts fiber mobility and the chance of snagging of fibers or filaments. Yarn twist creates lower surface friction and potential surface contact because of less yarn flattening under low levels of compressive loading. Increased twist tends to reduce softness, covering power, and bulkiness, in general, and hairiness in the case of spun yarns.

Fiber linearity and fiber-packing density in yarn structures are also important to the tactile qualities of a fabric, when not masked by twist. In untextured filament yarns, the fiber linearity and packing density are quite high. Consequently, the yarn leads to a smooth, uncompressible feel in fabric. With similar yarns that have been textured, the low packing density of filaments and the non-linear protruding filament loops produce a soft, compressible but resilient (spring-back) feel in fabric.

7.4 Fundamental structural features of yarn

Scardino [1] has also explained that yarn structural features depend mainly on the properties of the constituent fibers or filaments and the inherent characteristics of the processing systems. Excluding generic-related parameters (such as fiber friction, modulus, resilience, extensibility, and elasticity), the fiber properties of greatest importance are length, fineness, crimp, and cross-sectional shape. The inherent characteristics of the processing system are fiber orientation and entanglement. Fiber orientation refers to the position of the fiber or filament segments in relation to the yarn axis and, in general, the degree of linearity of the fibers or filaments in a yarn. Fiber entanglement, as used here, relates to both the nature of the entanglement and the frequency or the degree of entanglement.

7.5 Comparison of hand of fabrics produced with air jet and ring spun yarns

A study was conducted on objective evaluation of fabrics woven with air jet yarns in comparison with ring spun yarn. The study was published in two parts: Part I, for mechanical and surface properties (Vohs *et al.* [2]) and Part II, for hand properties (Vohs *et al.* [3]). The objective of the study was to use KES-F instruments to examine differences in properties of fabrics woven with the two types of yarns. The main intention of the study was to determine how mechanical and surface properties of fabrics woven with air jet spun (AJS) yarns are influenced by fabric weave and thread density. Also, subjective evaluations of the hand of the two fabrics were compared.

7.5.1 Experimental procedures

Test fabrics

A set of fabrics was woven that permitted a direct comparison of air jet and ring spun yarns in samples of similar construction. Twill and plain weaves were produced at three different pick densities. All the samples have 92 warp ends per inch and were unfinished, except for desizing.

The air jet yarn was produced on a Murata spinning frame and had a 28's cotton count. The ring yarn had a 27's count. Both types of yarn used a 65/35 blend of polyester and cotton fibers. Table 7.1 describes fabrics used in this research.

Table 7.1 Test fabrics

Yarn types	Fabric design	Pick density	Weight (mg/cm^2)
Air jet spun	Plain weave	50	15.32
Air jet spun	Plain weave	55	16.09
Air jet spun	Plain weave	60	16.89
Air jet spun	3/3 Twill weave	50	14.50
Air jet spun	3/3 Twill weave	55	15.21
Air jet spun	3/3 Twill weave	60	15.89
Ring spun	Plain weave	50	15.10
Ring spun	Plain weave	55	16.04
Ring spun	Plain weave	60	16.83
Ring spun	3/3 Twill weave	50	14.62
Ring spun	3/3 Twill weave	55	15.05
Ring spun	3/3 Twill weave	60	16.01

Source: Objective Measurement: Applications to Product Design and Process Control, by S. Kawabata, R. Postle and M. Niwa, 1986, The Textile Machinery Society of Japan.

Fabric testing

Two 20 cm ¥ 20 cm samples containing different warp and filling yarns were cut from each fabric sample and tested on the KES-F instruments for tensile and shearing, bending, compression, surface smoothness and friction properties. Four separate measurements were taken on each sample. For the directional properties, two measurements were taken in the filling direction and two in the warp direction. For some surface testing, four measurements were taken in each direction. Table 7.2 lists the properties measured by the KES-F system.

Table 7.2 Mechanical property parameters

Property block	Symbol	Characteristic value	Unit
Tensile	LT	Linearity	–
	WT	Tensile energy	gf · cm/cm^2
	RT	Resilience	%
Bending	B	Bending rigidity	gf · cm^2/cm
	2HB	Hysteresis	gf · cm/cm
Shearing	G	Shear stiffness	gf/cm · degree
	2HG	Hysteresis at q = 0.5°	gf/cm
	2HG5	Hysteresis at q = 5.0°	gf/cm
Compression	LC	Linearity	–
	WC	Compressional energy	gf · cm/cm^2
	RC	Resilience	%
Surface	MIU	Coefficient of friction	–
	MMD	Mean deviation of MIU	–
	SMD	Geometrical roughness	micron
Weight	W	Weight per unit area	mg/cm^2
Thickness	T	Thickness at 0.5 gf/cm^2	mm

Source: *Objective Measurement: Applications to Product Design and Process Control*, by S. Kawabata, R. Postle and M. Niwa, 1986, The Textile Machinery Society of Japan.

Yarn testing

In order to examine the contribution of yarn properties to fabric properties, yarn samples from the filling supply package were tested for compression, bending and tensile properties on the KES-F instruments. To test yarn tensile and bending properties, a special procedure was developed for mounting parallel arrays of yarns in the instrument jaws. Three groups of 25 yarns were tested from each yarn type. High-sensitivity test settings were used.

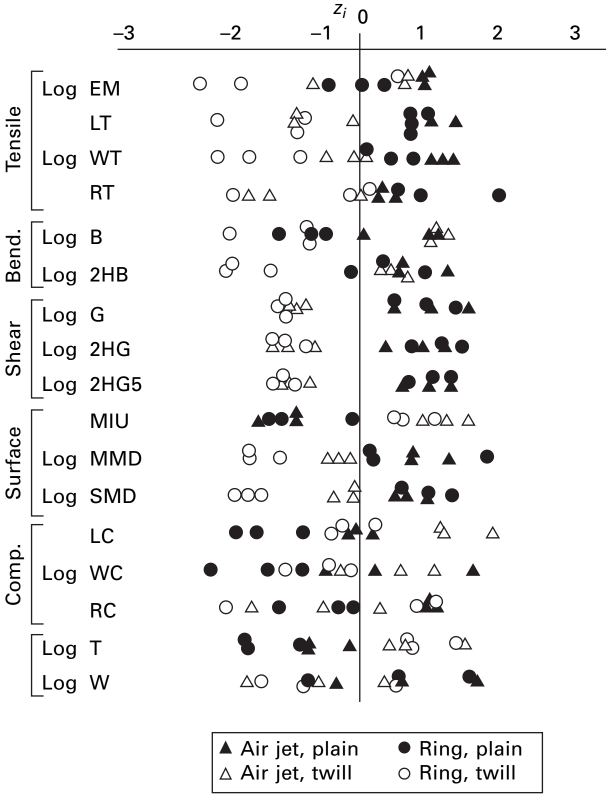
7.5.2 Results and summary

The following properties were tested for the yarns and fabrics:

- Yarn properties: compression, bending stiffness, and tensile properties
- Fabric properties: thickness, compression, bending, shear, tensile properties, and surface properties.

Figure 7.5 summarizes comparisons between mechanical and surface properties of fabrics woven with AJS yarn and fabrics made with ring spun yarns. Findings can be summarized as follows:

1. AJS yarns produce fabrics that are thicker and less compressible than fabrics made with ring spun yarns. The differences in fabric compressional properties related to yarn type increase with the thread count of the fabric and are more obvious in comparisons made between tightly woven plain weave constructions. The greater bending stiffness of AJS yarns apparently



7.5 Summary of comparison of standardized KES properties of fabrics. A standardized value of zero means that the fabric property is equal to the mean for all fabrics. *Source:* 'Objective evaluation of fabrics woven with air-jet yarns', by K.M. Vohs, R.L. Barker and M.H. Mohamed, from *Objective Measurement*: *Applications to Product design and process control*, 1986, The Textile Machinery Society of Japan.

plays a greater role in determining the compressional response of fabric in constructions that produce higher yarn interlacing and higher yarn crimp levels.

2. Fabrics made with AJS yarns are significantly more extensible than similar fabrics made with the ring spun yarns when the tensile load is applied in the direction of the filling yarns. Fabric weave is the overriding factor determining extension, with plain weaves being more stretchable than twill weaves regardless of the yarn type used in fabric construction.
3. For all fabric constructions, AJS yarns produce fabrics that are stiffer in bending than fabrics made with ring spun yarn. However, differences in bending stiffness caused by AJS yarns are greater when comparisons are made between twill weaves and when the bending deformation is in the direction of the warp yarns. In general, fabrics made with AJS yarns recover less energy in bending than fabrics woven with ring spun yarns. The bending stiffness of AJS fabrics (in the filling direction) is lower in twill constructions.
4. Fabric construction (i.e., weave, thread density, not differences in yarn properties) plays the major role in determining fabric shear stiffness. Since shearing properties are controlled by fabric weave and thread density, there is little disadvantage in using AJS yarns from the standpoint of fabric shearing rigidity.
5. KES surface measurements show that fabrics produced with ring spun yarns are smoother and, generally, have lower contact friction than similar constructions that use AJS yarns. However, the roughness of fabrics made with AJS yarns is significantly reduced by choosing twill weaves or weaves with longer surface floats.

This study demonstrated that observed differences in fabric mechanical and surface properties were consistent with expected differences in the properties of yarns formed using air jet or ring spinning systems. It suggested that comparisons made between fabrics woven from these types of yarns can be drastically affected by the choice of weave design and construction. The study provided an explanation for the characteristic hand of air jet spun yarn fabrics and suggested that many negative properties, especially surface harshness, compressional response and bending stiffness, might be improved by choosing a weave that permits the greatest yarn mobility (e.g., twill or satin weaves).

7.6 Subjective hand evaluation of fabrics

Sensory evaluation methods used were based on the protocols adapted by Winakor *et al.* [4] and Kim and Piromthamsiri [5]. This test began by defining the primary components of hand in terms of polar word pairs, or words that have opposite meaning such as stiff and flexible, or gentle and harsh. These words were selected to match the modes of deformation that occur when a fabric is tested using KES-F instruments. Table 7.3 lists these polar word pairs.

Table 7.3 Hand components used in subjective test

Word pair	Associated property
Gentle – Harsh	Surface
Smooth – Rough	Surface
Soft – Hard	Compression
Thin – Thick	Thickness
Light – Heavy	Weight
Flexible – Stiff	Bending
Limp – Crisp	Bending
Sleazy – Firm	Shear
Loose – Compact	Shear/Tensile
Stretchy – Not stretchy	Tensile
Desirable – Undesirable	Fabric Hand

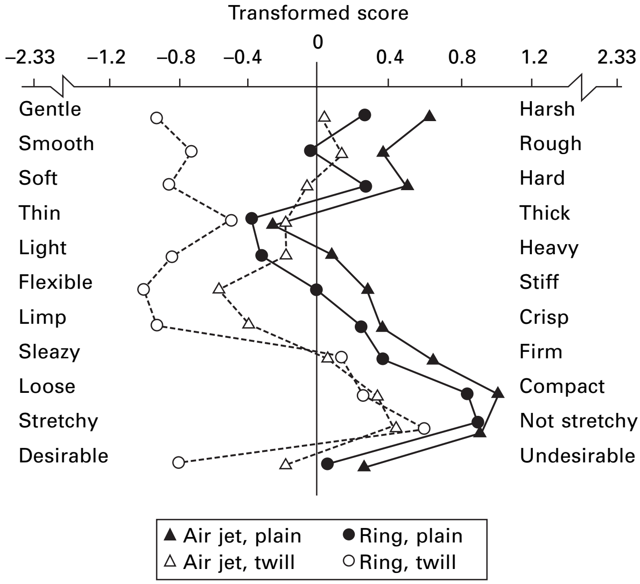
Source: *Objective Measurement: Applications to Product Design and Process Control*, by S. Kawabata, R. Postle and M. Niwa, 1986, The Textile Machinery Society of Japan.

7.6.1 Procedure for subjective evaluation of fabric hand

Twenty-eight college students participated in the survey. While the majority of the evaluators had some background in textiles, the overall makeup of the panel was more like consumers than experts. There were 15 male judges and 13 female judges ranging in age from 19 to 29 years old. This was a blind test: a simple screen was set up so the judges could feel but not see the fabrics. The judges gave two types of responses using a 99-point certainty scale. The first response indicated which adjective of the word pair best described the fabric, and the second response indicated how certain they were of their response. A score of 1 meant the judge felt very strongly that the left adjective best described the pair. A score of 99 meant that the judge felt very strongly that the right adjective best described the pair. A score of 50 meant that the judge was uncertain about which adjective best described the fabric. Evaluators rated each fabric for the complete set of quality word pairs. They used the same material rating scale to evaluate each fabric on the basis of total or overall desirability of hand. A detailed description of the protocol used in the subjective test is found in Reference 6.

7.6.2 Results

Sensory data were transformed to normal deviates (or linear responses) using the PROBIT function of SAS [7]. The transformation weights scores at the ends of the scale higher, reflecting more certainty of judgment. The scores near the middle of the scale receive lower weightings, reflecting less certainty. A score of 50 was transformed to 0, a score of 1 to –2.33, and a score of 99 to +2.33. These scores were averaged and plotted on sensory response diagrams (Fig. 7.6). The horizontal axis of the sensory response profile shows the scale of the transformed data and the vertical axis lists the word pairs. These diagrams, along with the analysis of variances, provide a wealth of information on factors influencing fabric hand.



7.6 Sensory response profiles for fabrics woven with AJS yarns and ring spun yarns. *Source:* 'Objective evaluation of fabrics woven with air-jet yarns', by K.M. Vohs, R.L. Barker and M.H. Mohamed, from *Objective Measurement*: *Applications to Product design and process control*, 1986, The Textile Machinery Society of Japan.

7.6.3 Effect of yarn type and fabric weave

The subjective evaluation showed that hand was primarily determined by weave and by whether AJS yarns or ring spun yarns were used in the construction. Fabric thread density had no significant effect on the hand ratings. Comparisons (shown in Fig. 7.6) can be summarized as follows:

1. Fabrics woven with ring spun yarns were judged to have characteristics of gentleness, smoothness, and softness, and were thought to feel light and limp. Similar fabrics made with AJS yarns were rated as harsh, rough and hard. Fabrics made with AJS yarns were judged to be less desirable, apparently in the perception of negative surface textures. There was little

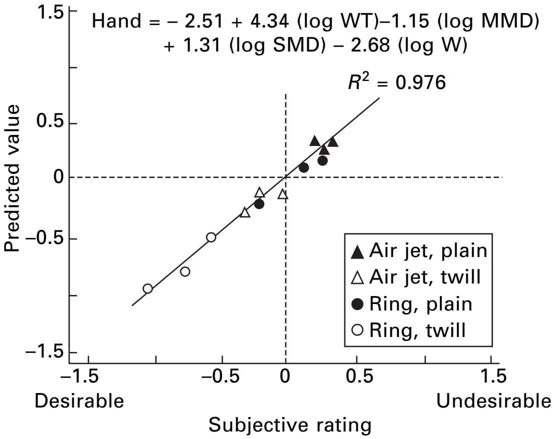
difference between AJS yarn fabrics and ring spun yarn in perceived thickness, firmness, compactness or stretchiness. As predicted by the analysis of mechanical properties, these characteristics were controlled more by the fabric construction than by the type of yarn component.

2. Twill weave constructions, regardless of the component yarn, were judged to be gentle, smooth, soft, flexible, and limp, and to have a desirable hand. Plain weave fabrics, as a group, were rated as harsh, rough, stiff, crisp, firm, and less desirable than twill weaves.

The most significant finding from subjective testing was that fabric weave had a greater influence on hand and primary hand components than the yarn component used in the construction of these fabrics. In spite of the inherent disadvantages of AJS yarns from the standpoint of hand, comparisons could be made to find fabrics woven with AJS yarns more highly rated than fabrics made with ring spun yarns. This was true in the case of a comparison between AJS twill constructions and plain woven fabrics using ring spun yarns (see Fig. 7.6).

7.6.4 Predicting hand from KES measurements

A formula was derived for predicting subjective hand ratings from fabric properties measured on the KES-F instruments. This was done using multivariate linear regression techniques to qualify the relationships between sensory assessments and fabric mechanical and surface properties. This yielded useful information regarding the relative contribution of specific properties to hand evaluation. Figure 7.7 shows how fabric properties combine to predict



7.7 Hand rating in subjective evaluation compared with rating computed from measured fabric properties. *Source*: 'Objective evaluation of fabrics woven with air-jet yarns', by K.M. Vohs, R.L. Barker and M.H. Mohamed, from *Objective Measurement: Applications to Product design and process control*, 1986, The Textile Machinery Society of Japan.

hand for this group of fabrics woven with AJS and ring spun yarns. These results show that the hand of this small group of fabrics can be reliably predicted using only a few of the data generated by KES instruments. Tensile energy, bending hysteresis, and surface roughness emerge as the most important predictors of hand.

7.6.5 Conclusions

Sensory analysis shows that fabric hand can be influenced more by fabric weave than by the component yarn. Weaves that use fewer yarn interlacings improve the otherwise poorer hand characteristics of fabrics made with air jet spun yarns.

The study showed that it could reliably predict the hand of a small collection of similar weight fabrics using only three or four of the constants generated by KES instruments. Analysis of contributing properties shows that the hand of fabrics woven with AJS yarns can be improved by reducing bending stiffness, especially the inelastic component of bending deformation. AJS yarn fabrics could also be improved by changes in the weave or finish that reduce the energy needed to deform the fabric and by improving surface properties to achieve a ‘smoother feel’.

7.7 Assessment of hand property of fabrics woven from various types of staple-fiber yarn

A study was conducted by Lord *et al.* [8] to establish a correlation between measured parameters and the perceived properties of a series of woven fabrics in which each warp was intersected with a variety of wefts of the same nominal count. Three types of weft yarns were used: ring spun, rotor spun, and friction-spun yarns.

7.7.1 Fabric constructions

Fourteen fabrics with five constructions were studied. In each construction, except the first, three kinds of weft were intersected with a common warp at the same pick density. Both plain and 3/1 twill weaves were used. In plain weave, two ends and four ends per dent were used. Details of the fabrics are given in Tables 7.4, 7.5 and 7.6.

7.7.2 Assessment of fabric hand

A panel of 24 women from a homemakers’ club was asked to judge the series of fabrics, and the choice was made because these persons were thought to represent the ultimate consumer in the particular geographical area reasonably

Table 7.4 Normalized and visual assessments of plain-weave fabrics

	Fabric (ends/in ¥ picks/in)							
Warp	72 ¥ 70 30/1 (19.7-tex) Cotton		90 ¥ 50 30/1 (19.7-tex) Continuous-filament			62 ¥ 52 17/1 (34.7-tex) Polyester-fiber/wool		
Weft	Ring	Friction	Ring	Rotor	Friction	Ring	Rotor	Friction
Attributes								
Smooth/Rough	0.87	1.56	0.96	0.91	1.22	0.96	0.66	0.85
Silky/Scratchy	1.44	1.19	0.96	1.01	1.19	0.76	0.69	0.78
Crisp/Limp	1.08	1.01	1.10	1.03	1.08	0.91	0.88	0.88
Shiny/Dull	1.19	1.01	1.28	1.16	1.30	0.59	0.73	0.72
Thick/Thin	0.94	0.85	0.94	1.08	0.99	1.01	1.05	1.16
Loose/Compact	0.89	0.75	0.96	1.04	1.07	1.09	1.12	1.07
Averages	1.07	1.06	1.03	1.05	1.14	0.89	0.86	0.91

Values > 1.00 indicate that the fabrics were smoother, silkier, crisper, shinier, thicker, or looser than average as the case may be.
Values < 1.00 indicates that the fabrics were rougher, scratchier, limper, duller, thinner, or more compact than the average as the case may be.
Source: 'Assessment of the tactile properties of woven fabrics made from various types of staple-fiber yarn', by P.R. Lord, P. Radhakrishnaiah and G. Grove, from *Journal of the Textile Institute*, vol. 79, no. 1, p. 32, 1988. Reproduced with permission from *Journal of The Textile Institute*.

Table 7.5 Normalized manual and visual assessments of 3/1 twill fabrics

	Fabric (ends/in ¥ picks/in)						
Warp	56 ¥ 56 17/1 (34.7-tex) Cotton			56 ¥ 34 30/1 (19.7-tex) Cotton			
Weft	Ring	Rotor	Friction	Ring	Rotor	Friction	Average
Attributes							
Smooth/Rough	1.29	1.13	1.30	0.76	0.79	0.75	1.00
Silky/Scratchy	1.16	1.10	1.13	0.84	0.78	0.99	1.00
Crisp/Limp	1.17	1.16	1.11	0.87	0.93	1.19	1.00
Shiny/Dull	1.13	1.19	1.15	0.67	0.81	1.04	1.00
Thick/Thin	0.93	1.12	0.95	1.06	0.93	1.02	1.00
Loose/Compact	0.88	0.96	0.95	1.07	1.07	1.08	1.00
Averages	1.09	1.11	1.10	0.88	0.89	1.01	1.00

Values > 1.00 indicate that the fabrics were smoother, silkier, crisper, shinier, thicker, or looser than average as the case may be.
Values < 1.00 indicates that the fabrics were rougher, scratchier, limper, duller, thinner, or more compact than the average as the case may be.
Source: 'Assessment of the tactile properties of woven fabrics made from various types of staple-fiber yarn', by P.R. Lord, P. Radhakrishnaiah and G. Grove, from *Journal of the Textile Institute*, vol. 79, no. 1, p. 32, 1988. Reproduced with permission from *Journal of The Textile Institute*.

Table 7.6 Relative values of surface roughness determined by manual assessment

	Manual		Kawabata	
Weft	Rotor	Friction	Rotor	Friction
Weave (ends/in ¥ picks/in) Warp				
Plain 72 ¥ 70 30/1 Cotton	–	1.82	–	1.01
Plain 90 ¥ 50 30/1 Continuous-filament	0.94	1.26	0.96	1.10
Plain 62 ¥ 52 17/1 Polyester-fiber/wool	0.68	0.88	1.19	1.08
3/1 Twill 56 ¥ 56 17/1 Cotton	0.88	1.01	1.05	1.12
3/1 Twill 56 ¥ 34 17/1 Cotton	1.05	1.01	0.90	1.12
Averages	0.89	1.20	1.03	1.09

Values > 1.00 indicate that the fabric is smoother than ring fabric.
Values < 1.00 indicate that the fabric is rougher than ring fabric.
Source: 'Assessment of the tactile properties of woven fabrics made from various types of staple-fiber yarn', by P.R. Lord, P. Radhakrishnaiah and G. Grove, from *Journal of the Textile Institute*, vol. 79, no. 1, p. 32, 1988. Reproduced with permission from *Journal of The Textile Institute*.

well. At first, the fabrics were mounted on boards, so that only the face of the fabric could be felt or seen, and the assessments for smoothness/roughness were carried out. The fabrics were then removed from the boards so that they could be handled between the thumb and fingers in the normal fashion. No attempt was made to make the hand assessments with the fabrics hidden from view, since this is not a circumstance that occurs in normal purchasing by an ordinary buyer.

The participants used a 0–5 scale, the higher value being associated with the last-named of each pair of attributes in the tables. In this paper, the rating scale used is 0–5, the higher number representing the first-named attribute mentioned in the tables. Assessors are normally reluctant to give low ratings, and bias is usually evident. Thus, when the results were translated by subtracting the assessor ratings from 5, the results came out low, but the bias was removed, even if the width of the scale was, in reality, narrowed. Ratings on this basis, and normalized against the average value for each pair of attributes, are given in Tables 7.4 and 7.5.

It was desired to test whether the assessors were capable of detecting differences between the various fabrics. For this purpose, the data relating to all attributes for a given fabric were lumped together, and a global average was calculated. The global average *per se* is not very valuable, but the comparison of the global averages at least shows whether the assessors could discriminate between the fabrics. The global average rating for all plain-weave fabrics with a 30/1 (19.7-tex) warp was 1.94, the average of the plain-weave fabrics with a 17/1 (34.7-tex) warp was 1.58, and the average for all the twill fabrics with a 17/1 (34.7-tex) warp was 1.64. It is clear that the assessors were able to discriminate between fabric construction and warp linear density. They were also able to discriminate between very loose and normal twills.

The overall averages for ring, rotor, and friction plain-weave fabrics were 1.80, 1.70, and 1.88 respectively. There was no sample with rotor-spun weft for the 70 ¥ 72 fabric, and this is likely to have reduced the 1.70 value below what it should have been; nevertheless, the comparable values in the two other plain-weave fabrics were low with respect to the others. The corresponding averages for the twill fabrics were 1.62, 1.65, and 1.67, respectively. In general, the friction fabrics showed up well in the aesthetic properties assessed, whereas the rotor fabrics appeared to be slightly inferior to the others. It was reasonably clear that the assessors could discriminate between ring, rotor, and friction fabrics.

Since it is a matter of taste whether a fabric should be silky, scratchy, shiny, dull, thick, thin, loose, or compact, and since the perception associated with these words varies, normalized values will be limited to the smoothness/roughness assessments. The relative ratings are given in Table 7.6, in which the assessments of the fabrics with rotor- and friction-spun wefts are expressed as ratios of the assessments of similar fabrics with ring-spun wefts. The perception that friction plain-weave fabrics were smoother than the others was clear, but, with heavy warps, the differences were worse than the others in plain weaves, but the differences narrowed in the twill weaves. Plain weaves were more sensitive to changes in the structure of the weft yarns.

7.8 Conclusions

Correlation between human evaluation and the surface-roughness measurements was quite reasonable over the frequency range from 20 to 100 repeats/in. Correlations were also noticed between surface roughness and many of the perceptions of the panel of assessors. It seemed likely that there were interactions and many of the perceptions were based on several attributes of the fabrics rather than single ones.

7.9 References

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8

Effect of woven fabrics on the fabric hand of cotton and CO/PES fabrics assessed on the Instron tensile tester

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8.1 Introduction

In this chapter it is shown that objective hand tests made on a very complicated and expensive system can be replaced by less complicated tests done on the Instron tensile tester; a derivation of general hand factor (GHF) for such measurements is presented. The second problem outlined concerns the main factors that influence fabric hand. Third, the chapter presents the results of tests on mechanical properties under small stresses for cotton and CO/PES fabrics.

The trends predicted in the near future concerning hand assessment can be described as follows. People would like to be conscious that hand is a measurable value; 75 years ago this was not so obvious for everybody. This tendency has become more common and hopefully will be natural in a few years.

Textiles produced for apparel first of all have to comply with modern fashion trends. Second, clothing fabrics should assure an appropriate degree of comfort for the apparel user [1, 4]. Comfort impression is a very sophisticated feeling. It is defined as a nice state of psychological, physiological and physical harmony between the human being and the environment. It is determined mainly by means of physiological and mechanical fabric properties as well as by fitting of these properties to the appropriate clothing.

One of the comfort components is sensorial comfort, which can be expressed by the fabric hand [1, 5, 10–15, 24, 30, 31, 33], including such properties as softness, elasticity, smoothness, and so on. It is very important to know the behavior of woven fabrics in use. Woven fabrics for clothing manufacture, which are exposed to the action of mechanical forces, require tests concerning the influence of these forces on their hand. Knowledge of this latter feature is needed for the selection of suitable fabric assessment criteria for utility clothing.

Fabric hand is a property assessed very often in daily life, providing information mostly for the finishing and clothing industry. In the past, it was a feature evaluated organoleptically. The first approach to objective hand measurement was given by Peirce in 1930 [30].

Nowadays, it is possible to measure fabric hand on two systems: FAST (Fabric Assessment System for Textiles) [2, 3], invented in CSIRO (Australia) by Postle, or KES-FB (Kawabata Evaluation System for Fabrics) [16]. The fabric's formability coefficient, which is defined as the ratio of bending rigidity to the initial modulus, can be calculated on the basis of results obtained by the FAST system.

The KES-FB was invented in 1986 by Kawabata in Japan [16–23]. An automatic version of the system called KES-FB-AUTO is presently produced [6]. KES-FB-AUTO consists of four devices measuring 16 fabric parameters, which can be grouped into six blocks: tensile, shear, bending, compression, surface properties and physical parameters. On the basis of these 16 parameters describing the mechanical behavior of fabrics under small stresses, Kawabata and Niwa [21–23] proposed the calculation of Total Hand Value (THV) using a block-stepwise regression method.

Kawabata proposed that a given fabric can be estimated using two factors calculated on the basis of mechanical parameters determined by the KES-FB system: the aforementioned Total Hand Value (THV), which expresses the general hand value, and the Total Appearance Value (TAV), which determines the fabric appearance. Kawabata in his further work tried to find out the ideal fabric for winter and summer suiting [20]. For winter he used wool and for summer polyester as a raw material.

Because the KES-FB system is very expensive, similar measurements of mechanical fabric parameters can be done using the Instron tensile tester following the procedure proposed by Pan [29, 35]. Using this procedure the mechanical parameters of fabrics under small stresses can be measured. Only a graphic multi-axial system for presenting the data, which characterizes a flat textile product, has been elaborated by Pan; in such a system, each quantity measured by the Instron tensile tester was presented on individual axis [29]. A summarized factor, the so-called General Hand Factor (GHF), which would be a measure of the fabric's hand based on the objective instrumental assessment with the use of an Instron tensile tester, has been developed by Frydrych and Matusiak [10].

From the analysis of performed tests (section 8.4), raw woven fabrics are characterized by the lowest value of GHF, whereas woven fabrics with elastomeric finishing have the highest GHF value; this is in accordance with the assumption accepted in the planning phase of the experiments. When considering the type of weave, fabrics with twill and canvas weaves were characterized by the best hand; whereas those with a plain weave were characterised by the worst one. The highest values of GHF were obtained for fabrics with the lowest weft density.

KES-FB as well as FAST was invented initially to measure the mechanical properties of worsted, woolen or blended (wool/PES) fabrics. Then, Matsudaira and colleagues [23, 25–28] tried to measure the mechanical properties of silk fabrics. In research presented in this chapter we tried to determine the hand of cotton and cotton/PES fabrics [7–10].

In section 8.5 we consider the mechanical parameters assessed on the Instron tensile tester, and investigate whether the type of raw material, weave and finishing, the spinning system, and weft density in the case of plain weave, influence the analyzed parameters [7]. Other factors influencing hand have already been analyzed elsewhere [9, 34], even the influence of pigment printing on mechanical fabric properties [32].

8.2 Description of measurement procedure on the Instron tensile tester

The majority of the parameters measured by KES-FB can also be measured on the Instron tensile tester as was proposed by Pan *et al.* [29]. A short description of the measurement procedure is given below. It is very important to maintain the appropriate stress level (much lower than the breaking one). Nevertheless, the stress level should enable the detection of nonlinear fabric behavior. All the measurements can be done at the determined jaw displacement or strain.

The sample sizes and Instron tester adjustments are given in Table 8.1. The following fabric parameters were determined:

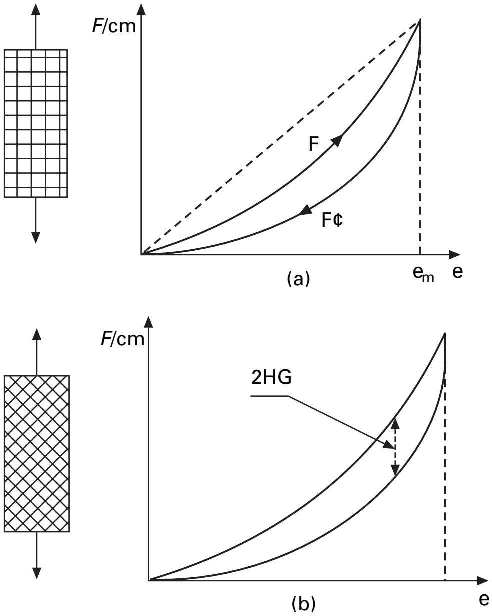
- Tensile linearity (LT)
- Tensile loading energy (WT)
- Tensile resilience (RT)
- Width of the hysteresis loop at shearing (HG)
- Width of the hysteresis loop at bending (HB)
- Compression loading energy (WC)
- Compression linearity (LC)
- Compression resilience (RC)
- Coefficient of static friction (μ_s)
- Coefficient of kinetic friction (μ_k)

Table 8.1 Sample sizes and Instron tester adjustment

Measurement conditions	Tensile/ shear	Bending	Compression	Friction
Sample length (cm)	7.6	3.8	3.8	20
Sample width (cm)	1.3	1.9	3.8	10
Speed of crosshead (mm/min)	1	10	0.5	10
Displacement (mm)	2	2	to 2.5 g/cm^2	40

8.2.1 Tensile and shear test

Because the Instron tester is designed for tensile testing, there is no problem in realizing this test. Table 8.1 gives the sample size parameters and appropriate Instron adjustments during the tensile and shear tests. Figure 8.1 presents graphs obtained in tensile and shear tests.



8.1 (a) Tensile hysteresis of fabric; (b) shear test [23].

On the basis of the tensile test done on samples cut along the warp and weft directions, the following parameters were determined (Fig. 8.1(a)):

- Tensile linearity: $$\mathrm{LT} = \frac{\mathrm{WT}}{\mathrm{WOT}} \tag{8.1}$$
- Tensile loading energy: $$\mathrm{WT} = \int_0^{\varepsilon_\mathrm{m}} f\,\mathrm{d}\varepsilon \tag{8.2}$$
- Tensile resilience: $$\mathrm{RT} = \frac{\mathrm{WT}'}{\mathrm{WT}} \times 100\% \tag{8.3}$$

where WT = tensile loading energy (area under the curve F),
WOT = tensile energy of the sample in the case of a linear relationship (area surrounded by the dotted line):

$$\mathrm{WOT} = F_\mathrm{m}\varepsilon_\mathrm{m}/2 \tag{8.4}$$

where F = tensile force per fabric unit width,
F'= stress relieving force,
WT$'$ = tensile energy corresponding to the relieving force (area under the curve F$'$),
F_m and ε_m = maximum values of F and ε respectively,
ε = tensile strain (not a % unit, but dimensionless).

Shearing the fabric is done mainly to measure a thread displacement inside the fabric. Because carrying out the pure shear test on the Instron tensile tester was impossible, the skew tensile test was adopted (similar to that used in the FAST system).

Although Grosberg indicated that there are some differences between the shear test and the skew tensile test, at small stresses both provide the same information on the thread displacement. Therefore, the shear test can be replaced by the skew tensile test. The shear test was done by stretching the samples cut at an angle of 45° in relation to the warp and weft directions. For these samples the width of the hysteresis loop HG in the widest place was measured (Fig. 8.1(b)).

8.2.2 Bending and compression test

In order to carry out the bending test on the Instron tester, a compression head is used. By sewing the rectangular sample its cylindrical shape can be obtained. The bending test is performed by compressing the cylindrical sample to the determined jaw displacement (Table 8.1) as shown in the Fig. 8.2(a).

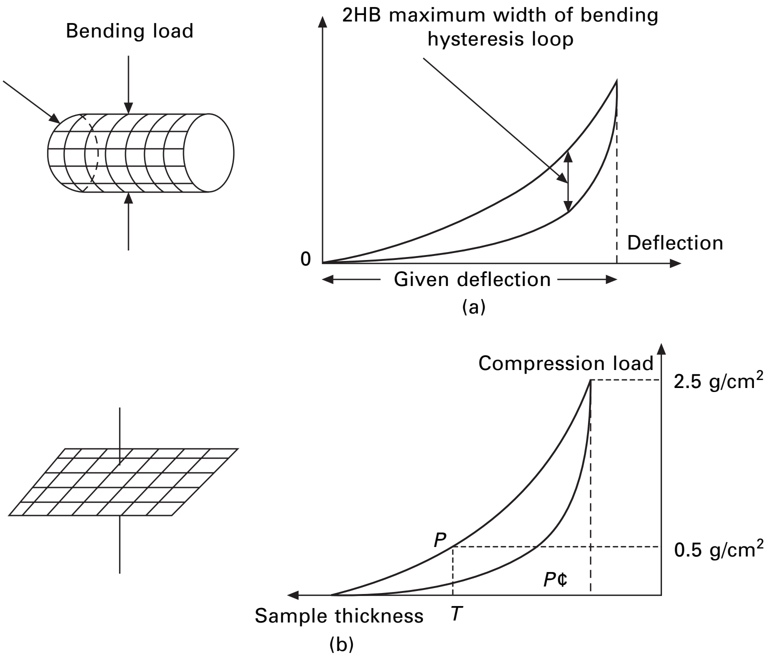
It is also easy to carry out the fabric compression test on the Instron tester (Fig. 8.2(b)). The operator should pay attention to maintaining the appropriate optimum compression load for all the samples (Table 8.1). Parameters from the compression test are calculated as follows:

- Compression linearity: $$\mathrm{LC} = \frac{\mathrm{WC}}{\mathrm{WOC}} \tag{8.5}$$
- Compression energy: $$\mathrm{WC} = \int_{T_0}^{T_m} P\,\mathrm{d}T \tag{8.6}$$
- Compression resilience: $$\mathrm{RC} = \frac{\mathrm{WC}'}{\mathrm{WC}} \times 100\% \tag{8.7}$$

where WC = compression energy (area under the curve P),
WOC = compression energy of the sample in the case of a linear relationship (area surrounded by the dotted line):

$$\mathrm{WOC} = P_m(T_0 - T_m)/2 \tag{8.8}$$

where P = compression force per fabric unit width,



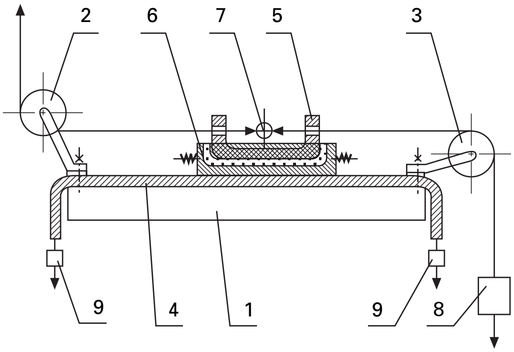
8.2 (a) Bending hysteresis loop; (b) compression hysteresis of fabric [23].

P' = stress relieving force,
WC¢= compression energy corresponding to the relieving force (area under the curve P¢),
T = sample thickness,
T_m = sample thickness at the maximum pressure,
T_0 = sample thickness at the minimum pressure,
P_m = compression force at the maximum pressure.

8.2.3 Friction test

In order to determine the coefficient of fabric friction in wear it is essential to reproduce the friction conditions on a laboratory scale. In the case of fabrics a reciprocating, rather than unidirectional, rubbing motion is most often encountered.

An original method of measuring the coefficient of fabric friction has been developed in the Institute of Textile Metrology, Nonwovens and Clothing Technology of the Technical University of Łódź (Polish Patent No. 119497). The device developed for measuring the real friction force between the fabrics being tested and the rubbing medium (Fig. 8.3) consists of the plate 1 fastened in the lower clamp of the tensile tester and rotary blocks 2 and 3



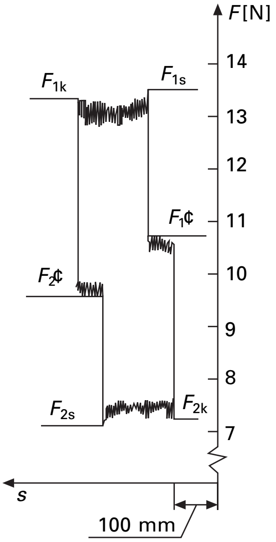
8.3 Device for measuring the friction coefficient: 1 – plate; 2, 3 – rotary blocks; 4 – rubbing medium; 5 – carriage; 6 – test fabric specimen; 7 – rod; 8, 9 – weights.

mounted at opposite edges of the plate 1. The rubbing medium 4 loaded with weight 9 and the hollow rectangular prism 5 (carriage) with the test fabric specimen 6 are all installed on the plate 1. The rod 7 positioned inside the hollow rectangular prism 5 is connected with a pull cord, one end of which passes round the block 2 and is attached to a load cell, while the other pull cord end passes round the block 3 and is loaded by weight 8. The magnitude of the weight 8 is selected in such a way that the force exerted by it on the pull cord exceeds the friction forces between the specimen 6 and the rubbing medium 4 as well as those acting on blocks 2 and 3. During measurements the rectangular prism block 5 moves initially with respect to plate 1 and towards the load cell, and the force acting on the load cell is recorded. The direction of motion of plate 1 is then reversed, so that the cubicoid block 5 is pulled backwards by weight 8, and the force acting on the load cell is simultaneously recorded.

The mass of the weight is 1000 g, the carriage dimensions are 50 mm ¥ 73 mm, the carriage weight is 316.3 g, the tensile tester cross-head speed is 50 mm/min, the recorder chart speed is 100 mm/min, and the carriage travel is 500 mm.

A typical recorder trace obtained for a measuring cycle is shown in Fig. 8.4. In the initial stage of plate 1 downwards motion, the tension of the pulling cord is F_1. When the rod 7 touches the front wall of the rectangular prism (carriage) the pulling cord is taut. Once the pulling cord tension has attained a value equal to the static friction force between the test fabric specimen and the rubbing medium (F_{1s}), the carriage starts to move forward. At the same time, the pulling cord tension keeps decreasing until a tension value corresponding to the kinetic friction force is reached (F_{1k}).

In the case of upwards travel of plate 1 analogous forces F_2¢, F_{2s} and F_{2k} are obtained. The friction force between the bodies being investigated is given by the following formula:



8.4 Relationship between magnitude of friction force and carriage reciprocating motion (according to the new testing method): *s* – distance, *F* – force.

$$T = \tfrac{1}{2}(F_1 - F_2) - F_w \tag{8.9}$$

where T = net friction force between bodies being investigated,
F_1 = force indicated by the load cell, when the test specimen moves towards the load cell,
F_2 = force indicated by the load cell during test specimen return motion,
F_w = friction force acting on the blocks.

The static friction force is calculated based on the recorded data by substituting the values of F_{1s} and F_{2s} into equation (8.9). The kinetic friction force is determined by substituting the recorded values of F_{1k} and F_{2k} into the same equation. The friction force F_w is obtained from the load cell readings F_1' and F_2' using the equation:

$$F_w = \tfrac{1}{2}(F_1' - F_2') \tag{8.10}$$

Recorded traces obtained for three successive testing cycles for a given pair of test specimens were found to be almost ideally superimposed one on another in the successive testing cycles, which indicates that the testing procedure applied gives the real value of the friction force of fabrics. No reduction of friction force values with an increasing number of testing cycles was observed. Since friction force changes in successive testing cycles were negligibly small, the time required to perform the tests is considerably reduced in comparison with that of testing procedures with the use of the tensile tester applied so far. In this testing method it is sufficient to execute a single complete loop, i.e., a single testing cycle, instead of the many cycles required by some other test methods with the use of the tensile tester applied before. It is worth mentioning that the standard deviation of measurements is very small.

8.3 General hand factor (GHF) of fabrics based on the mechanical parameters from the Instron tester

The fabric General Hand Factor (GHF) on the basis of the mechanical parameters measured under small stresses by the Instron tensile tester was proposed by Frydrych and Matusiak [10]. GHF was elaborated experimentally in the frame of research granted by the Polish Scientific Council (7 T09E 04616).

8.3.1 Description of material used for experiment

In order to elaborate the GHF and to assess the influence of fabric structure factors on the GHF value, raw fabrics characterized by different weaves and different cover factor values resulting from the different weft density values were produced; next, they were finished using two types of finishing. In order to produce the woven fabric samples the following yarns of nominal linear density 20 tex were applied:

- Cotton 100% rotor and combed ring-spun
- Ring-spun blended cotton/PES of successive 33%, 50%, and 67% shares of PES fibers.

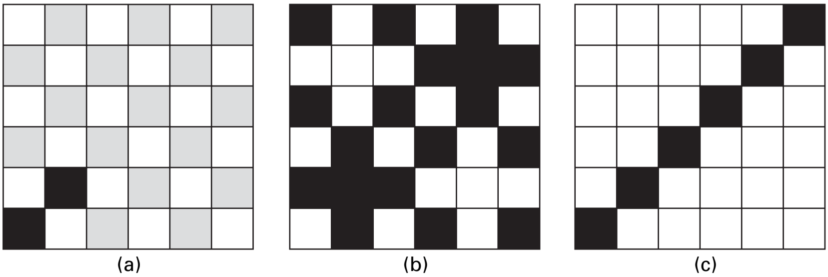
The physical and mechanical properties of the yarns used are presented in Table 8.2. From the mentioned yarns, plain raw fabrics of the same nominal warp density (33/cm), but of different weft densities (22/cm, 27/cm and 32/cm) were produced. Moreover, fabrics of the same nominal warp (33/cm) and weft (32/cm) densities, but of different weaves (plain, canvas and twill (1/5)) were manufactured (Fig. 8.5). The set of sample variants is given in Table 8.3.

The samples of raw fabrics were finished using two types of finishing: classic (starch) and ennoblement (elastomeric). The fabric finishing process was carried out according to the following scheme:

- Desizing
- Washing in warm (50°C) and cold water

Table 8.2 Specification of yarn parameters used for woven fabric manufacture

Parameter	Unit	CO100%OE	CO100%	CO67%/PES33%	CO50%/PES50%	CO33%/PES67%
Linear density	tex	19.9	20.1	20.2	20.7	20.3
Variation coefficient of linear density	%	0.94	1.31	1.03	1.04	1.16
Breaking force	cN	248.4	349.3	342.0	377.4	394.3
Variation coefficient of breaking force	%	6.40	5.70	6.93	8.52	10.30
Tenacity	cN/tex	12.5	17.4	16.9	18.2	19.4
Strain	%	6.90	6.90	7.43	8.99	9.89
Variation coefficient of strain	%	7.20	6.30	7.38	7.35	7.80
Twist	m^{-1}	803	916	933	948	892
Twist variation coefficient	%	5.30	5.03	4.01	5.13	4.60
Metric twist coefficient		113.3	129.9	132.4	136.4	127.1
CV%	%	15.10	14.70	14.42	14.12	15.36
Thin places /1000 m		13.6	3.2	6.4	0	26.4
Thick places/1000 m		20	46	66	36	128
Neps /1000 m		24	64	50	47	49



8.5 Weaves of fabrics: (a) plain, (b) canvas, (c) twill.

Table 8.3 The set of fabric variants

Raw material content	Weave	Weft density per cm	Number of fabric specimen		
			Raw	Starch	Elastomeric
CO 100% OE	Plain (P)	22	1	26	51
		27	2	27	52
		32	3	28	53
	Combined (canvas C)	32	4	29	54
	Twill (1/5 Z) (T)	32	5	30	55
CO 100%	Plain (P)	22	6	31	56
		27	7	32	57
		32	8	33	58
	Combined (canvas C)	32	9	34	59
	Twill (1/5 Z) (T)	32	10	35	60
CO 67% PES 33%	Plain (P)	22	11	36	61
		27	12	37	62
		32	13	38	63
	Combined (canvas C)	32	14	39	64
	twill (1/5 Z)(T)	32	15	40	65
CO 50% PES 50%	Plain (P)	22	16	41	66
		27	17	42	67
		32	18	43	68
	Combined (canvas C)	32	19	44	69
	Twill (1/5 Z) (T)	32	20	45	70
CO 33% PES 67%	Plain (P)	22	21	46	71
		27	22	47	72
		32	23	48	73
	Combined (canvas C))	32	24	49	74
	Twill (1/5 Z) (T)	32	25	50	75

- Treating with 100% NaOH
- Washing in water at 50°C
- Bleaching
- Washing in water at 50°C again
- Neutralization
- Drying at 100–130°C, over 5%
- Appreting and optical lightening
- Drying.

The appret bath content is given in Table 8.4, and properties of the raw and finished fabrics are presented in Table 8.5.

Table 8.4 Appret bath content

	Type of finishing	
	Starch	Elastomeric
Components	White dexin – 40 g/l Perustol VNO 500 – 10g/l Volturin M – 5 g/l Heliofor PBD – 4 g/l	Stabilex GFA–50g/l $MgCl_2$ – 5 g/l Rucofin GWS – 20 g/l Heliofor PBD – 4 g/l
Drying temperature	140°C	150–160°C

Starch finishing (designated further as A) is applied in general to bed linen, whereas elastomeric finishing (designated as B) is generally used for fabric improvement. The finishings mentioned above were selected at the experiment planning phase; the intention was to select those types of finishing that could facilitate the differentiation of the fabric's hand after processing, and also to ensure significant differences in the hand after finishing in comparison with that of raw fabrics.

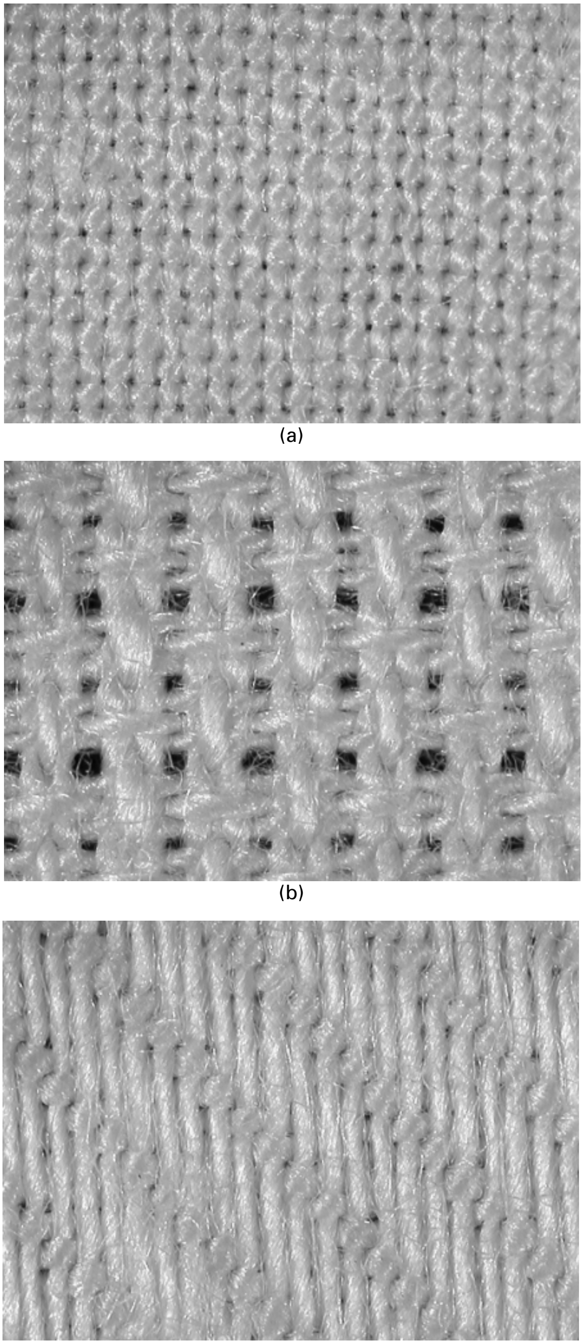
Figure 8.6 presents microscopic images of fabrics made of blended yarn CO33%/PES67%. These fabrics are characterized by weft density 32/cm, elastomeric finishing and three weaves: plain, canvas and twill. These images clearly show the differences in the fabric structure. The fabrics of canvas weave have the most porous structure. The microscopic observations confirmed also the lower porosity of fabrics with elastomeric finishing in comparison to fabrics with the starch finishing. At the same time they have lower porosity than raw fabrics (Fig. 8.7).

8.3.2 Derivation of general hand factor of fabrics

When elaborating the general hand factor, the assumption was made that the finished woven fabrics should have a better hand than the raw fabrics, and that the elastomerically finished fabrics should also be characterized by a

Table 8.5 The mechanical properties of fabrics

		Unit		CO 100% OE					CO 100%					CO 67%/PES 33%					CO 50%/PES 50%					CO 33%/PES 67%				
				P-22	P-27	P-32	C-32	T-32	P-22	P-27	P-32	C-32	T-32	P-22	P-27	P-32	C-32	T-32	P-22	P-27	P-32	C-32	T-32	P-22	P-27	P-32	C-32	T-32
Raw	Width	cm		154.0	153.2	152.8	152.2	151.7	153.8	152.8	152.2	152.2	151.7	149.4	146.8	147.8	148.7	150.2	150.5	147.1	147.5	148.0	149.1	153.2	152.2	150.3	151.1	150.8
	Number of threads per 1 dm		warp	316.0	317.0	318.0	321.0	321.0	319.0	321.0	322.0	323.0	322.0	325.0	328.0	330.0	326.0	324.0	323.0	329.0	329.0	328.0	324.0	318.0	319.0	321.0	327.0	329.0
			weft	229.0	284.0	333.0	332	327.0	230.0	283.0	335.0	331.0	329.0	253.0	316.0	335.0	326.0	322.0	262.0	336.0	341.0	337.0	335.0	238.0	294.0	357.0	321.0	311.0
	Crimp of threads	%	warp	6.5	7.3	10.1	5.1	2.8	6.5	6.1	8.3	4.4	2.7	8.2	9.2	11.3	5.8	2.7	10.7	12.5	12.5	6.5	3.7	6.7	6.4	9.3	4.1	2.3
			weft	5.3	6.0	7.7	8.0	7.1	5.5	6.3	6.9	7.0	6.7	6.0	7.8	7.7	7.9	7.3	5.7	8.2	8.2	7.8	7.7	5.2	6.2	8.0	7.9	7.3
	Mass per square meter	g/m^2		123.5	135.8	147.3.	145.0	140.7	123.4	135.4	147.8	145.4	143.5	124.5	138.2	151.6	141.2	139.1	137.9	158.8	159.7	154.5	151.2	134.4	150.4	153.0	147.9	144.1
	Thickness	mm		0.33	0.32	0.32	0.38	0.4	0.32	0.32	0.33	0.39	0.41	0.34	0.32	0.34	0.43	0.43	0.31	0.31	0.33	0.42	0.4	0.32	0.32	0.33	0.39	0.38
Starch finishing	Width	cm		142.0	141.5	141.0	141.5	140.7	140.0	140.1	140.1	140.8	140.5	140.5	138.2	138.5	146.1	141.9	140.6	139.4	138.9	140.5	140.5	141.4	139.8	139.3	140.6	141.8
	Number of threads per 1 dm		warp	343	345	344	342	345	344.0	345.0	345.0	343.0	345.0	345.0	349.0	349.0	344.0	344.0	342.0	344.0	346.0	344.0	345.0	341.0	343.0	347.0	344.0	341.0
			weft	226	275	326	331	332	223.0	272.0	312.0	316.0	320.0	232.0	299.0	326.0	322.0	331.0	225.0	285.0	333.0	333.0	335.0	229.0	281.0	316.0	304.0	308.0
	Crimp of threads	%	warp	3.3	4.2	4.6	2.7	1.7	2.7	3.5	3.8	2.4	1.5	3.8	4.8	5.6	2.6	1.7	3.9	4.9	5.0	3.0	1.5	4.2	4.9	5.0	2.9	1.8
			weft	9.1	9.3	10.3	8.5	8.6	7.6	8.4	9.4	8.2	8.6	9.5	10.2	10.5	8.7	9.4	8.2	9.3	9.6	8.9	9.2	7.4	8.1	9.6	9.3	8.8
	Mass per square meter	g/m^2		114.3	126.0	137.57	135.4	136.1	116.1	128.5	137.09	135.8	136.4	124.75	142.4	151	145.2	145.2	127.28	142.1	153	148.2	150.2	123.9	139.4	144.9	142.7	139.9
	Thickness	mm		0.26	0.28	0.32	0.34	0.33	0.28	0.28	0.31	0.35	0.36	0.33	0.34	0.36	0.4	0.4	0.29	0.32	0.33	0.37	0.41	0.28	0.32	0.30	0.39	0.4
Elastomeric finishing	Width	cm		141.7	141.0	140.4	140.0	139.5	141.1	140.1	139.8	139.9	139.0	140.7	140.0	138.6	139.6	140.1	139.6	139.6	139.5	140.5	140.5	140.8	140.2	139.5	139.9	141.3
	Number of threads per 1 dm		warp	342	344	343	347	345	342.0	347.0	346.0	352.0	348.0	344.0	343.0	346.0	345.0	345.0	345.0	344.0	346.0	344.0	343.0	344.0	344.0	346.0	346.0	342.0
			weft	225	274	305	307	311	227.0	278.0	308.0	318.0	318.0	240.0	287.0	333.0	326.0	328.0	242.0	286.0	333.0	337.0	328.0	229.0	281.0	316.0	320.0	329.0
	Crimp of threads	%	warp	4.8	5.6	5.7	3.5	2.3	4.2	4.5	5.1	3.3	2.1	4.4	4.9	5.2	3.1	2.0	4.7	5.1	6.3	3.5	1.7	3.8	4.5	5.7	3.2	1.8
			weft	8.2	9.1	10.0	9.7	10.0	9.5	10.2	11.3	10.7	11.5	8.3	9.2	10.7	9.7	10.0	9.7	9.2	9.6	9.8	10.0	8.4	8.8	9.5	9.4	8.9
	Mass per square meter	g/m^2		115.86	127.3	136.43	134.8	136.8	116.32	130.1	137.81	139.5	139.3	125.4	134.1	145.9	142.9	141.0	129.88	145.03	154.66	151.6	147.7	120.92	134.64	148.5	145.7	144.5
	Thickness	mm		0.33	0.32	0.32	0.38	0.4	0.32	0.32	0.33	0.39	0.41	0.34	0.32	0.34	0.43	0.43	0.31	0.31	0.33	0.42	0.4	0.32	0.32	0.33	0.39	0.38

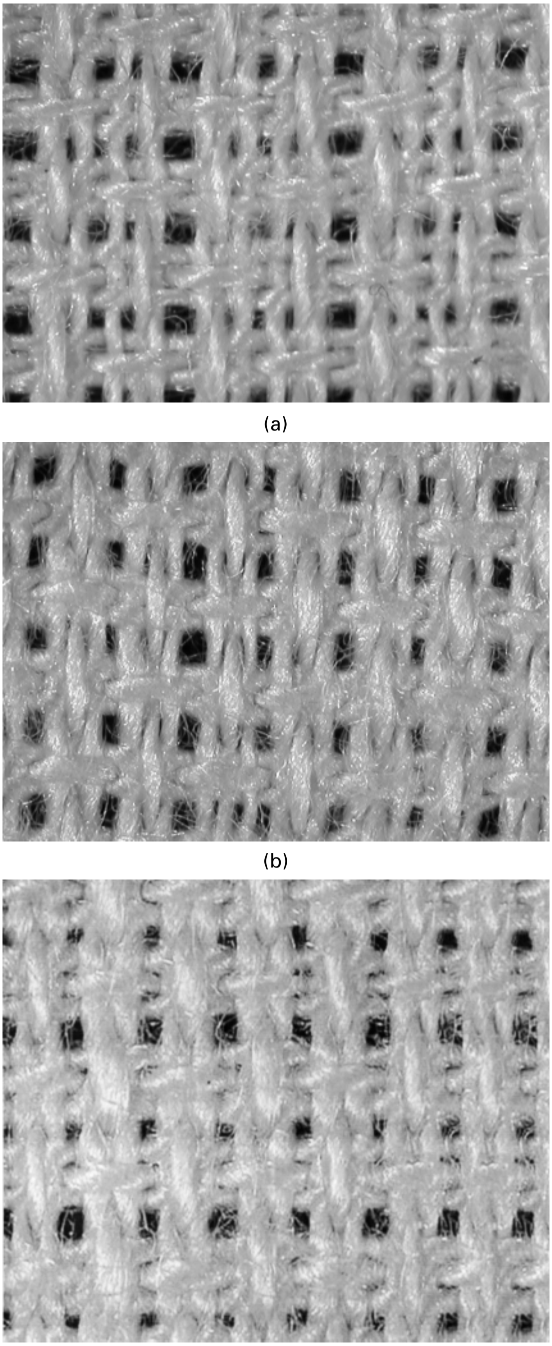


(a)

(b)

(c)

8.6 Comparison of microphotographs of fabric structure (elastomeric finished fabrics, weft density 32/cm): (a) plain, (b) canvas, (c) twill.


(a)

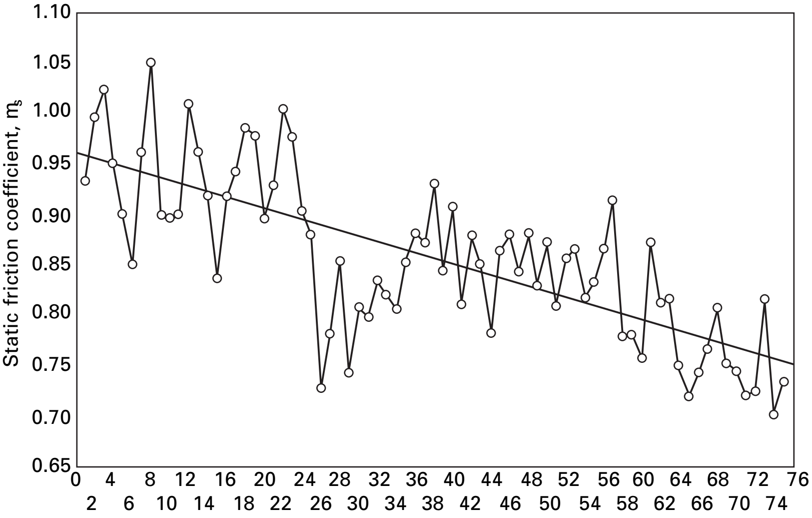
(b)

(c)

8.7 Comparison of microphotographs of fabrics of canvas weave (a) raw, (b) with starch finishing, (c) with elastomeric finishing.

better hand (due to the better mean applied for finishing) than those finished in a classic way by starch.

In the first investigation phase, estimation was made of which trends in changes of the particular parameters (determined by the Instron tensile tester) exist depending on the type of finishing. Next, plots of values of the particular mechanical parameters for all raw and finished fabrics were drawn. The particular test variants were arranged on the abscissa of every plot (for every parameter). The order was arranged in such a manner that the first group consisted of raw fabrics, the next group of fabrics with starch finishing, and the last with elastomeric finishing (Fig. 8.8). Straight lines, which characterized the trends of changes for each parameter determined, were drawn on the plots (beginning from the raw fabrics in the direction of the starch (A) and the elastomerically (B) finished fabrics).



8.8 Trend of the static friction coefficient for arranged fabrics, starting with raw fabrics, through fabrics finished with starch to fabrics elastometrically finished.

The analysis of these plots allowed estimation of how the values of the particular parameters are changed depending on type of finishing, which (in accordance with the assumption accepted at the beginning of our consideration) should improve the hand of fabrics. The analysis performed revealed that in the case of tensile linearity (LT) and tensile resilience (RT) no visible trend occurs that depends on the finishing. Therefore, these two parameters were omitted in further considerations as having no distinct influence on the fabric's hand.

It was observed that the values of the remaining mechanical parameters decreased, starting with the highest parameter values for raw fabrics, through those of fabrics with starch finishing (A), and ending with the parameters of fabrics that were elastomerically (B) finished. Only in the case of compression linearity (LC) was a contrary tendency noted, i.e., an increase of the parameter value in the direction of fabrics with better finishing. These observations allowed us to assume that the following parameters (determined with the use of the Instron tensile tester) influence the fabric's hand:

- Tensile loading energy (WT)
- Width of the hysteresis loop at shearing (HG)
- Width of the hysteresis loop at bending (HB)
- Compression linearity (LC)
- Energy of compression (WC)
- Compression resilience (RC)
- Coefficient of static friction (μ_s)
- Coefficient of kinetic friction (μ_k).

A procedure similar to that used during elaboration of the general quality factor, GQF, [10], was applied in further considerations, approaching the derivation of one summarized fabric hand factor (the general hand factor, GHF). All the parameters listed above were accepted as the individual mechanical parameters for elaborating the general factor.

Degrees of importance u (from $u = 1$ to $u = 5$) were assigned to all parameters determined by the Instron tensile tester, proportionally to the pitch of the line, which indicates the trend of the particular parameters (in the direction from the raw fabrics to the fabrics finished elastomerically). The greater the trend of deflection from the horizontal line, the higher the degree of importance. Next, the weight coefficient was calculated for each parameter from the following formula:

$$p_i = \frac{u_i}{\sum_{i=1}^{8} u_i} \times 100 \qquad (8.11)$$

where u_i = degree of importance of the ith parameter,
p_i = weight coefficient of the ith parameter.

The assigned degrees of importance (u_i) and weight coefficients (p_i) calculated are specified in Table 8.6.

Next, the relative values of the particular factors were calculated. These values are equal to the ratio of the particular parameter's value of the given variant of fabric to the maximum value of all values, which were obtained in this parameter:

$$b_{ik} = \frac{a_{ik}}{a_{i\max}} \qquad (8.12)$$

where b_{ik} = relative value of the ith parameter for the kth fabric variant,
a_{ik} = absolute value of the ith parameter for the kth fabric variant,
$a_{i\max}$ = maximum value of the ith parameter from all values of this parameter determined by the Instron tensile tester.

It should be emphasized that usually, when elaborating the general quality factor (GQF), the quotient of the value of the determined parameter is calculated using the optimal value as a divider. However, in the case analyzed, there has hitherto been a lack of data, which could allow the acceptance of the optimal value as a divider, and the maximum value obtained by measurement was taken instead of this.

The value of the general quality factor (GQF) was calculated for each fabric variant from the formula:

$$\mathrm{GQF}_k = \sum_{i=1}^{8} p_i b_{ik} \tag{8.13}$$

where GQF_k is the value of the general quality factor GQF for the kth fabric variant.

Considering that the trend of compression linearity (LC) changes depending on fabric finishing is contrary to the trends of all remaining parameters, the sign of the component concerning compression linearity in the GQF_k sum was accepted as negative. Finally, the equation describing the general quality factor as determined on the basis of the parameters measured with the use of the Instron tensile tester ($\mathrm{GQF}_{\mathrm{IN}}$) can be described as follows:

$$\begin{aligned}\mathrm{GQF}_{\mathrm{IN}} = {} & 6.3\frac{\mathrm{WT}}{\mathrm{WT}_{\max}} + 6.3\frac{\mathrm{HG}}{\mathrm{HG}_{\max}} + 15.6\frac{\mathrm{HB}}{\mathrm{HB}_{\max}} - 9.4\frac{\mathrm{LC}}{\mathrm{LC}_{\max}} \\ & + 15.6\frac{\mathrm{RC}}{\mathrm{RC}_{\max}} + 15.6\frac{\mu_s}{\mu_{s\max}} + 15.6\frac{\mu_k}{\mu_{k\max}}\end{aligned} \tag{8.14}$$

Table 8.6 Specification of importance degrees *u* and weight coefficients *p*

No.	Parameter	Designation	*u*	*p*
1.	WT	a_1	2	6.3
2.	HG	a_2	2	6.3
3.	HB	a_3	5	15.6
4.	WC	a_4	5	15.6
5.	LC	a_5	3	9.4
6.	RC	a_6	5	15.6
7.	μ_s	a_7	5	15.6
8.	μ_k	a_8	5	15.6
Total			32	100

The procedure that was accepted for calculating the general quality factor assumed that the value of the output parameters increases with the increase of the fabric's quality. In the case of the mechanical parameters determined with the use of an Instron tensile tester, a contrary situation was observed; that is, with the increase in the value of particular output parameters (excluding the compression linearity, LC), a worsening in hand is observed.

Considering such a behaviour of the finished fabrics, the reciprocal of the general quality factor calculated from formula (8.14) was proposed as a measure of the fabric's hand. This measure was designated as the general hand factor (GHF) of fabrics and its value can be calculated from the following formula:

$$\mathrm{GHF}_{\mathrm{IN}} = \frac{1}{\mathrm{GQF}_{\mathrm{IN}}} \tag{8.15}$$

The final form of the equation, which allows calculation of the general hand factor on the basis of measurements of the mechanical fabric parameters with the use of the Instron tensile tester, was obtained by the substitution of $\mathrm{GQF}_{\mathrm{IN}}$ in formula (8.15) by equation (8.14):

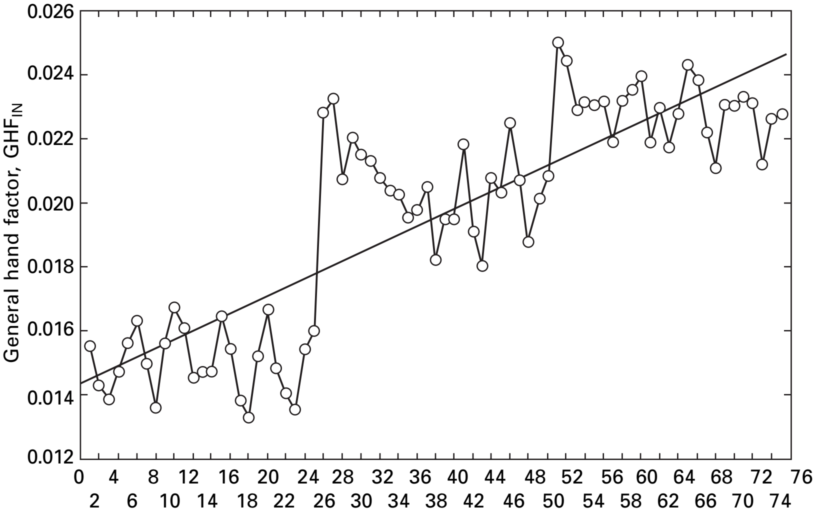
$$\mathrm{GHF}_{\mathrm{IN}} = \frac{1}{\begin{array}{l} 6.3\dfrac{\mathrm{WT}}{\mathrm{WT}_{\max}} + 6.3\dfrac{\mathrm{HG}}{\mathrm{HG}_{\max}} + 15.6\dfrac{\mathrm{HB}}{\mathrm{HB}_{\max}} \\ -9.4\dfrac{\mathrm{LC}}{\mathrm{LC}_{\max}} + 15.6\dfrac{\mathrm{RC}}{\mathrm{RC}_{\max}} + 15.6\dfrac{m_{\mathrm{s}}}{m_{\mathrm{s}\max}} + 15.6\dfrac{m_{\mathrm{k}}}{m_{\mathrm{k}\max}} \end{array}} \tag{8.16}$$

With the use of equation (8.16), the values of the general hand factor for all variants of raw and finished fabrics manufactured for conducting the experimental part of this investigation were calculated. The values obtained are presented in Fig. 8.9. According to our expectations, it could be stated that the values of the factor increase, starting with those of raw fabrics, through those of fabrics with starch finishing (A), and ending with values for elastomeric finishing (B). This confirms the appropriateness of the proposed procedure (Fig. 8.9), as by experimental planning such types of finishing were accepted that could enable differentiation of the fabrics' hand, and of its improvement compared to the hand of raw fabrics.

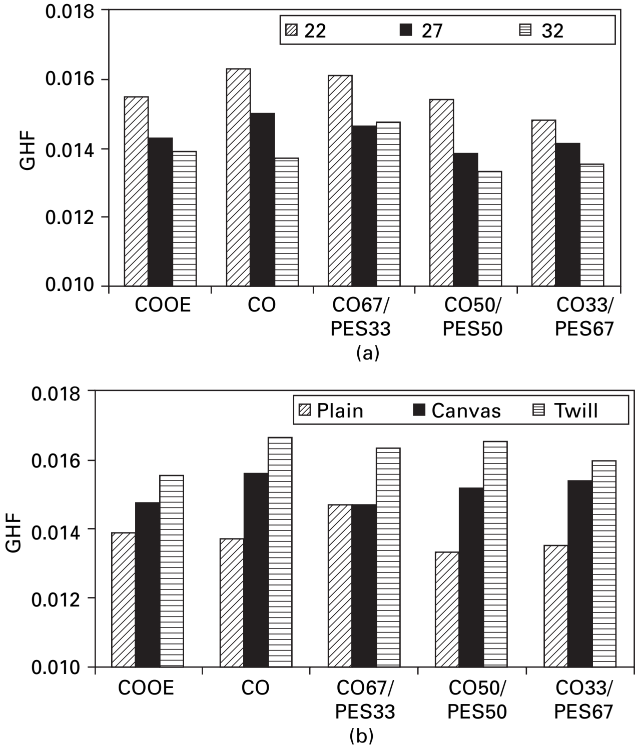
However, on the basis of calculated values it can be stated that the remaining factors, i.e., the type of raw material used, weave, and weft density, also influence the GHF independently of the influence of finishing type.

8.4 Analysis of influence of the weft density, weave, and finishing type on the general hand factor

The influence of weft density and weave used on the general hand factor (GHF) of raw fabrics is shown in Fig. 8.10.



8.9 Trend of the general hand factor (GHF$_{IN}$) for all fabric variants.



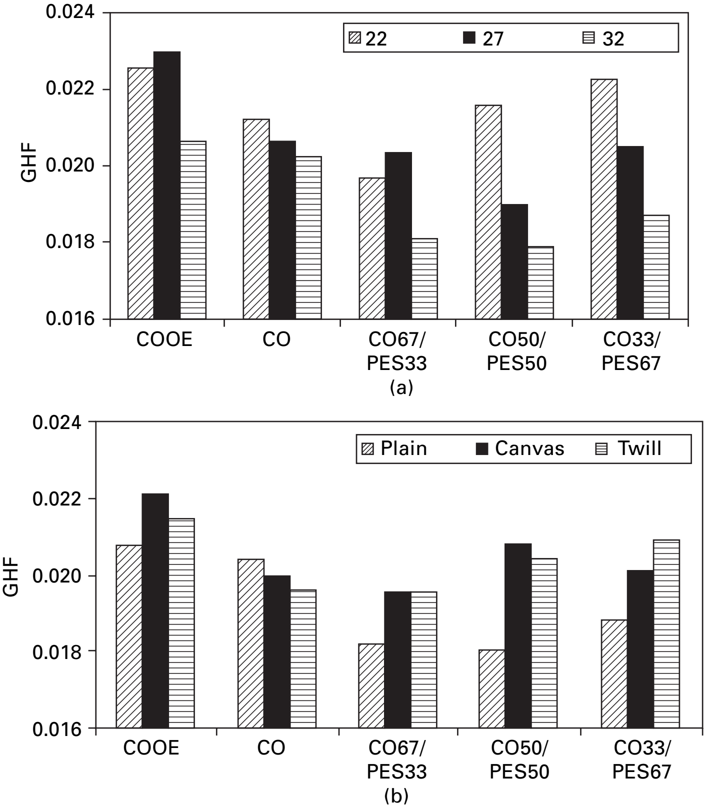
(a)

(b)

8.10 General hand factor (GHF) for raw fabrics depending on (a) weft density, (b) fabric weave.

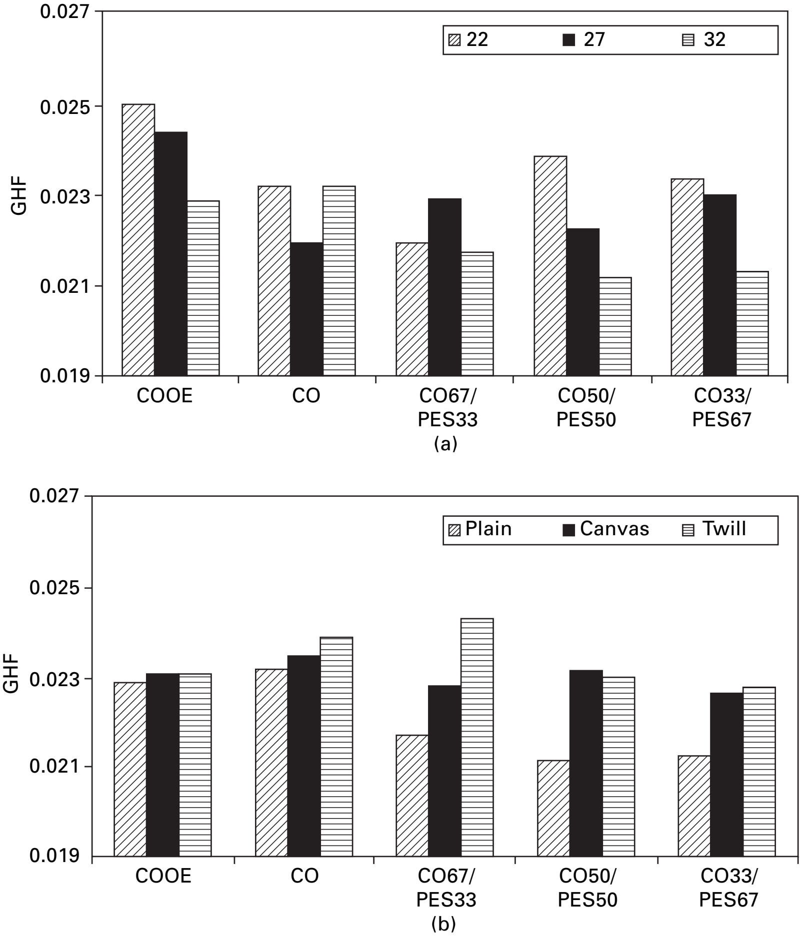
Plain woven fabrics with the smallest weft density (22/cm) are characterized by the best hand, those of 27/cm weft density by a worse hand, and those of 32/cm by the worst one. Among fabrics of 32/cm weft density, the highest value of the general hand factor was noted for fabrics with twill weave, a lower value for fabrics with canvas weave, and the lowest for those with plain weave.

Similar trends could also be observed for the majority of finished fabrics, although not for all (see Figs 8.11 and 8.12).



8.11 General hand factor (GHF) for fabrics finished with starch depending on (a) weft density (b) fabric weave.

For fabrics with starch finishing manufactured from cotton rotor yarn and cotton/polyester ring spun yarn with a content of CO67%/PES33%, the maximum value of the general hand factor was achieved for fabrics of intermediate weft density – 27/cm (Fig. 8.11(a)). Moreover, the fabrics manufactured from the cotton rotor yarn and blended ring spun yarn with a content of CO50%/PES50% and canvas weave are characterized, in the case



8.12 General hand factor (GHF) for elastomerically finished fabrics depending on (a) weft density, (b) fabric weave.

of starch finishing, by better hand than fabrics of twill and plain weave (Fig. 8.11(b)).

Using elastomeric finishing it was noted that in two cases (for fabrics of plain weave manufactured from cotton rotor yarn and of blended cotton/polyester ring spun yarn with a content of CO67%/PES33%) a distinct difference in the trends observed for raw fabrics was observed, together with opposite trends for both of the fabric groups mentioned above (Fig. 8.12).

No explicit influence of the type of raw material used on the hand of raw and finished fabrics was observed, though fabrics manufactured from different raw materials differ among themselves by the value of the general hand factor. However, as a rule it can be stated that the factors of fabrics with a content of PES fibers have lower GHF values.

The influence of the type of fabric finishing on the value of the general hand factor (GHF) is presented in Fig. 8.13. The results are arranged separately for each group of fabrics manufactured from the same raw material:

- Fabrics from cotton rotor yarn
- Fabrics from cotton ring spun yarn
- Fabrics from blended ring spun yarn of content CO67%/PES33%
- Fabrics from blended ring spun yarn of content CO50%/PES50%
- Fabrics from blended ring spun yarn of content CO33%/PES67%.

The highest general hand factor of all analyzed groups of fabrics was noted for fabrics with elastomeric (B) finishing, whereas raw fabrics were characterized by the lowest value of the general hand factor, which means the worst hand.

In the end it can be stated that there is a possibility of anticipating the fabric's hand on the basis of mechanical fabric parameters with the use of the Instron tensile tester.

8.5 Effect of weave, weft density, raw material content, and finishing type on the mechanical fabric hand parameters

General hand factor is an objective measure of fabric hand calculated based on the values of mechanical parameters determined using the Instron tensile tester.

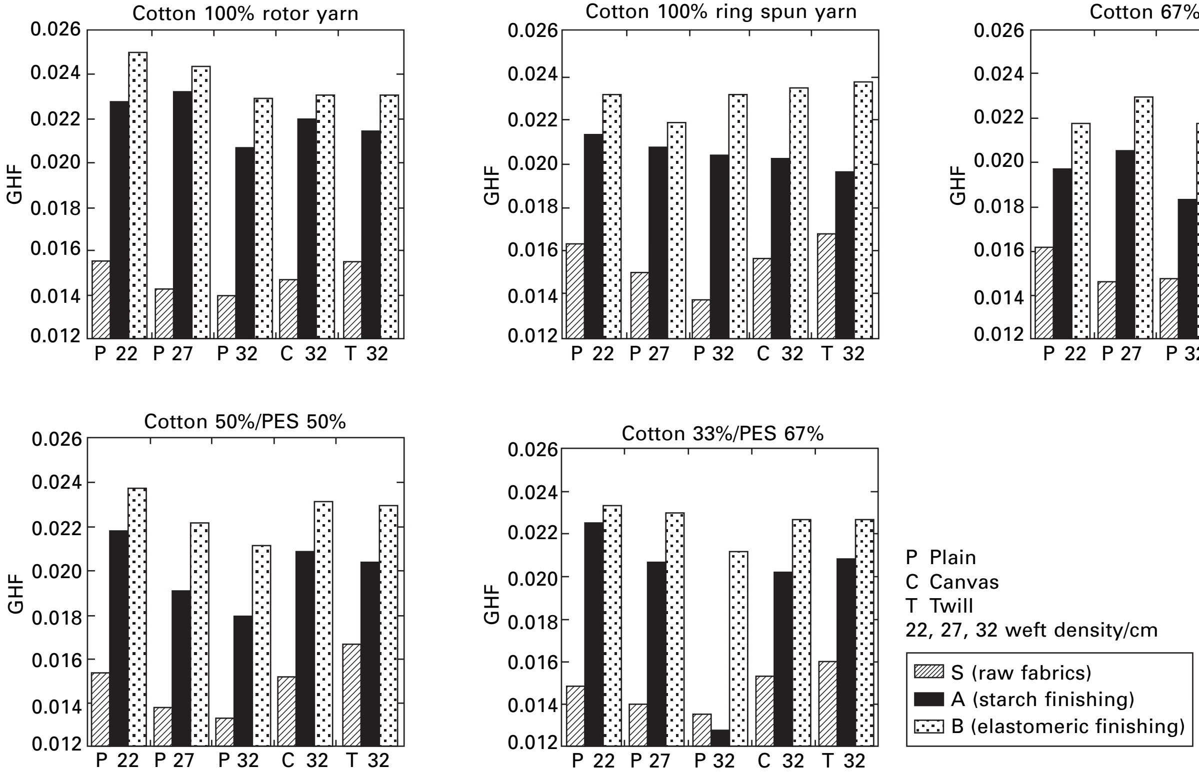
As was mentioned earlier (section 8.3.2) among 10 parameters determined in particular tests on the Instron tensile tester only eight contribute to the GHF value. These parameters depend on type of raw material, fabric structure and finishing. Knowing these relationships the values of mechanical parameters determined on the Instron tensile tester can be shaped in an appropriate way, and at the same time influence the fabric hand.

Since tensile linearity (LT) and tensile resilience (RT) do not contribute to the GHF value, the description of influence of particular structural parameters and type of finishing on these two parameters was omitted in further considerations.

In order to assess the influence of:

- type of weave, when the weft density is the same,
- weft density for plain fabrics,
- different finishings (raw fabrics, fabrics with starch and elastomeric finishing),
- different yarn compositions (100%CO, 67%CO/33%PES, 50%CO/50%PES, 33%CO/67%PES),

on the mechanical parameters measured at small stress action on the Instron



8.13 Influence of type of finishing on the general hand factor (GHF).

tensile tester in the Department of Textile Metrology of the Technical University of Łódź, a multivariate analysis of variance was applied. First, the distribution of the mechanical parameters mentioned was tested. In all cases a normal distribution was found. In a majority of cases the stated influence of particular factors was significant, both independently and in interactions with the other factors. For checking the statistical significance of differences, Tukey's test was applied.

8.5.1 Tensile test

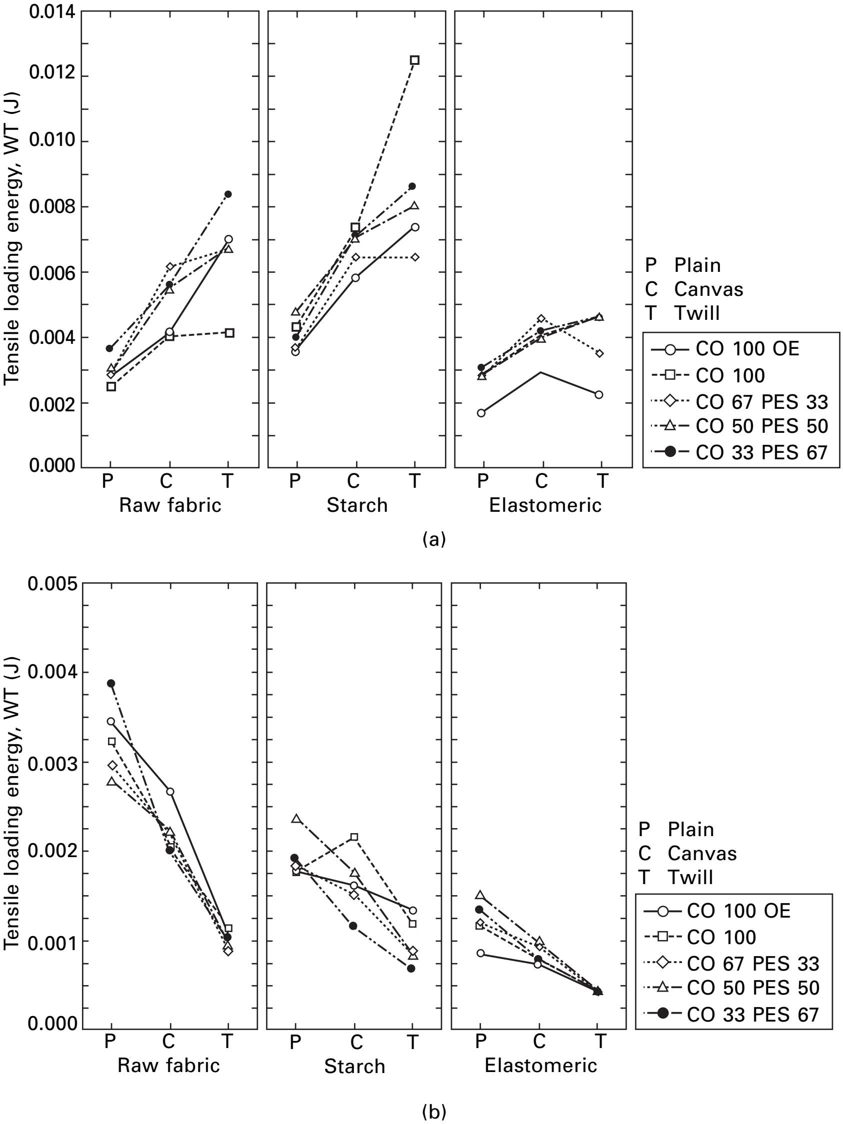
Influence of raw material content, weave and type of finishing

Tensile loading energy, WT

The factors introduced were type of raw material (1), weave (2), and finishing (3). The results concerning the influence of the analyzed factors on tensile loading energy (WT) are given in Fig. 8.14 for (a) the warp direction, and (b) the weft direction. When analyzing the results for the warp direction presented in Fig. 8.14(a) one can see that the lowest tensile loading energy (WT) is needed to stretch the plain fabrics, and the highest to stretch the twill. This may result from the longest length of warp per fabric length unit due to the highest number of interlacements in the plain fabric, and from the opposite situation in the twill.

The situation is quite different in the case of the weft direction – Fig. 8.14(b). Due to the calendering operation during the finishing process, fabrics were extended in the warp direction. This resulted in the increase of the warp density and decrease of the weft density (see Table 8.5 and the table in Reference 8). For this reason the tensile loading energy (WT) in the weft direction takes much lower values than in the warp direction. The effect of such a phenomenon is stronger for fabrics with the longer float length, i.e., canvas and twill. Loading energy in the weft direction is also lower because of the lower weft density and higher weft crimp. For the plain weave the tensile loading energy (WT) takes almost the same value in the weft and warp directions, while for twill and canvas it is much lower for the weft. This may result from the highest number of interlacements in a plain fabric, making the fabric structure more resistant to deformation.

After finishing, the tensile loading energy (WT) in the warp direction increases for the starch add-on and decreases for the elastomeric one. For the weft direction the loading energy decreases for both types of finishing. The following conclusion can be drawn: the elastomeric finishing causes a decrease of loading energy and the starch finishing effects an energy increase. These effects are disturbed by an initial fabric extension in the warp direction during the calendaring process. Thus, for the warp direction, where the fabric has been initially extended during the finishing process, further stretching



(a)

(b)

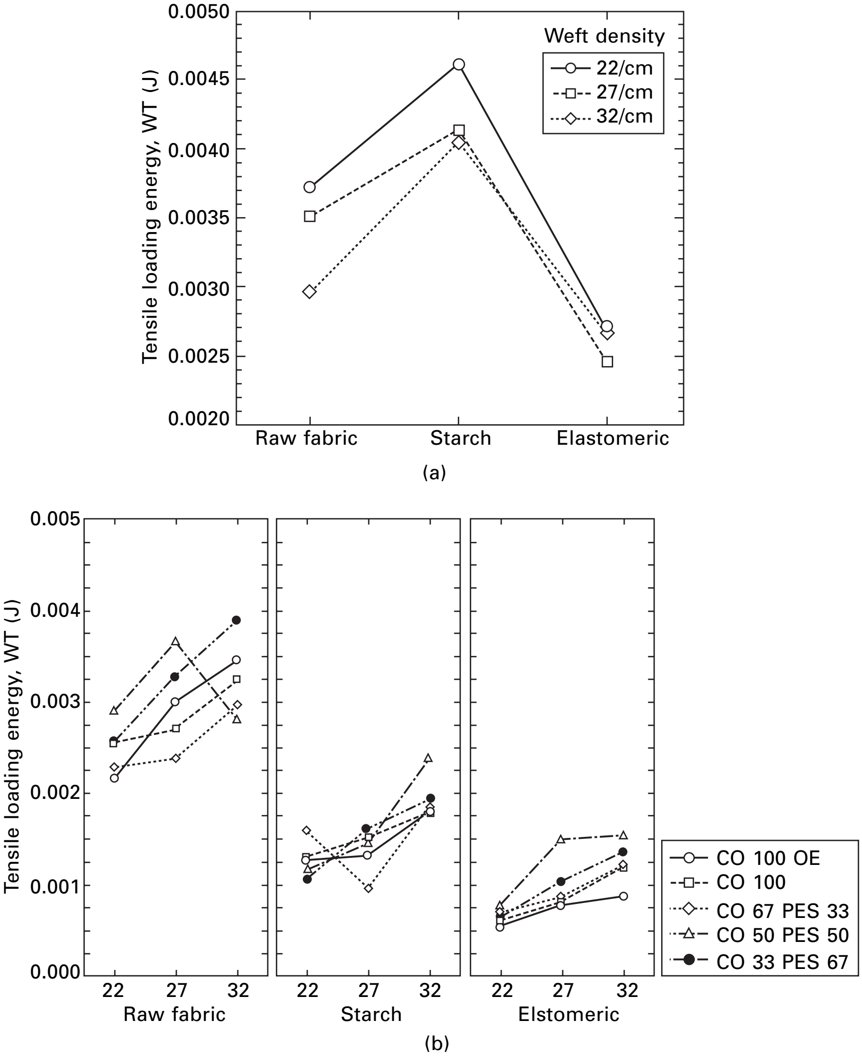
8.14 Influence of raw material content, weave and finishing on tensile loading energy (WT) in (a) the warp direction; (b) the weft direction.

needs more work to be done, while in the weft direction further stretching means a reversion to the raw fabric structure, despite the starch add-on.

Influence of raw material content, weft density and type of finishing

Tensile loading energy, WT

Results of multivariate analysis of variance concerning the tensile loading energy (WT) for plain fabrics of different weft densities are presented in Fig. 8.15.



8.15 (a) Influence of weft density and kind of finishing on tensile loading energy (WT) in the warp direction; (b) influence of raw material content, weft density and kind of finishing on WT in the weft direction.

In the warp direction (Fig. 8.15(a)) the highest value of tensile loading energy (WT) was noted for fabrics of weft density 22/cm. The higher the weft density, the lower the tensile loading energy (WT). In comparison to raw fabrics, starch finishing causes an increase of WT, whereas elastomeric finishing causes a decrease.

Tensile loading energy (WT) in the weft direction (Fig. 8.15 (b)) increases with the weft density. This is to be expected, because a higher weft density means more interlacements for both arrangements, and therefore, higher friction resistance. Moreover, with the increase of the weft density, more threads are stretched, which requires higher energy. This relationship occurs in raw fabrics as well as those finished by starch and elastomers. The fabric finishing causes a decrease of tensile loading energy (WT), elastomeric finishing decreasing WT more than starch finishing.

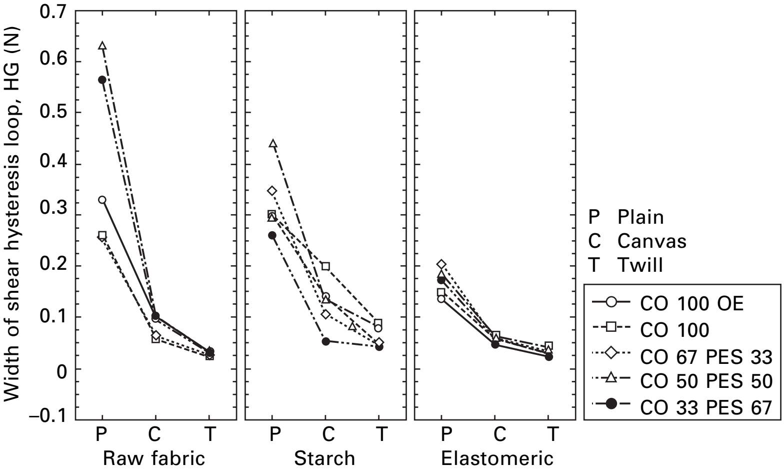
8.5.2 Shear test

Influence of raw material content, weave and type of finishing

Shear hysteresis loop width, HG

Fabric behavior under stretching in the 45° direction characterized by the width of the shear hysteresis loop (HG) shows an analogy with that under the tensile test. The highest values of HG were observed for plain weave, lower for canvas and the lowest for twill, regardless of the type of raw material and finishing.

The widest hysteresis loop was observed for raw plain fabric due to the highest number of interlacements (Fig. 8.16). This reflects the high fabric



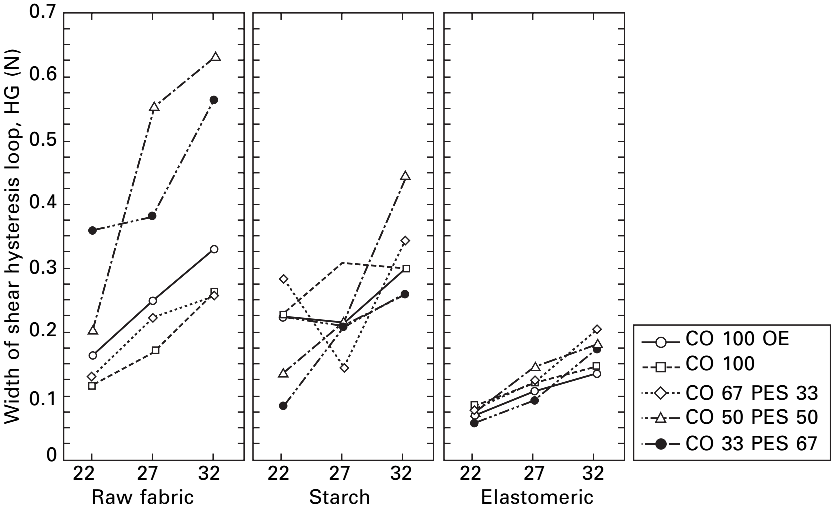
8.16 Influence of kind of raw material, weave and finishing on the width of the shear hysteresis loop (HG).

rigidity and a loss of elasticity of component yarns. The plain weave fabric is the only one for which the finishing changes the shear behavior significantly. In the case of the other weaves (especially twill) the finishing does not influence the shear parameter. This can be explained by the relatively low stress to which the fabric is subjected during stretching of the skewed sample to the same value of extension. That is why the fabrics with fewer interlacements and thus lower rigidity even after finishing still show good shear resilience, HG.

Influence of raw material content, weft density and type of finishing

Shear hysteresis loop width, HG

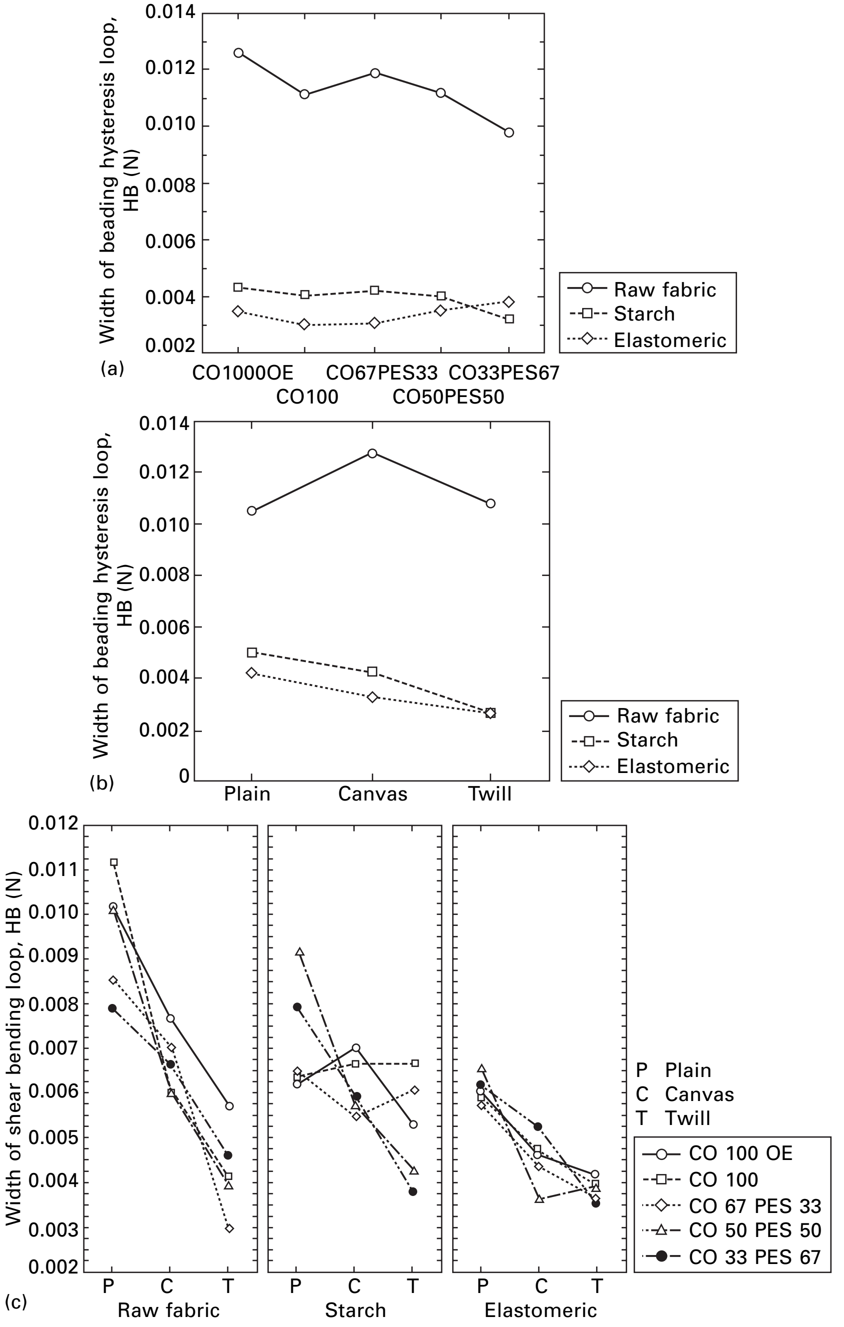
The shear hysteresis loop width (HG) increases with the increase of the weft density of plain fabrics, as seen in Fig. 8.17. The more dense the fabric and the more interlacements it has, the more difficult is its return to the primary shape after shear deformations. The fabric finishing reduces the shear hysteresis loop width (HG) and at the same time improves the shear resilience of fabrics. Starch finishing improves it less, but elastomeric finishing much more.



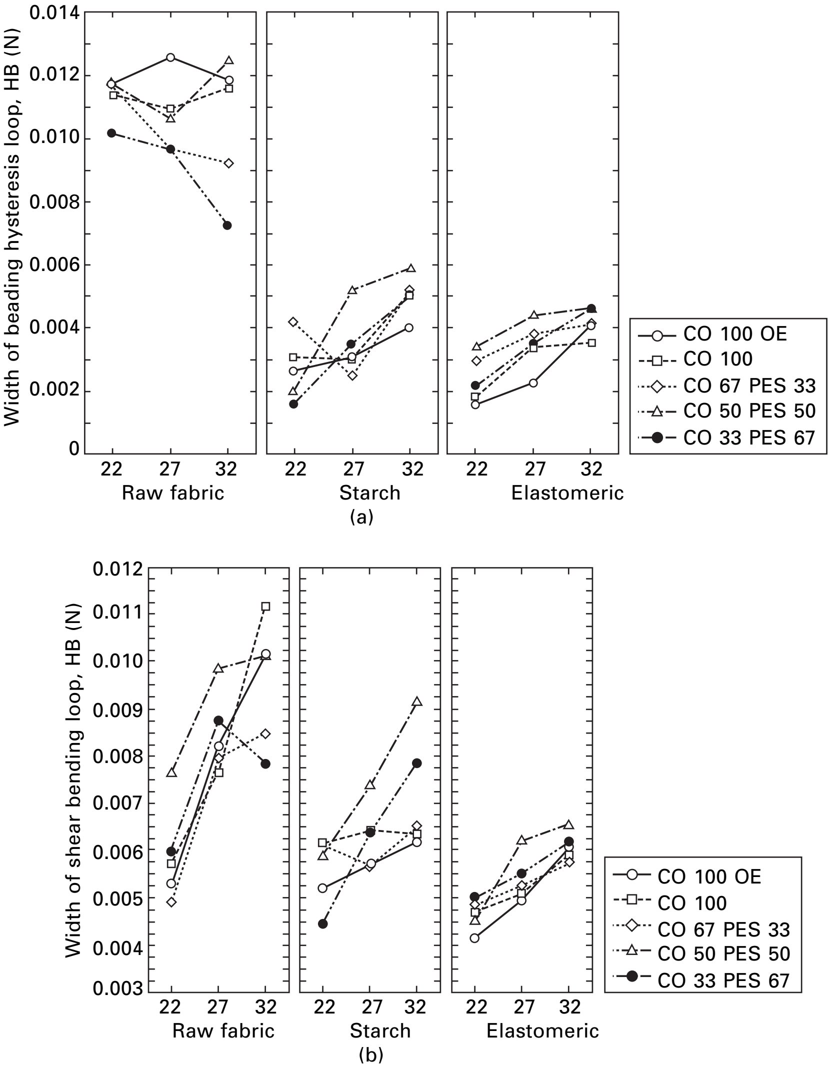
8.17 Influence of raw material content, weft density and finishing on the width of the shear hysteresis loop (HG).

8.5.3 Bending test

In the bending test under small stresses imposed by the Instron tester the width of the bending hysteresis loop (HB) was determined. The results of the bending test in the warp and weft directions are presented in Fig. 8.18 and 8.19.



8.18 (a) Influence of raw material content and finishing on the width of the bending hysteresis loop (HB) in the warp direction; (b) influence of weave and finishing on HB in the warp direction; (c) influence of raw material content, weave and finishing on HB in the weft direction.



8.19 (a) Influence of weft density, raw material content and finishing on the width of the bending hysteresis loop (HB) in the warp direction; (b) influence of raw material content, weft density and finishing on HB in the weft direction.

Influence of raw material content, weave and type of finishing

On the basis of the results obtained, the effect of raw material content, weave and type of finishing on the bending hysteresis loop width (HB) was analyzed. The stated relations are discussed for the warp and weft directions.

Bending hysteresis loop width, HB

The results of multivariate analysis of variance for the bending test in the warp direction are presented in Figs. 8.18(a) and 8.18(b).

On the basis of Fig. 8.18(a), for raw fabrics the lowest value of the bending hysteresis loop width (HB) was noted for fabrics with the biggest (67%) share of PES fibers and for fabrics made of cotton combed yarn.

For raw fabrics and fabrics with starch finishing the lowest value of HB of fabrics made from blended yarn (CO33%PES67%) results from a very good elasticity of PES fibers. Fabrics made of CO/PES blends are characterized by a diversified value of the bending hysteresis loop width (HB) depending on the proportion of PES fibers. The lower the PES fiber content, the higher the value of HB.

Considering only cotton fabrics, the classic yarn gives a lower value for HB than the rotor yarn. During fabric bending the displacement of fibers in the yarn can take place. The scale of this phenomenon depends on the cohesion forces between fibers and the tightness (compactness) of the yarn structure. The combed yarn is characterized by a tense structure and a more oriented fiber arrangement in comparison to the rotor yarn. This supports the stated differences between the HB values for cotton fabrics made of rotor and ring spun yarns.

The width of the bending hysteresis loop (HB) in the warp direction depends on the fabric weave (Fig. 8.18(b)). For raw fabrics the highest value is for canvas, whereas for finished ones it is for plain. The lowest value for all the fabrics is for twill, which has the fewest interlacements. The narrow bending hysteresis loop of twill fabrics results probably from the loose structure of this weave and a low fabric cover factor. The loose fabric structure facilitates return to a state close to the initial one after the release of bending stresses.

We also studied the influence of finishing on the results for the bending test parameter (HB) in the warp direction. Fabric finishing causes a big reduction of the value of HB in comparison to raw fabrics, meaning that the finishing improves the resilience after bending.

Type of finishing is also important. Fabrics with elastomeric finishing are characterized by a lower mean value of the bending hysteresis loop width (HB), and in the same way by better bending elasticity in the warp direction than fabrics with a starch finishing. The reason is that the elastomeric finishing causes the creation of a rubber-like substance on the fiber, which has excellent adhesion to its surface. Elastomers show an ability to return immediately to their primary shape after big changes in room temperature.

On the basis of this analysis of the results in the weft direction, as far as raw material content is concerned, statistically significant differences between the mean values of HB are noted for fabrics made of blended CO/PES yarns as well as between cotton fabrics made of different yarns (classic and rotor). Statistically insignificant were differences between the mean values of HB for cotton fabrics made of ring spun yarn and fabrics made of blended yarns with 33% and 50% PES fiber.

On the basis of these results it was stated that the width of the bending hysteresis loop (HB) in the weft direction for cotton fabrics made of rotor yarn is much higher than for cotton fabrics made of combed yarn. There was no universal tendency for HB to depend on the proportion of PES fiber. But it was noted that HB in the weft direction for fabrics with some PES fiber is lower than for cotton fabrics. This was confirmed by Tukey's test results.

The value of the bending hysteresis loop width (HB) in the weft direction, as in the warp direction, depends on the applied weave (Fig. 8.18(c)). The highest values are for plain fabrics, medium for canvas and the lowest for twill. There was a consistent relationship between the HB value and the number of interlacements in the weave pattern. The more interlacements, the wider was the bending hysteresis loop in the weft direction, and the more difficult the return to the primary shape after bending.

We also concluded that there was a significant effect of finishing on the bending hysteresis loop width (HB). Similarly as in the warp direction, also in the weft direction finishing causes a big reduction of HB. Moreover, fabrics with elastomeric finishing are characterized by a narrower bending hysteresis loop than fabrics with starch finishing. This can be explained by the high elasticity of elastomers used for finishing.

The influence of raw material content, weft density and type of finishing

Bending hysteresis loop width, HB

The results of multivariate analysis of variance for the bending test in the warp direction for plain fabrics are presented in Figs. 8.19(a) and 8.19(b).

In the warp direction the highest values of the bending hysteresis loop width HB are for raw fabrics. Much lower values of HB are noted for finished fabrics, but fabrics with starch finishing are characterized by a slightly wider bending hysteresis loop than fabrics with elastomeric finishing 8.19(a)). These relationships are in agreement with expectations, because the raw fabrics contain the sizing mean in the warp, which causes high rigidity of these fabrics in the warp direction. Elastomeric finishing of cotton and CO/PES fabrics limits their wrinkle formation. The presence of elastomers in the fabric structure facilitates an almost immediate return to the primary (or very close to the initial) state after release of the bending load. Therefore, they have the narrowest bending hysteresis loop compared to raw fabrics and fabrics with starch finishing.

In the case of finished fabrics, the weft density also had a clear influence on the width of the bending hysteresis loop (HB). In the majority of cases, HB increases with increase of the weft density. The denser a fabric, the more difficult is its return to the primary shape after bending. This relationship was not observed for raw fabrics.

There was no universal relationship between the results of the bending test in the warp direction and the type of raw material used for fabric production. It was noted only that among the finished fabrics a wider bending hysteresis loop occurred for fabric made from 50% CO/50% PES.

On the basis of Fig. 8.19(b) there was also no universal relationship between the bending hysteresis loop width (HB) in the weft direction and the type of raw material from which the fabric was produced. As in the warp direction, it was noted only that the highest value of HB occurred for fabrics made from blended yarn (CO50%/PES50%). This is true for the group of fabrics of different weft densities and also of different finishings.

Very clear tendencies were observed in the case of the other two factors (weft density and type of finishing). The width of the bending hysteresis loop (HB) in the weft direction increases with increase of weft density (Fig. 8.19(b)). The bigger the weft density, the more tense is the fabric structure. A high cover factor of fabrics causes the creation of initial stress in fibers, which can lead to plastic deformation or fiber breakage. Moreover, tenser fabric structure hinders the return to the primary state after fiber displacement caused by fabric bending.

Fabric finishing causes a significant decrease of the value of HB. Moreover, it was noted that elastomeric finishing gave a lower value of HB in the weft direction than did the starch finishing. This results from the ‘specifics’ of the applied means of finishing. Elastomeric finishing is an ennoblement and antishrinkage treatment. Elastomers at room temperature are able to return almost immediately to the primary state or very close to this after large deformation.

The stated differences between the mean value of HB in the weft direction for raw fabrics and all finished fabrics are statistically significant.

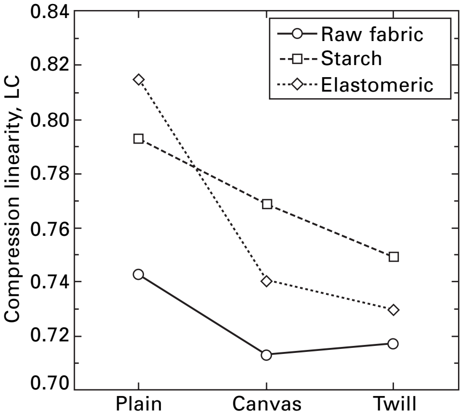
8.5.4 Compression test

Influence of raw material content, weave and type of finishing

Compression linearity, LC

Results of multivariate analysis of variance concerning the compression linearity (LC) are presented in Fig. 8.20. The highest value of LC was noted for fabrics made of cotton rotor yarn. The values of LC for fabrics made of cotton classic yarn as well as for blended yarns are more or less on the same level. This was confirmed by the Tukey’s test results (Table 8.7).

The compression linearity (LC) increases with more interlacements in the fabric weave pattern (Fig. 8.20). Plain fabrics are characterized by higher LC than fabrics of canvas or twill weaves. It was also stated that LC is much



8.20 Influence of weave and finishing on the compression linearity (LC).

Table 8.7 Results of Tukey's test for compression linearity, LT

(a) Main effect: raw material

LC		{1}	{2}	{3}	{4}	{5}
		0.761147	0.752774	0.744843	0.755134	0.745801
CO 100 OE	{1}		0.515253	0.018233	0.787875	0.032312
CO 100	{2}	0.515253		0.563985	0.991765	0.683054
CO67PES33	{3}	0.018233	0.563985		0.288894	0.999761
CO50PES50	{4}	0.787875	0.991765	0.288894		0.392948
CO33PES67	{5}	0.032312	0.683054	0.999761	0.392948	

(b) Main effect: weave

LC		{1}	{2}	{3}
		0.783491	0.740708	0.731621
Plain	{1}		2.18E-05	2.18E-05
Canvas	{2}	2.18E-05		0.068589
Twill	{3}	2.18E-05	0.068589	

(c) Main effect: finishing

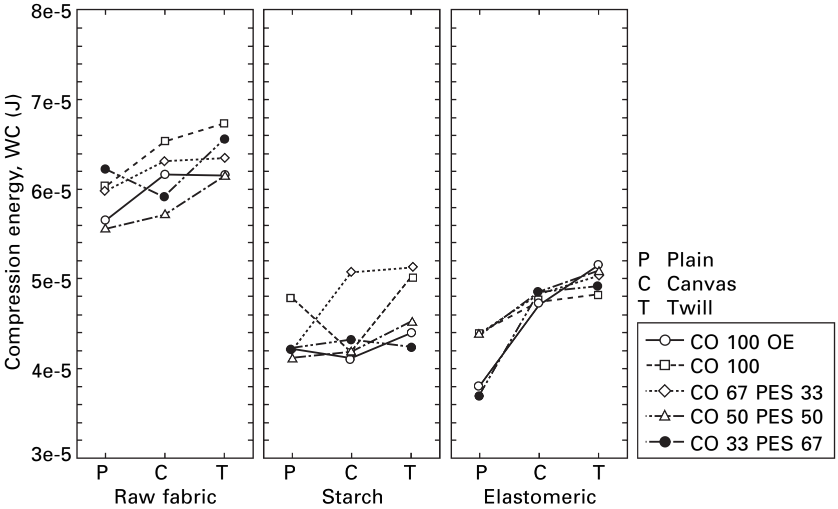
LC		{1}	{2}	{3}
		0.724104	0.770100	0.761615
Raw	{1}		2.18E-05	2.18E-05
Starch	{2}	2.18E-05		0.095295
Elastomeric	{3}	2.18E-05	0.095295	

lower for raw fabrics than for finished ones. The influence of finishing on the compression linearity is modified by the weave.

In the case of twill or canvas weaves fabrics with starch finishing are characterized by the highest compression linearity (LC), fabrics with elastomeric finishing by lower LC and raw fabrics by the lowest. Plain fabrics with elastomeric finishing are characterized by higher LC than fabrics with starch finishing and by much higher LC than raw fabrics.

Compression energy, WC

In Fig. 8.21 the results of multivariate analysis of variance concerning the compression energy (WC) are presented. The highest value of compression energy was observed for the group of fabrics made of classic combed cotton yarn (Table 8.7). The lowest was noted for fabrics made of OE cotton yarn and blended yarn, CO50%/PES50%.



8.21 Influence of weave, raw material content and finishing on the compression energy (WC).

Weave affected the compression energy. The lowest value of WC was observed in a majority of cases for plain fabrics, and the highest for twill. Fabric finishing reduced WC considerably. Fabrics finished with elastomeric finishing had higher WC than those with starch finishing (Table 8.8). The influence of weave on the compression energy is modified by the raw material content and type of finishing.

In the case of fabrics with elastomeric finishing, there is a clear relationship between compression energy (WC) and weave: the lowest value is for the

Table 8.8 Results of Tukey's test for compression energy, WC

(a)Main effect: raw material

WC		{1}	{2}	{3}	{4}	{5}
		0.000049	0.000052	0.000051	0.000049	0.000049
CO 100 OE	{1}		1.72E-05	1.72E-05	0.943304	0.507799
CO 100	{2}	1.72E-05		0.466131	1.72E-05	1.72E-05
CO 67 PES 33	{3}	1.72E-05	0.466131		1.73E-05	4.23E-05
CO 50 PES 50	{4}	0.943304	1.72E-05	1.73E-05		0.918213
CO 33 PES 67	{5}	0.507799	1.72E-05	4.23E-05	0.918213	

(b) Main effect: weave

WC		{1}	{2}	{3}
		0.000047	0.000050	0.000053
Plain	{1}		2.18E-05	2.18E-05
Canvas	{2}	2.18E-05		2.18E-05
Twill	{3}	2.18E-05	2.18E-05	

(c) Main effect: finishing

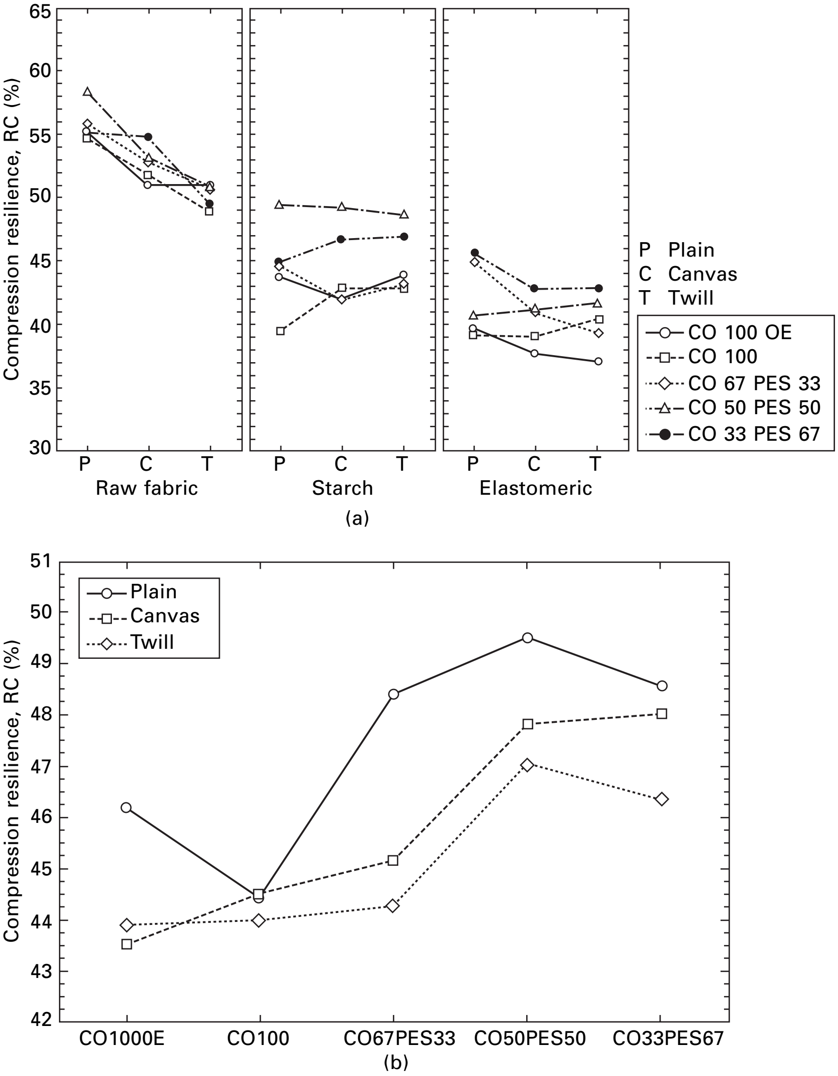
WC		{1}	{2}	{3}
		0.000061	0.000044	0.000045
Raw	{1}		2.18E-05	2.18E-05
Starch	{2}	2.18E-05		3.71E-05
Elastomeric	{3}	2.18E-05	3.71E-05	

plain, higher for canvas, and the highest for twill (Fig. 8.21). In the case of raw fabrics this tendency is seen only for fabrics made of cotton yarn and for those made from blended yarns (with 33% and 50% PES fibers). For fabrics finished by starch there is no universal relationship between WC and weave.

On the basis of Tukey's test results, differences between WC values of different weaves and types of finishing are statistically significant at the test probability 0.95 (Table 8.8). There were also statistically significant differences between WC values of fabrics made of cotton rotor yarn and of ring spun yarns: 100% CO and CO 67%/PES 33%. Statistically significant differences were also found between the values of WC for fabrics made of the blended yarns with different properties of PES fiber. In the other cases the observed differences are not statistically significant.

Compression resilience, RC

Compression resilience (RC) takes the highest values for fabrics of plain weave and the lowest for twill (Fig. 8.22(a)). This means that twill fabrics



8.22 (a) Influence of raw material content, weave and finishing on the compression resilience (RC); (b) influence of raw material content and weave on RC.

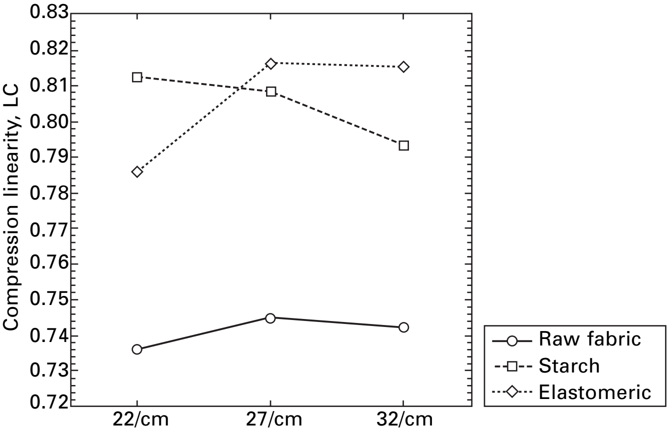
have the lowest ability to recover their primary shape after compression because of their least number of interlacements. We also studied the influence of fabric finishing on RC. The highest value of RC was observed for raw fabrics and the lowest for fabrics with elastomeric finishing (Fig. 8.22(a)), so finishing worsened the ability to recover the primary shape after compression. We also observed the influence of the raw material content on RC independently of the fabric weave (Fig. 8.22(b)). The highest values of RC were for fabrics with the highest percentage of PES fibers (50% and 67%), because of their high elasticity.

In the case of plain fabrics, the compression resilience (RC) for those made of cotton rotor yarn is higher than for those made of classic combed yarn. But in the case of fabrics of twill and canvas weaves, the value of RC is higher for fabrics made of cotton classic yarn than for fabrics made of rotor yarn.

The influence of raw material content, weft density and type of finishing

Compression linearity, LC

The highest value of compression linearity (LC) was observed for plain fabrics of the medium weft density, 27/cm. The influence of weft density on the value of LC is modified by the kind of finishing (Fig. 8.23). Among fabrics with elastomeric finishing, those of lowest weft density (22/cm) have the lowest value of LC, whereas among the fabrics with the starch finishing those of lowest weft density are characterized by the highest value of LC.

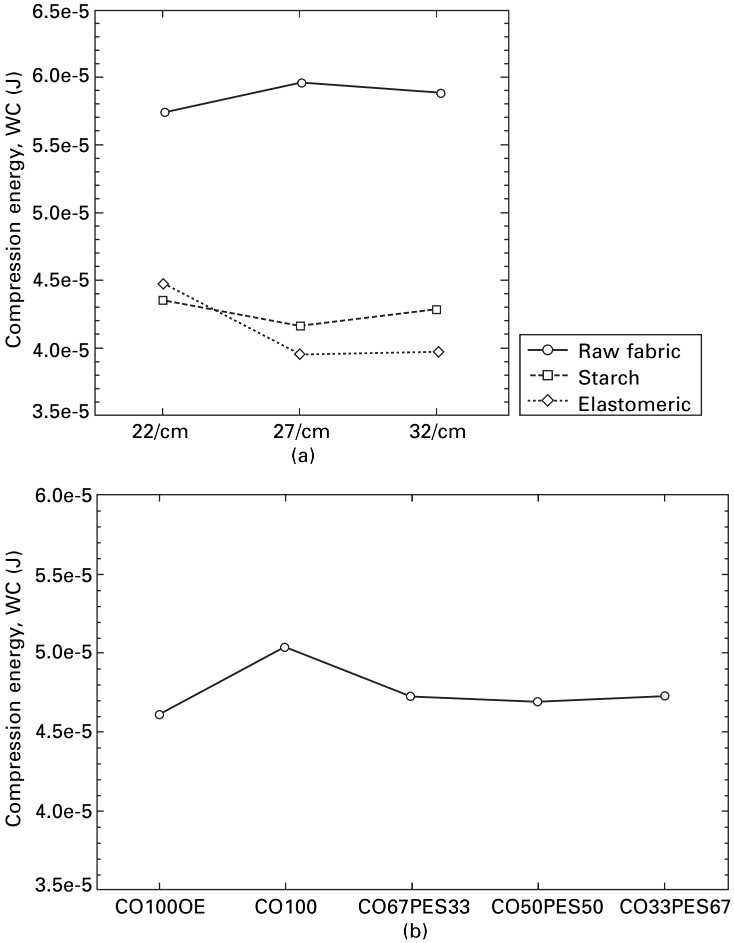


8.23 Influence of raw material content, weft density and finishing on compression linearity (LC).

Compression energy, WC

Results of multivariate analysis of variance concerning the compression energy (WC) of plain fabrics of different weft densities are presented in Figs. 8.24(a) and 8.24(b).

As in the case of fabrics of the same weft density but different weaves also in the case of plain fabrics the highest compression energy (WC) was noted for raw fabrics (Fig. 8.24(a)).



(a)

(b)

8.24 (a) Influence of weft density and finishing on compression energy (WC); (b) influence of raw material content as a main effect on WC.

In the case of finished fabrics, those with elastomeric finishing have lower values of WC than those with starch finishing. This is the opposite tendency to that fabrics of different weaves.

On the other hand, as for fabrics of different weaves, for plain fabrics those made of 100% cotton produced by the ring spinning system have the highest value of WC (Fig.8.24(b)). This is so for all the weft density variants (22, 27 and 32 wefts per cm). The compression energy of all the fabrics made of blended yarns is more or less on the same level independently of the PES fiber percentage.

Compression resilience, RC

Compression resilience (RC) of cotton and CO/PES fabrics made of the classic yarn increases with the proportion of PES fibers (Fig. 8.25(a)). In the case of 100% cotton fabrics, those made of the rotor yarn have higher RC, probably because of the rotor yarn morphology, which is characterized by a looser structure, worse fiber orientation and greater diameter than for the classic yarn of the same linear density. The compression resilience of plain fabrics is highest at the medium weft density, 27/cm (Fig. 8.25(b)).

There was a clear relationship between RC and type of finishing (Fig. 8.25(c)). The highest compression resilience was observed for raw fabrics. Fabric finishing (which includes a calendering operation) caused a decrease of mean RC. Among the finished fabrics, those with starch finishing are characterized by higher RC (better resilience) than fabrics with elastomeric finishing. The relationship between RC and type of finishing occurred independently of the raw material content.

8.5.5 Friction test

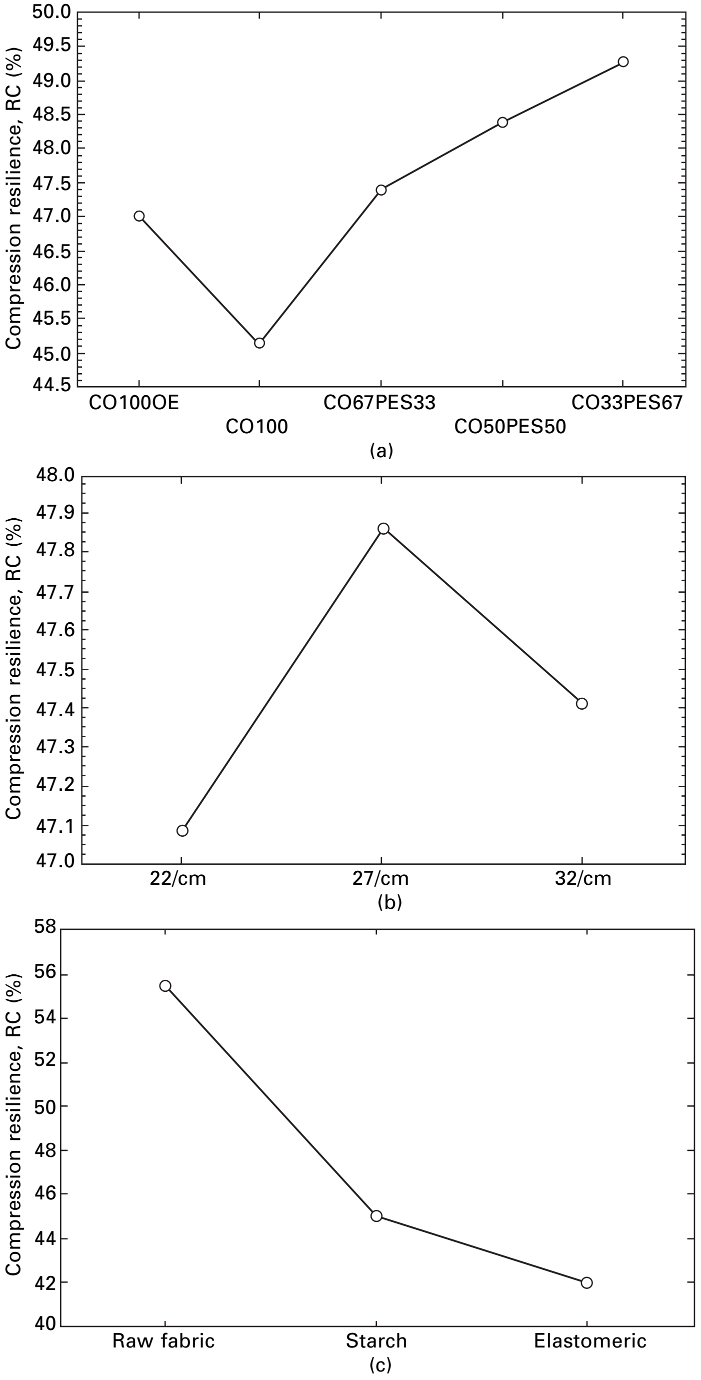
For each fabric variant a friction test was carried out in three arrangements: warp–warp, weft–weft, warp–weft. In each case five replications were done. Friction was tested on the face sides of the specimens. Two values of friction coefficient were determined: static μ_s and kinetic μ_k. Then, on the basis of the results obtained, the general friction coefficients (static and kinetic) were calculated as arithmetic means of the appropriate values for the three fabric arrangements.

Influence of raw material content, weave and type of finishing

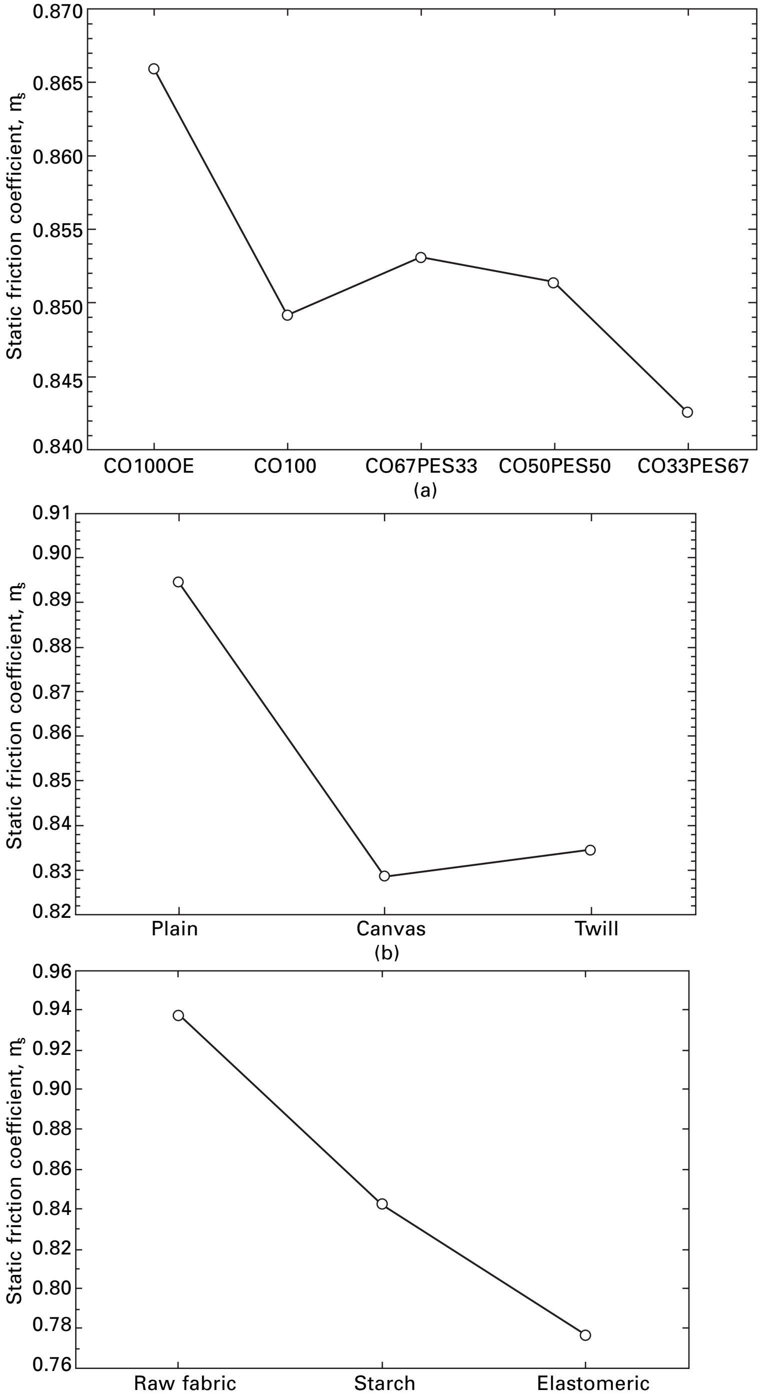
Static friction coefficient, μ_s

The static friction coefficient of cotton fabrics made of combed ring spun yarn is much lower than that for fabrics made of rotor yarn. This results from the characteristics of ring spun yarn, which has a more regular, denser and smoother structure than the rotor yarn, on the surface of which there are visible wrapped fibers (Fig. 8.26(a)). Moreover, ring spun yarns are characterized by smaller diameter than rotor yarns having the same linear density. This is why the surface of fabrics made of ring spun yarn is smoother than that of fabrics made of rotor yarn.

In the case of fabrics made of blended CO/PES yarns, the value of the static friction coefficient slightly decreases with the increase of PES fiber share. Nevertheless, the differences between the values of the static friction coefficient of particular blended fabric variants are not statistically significant. A statistically significant difference was noted only between the static



8.25 (a) Influence of raw material content as a main effect on compression resilience (RC); (b) influence of weft density as a main effect on RC of plain fabrics; (c) influence of type of finishing as a main effect on RC of plain fabrics.



(a)

(b)

(c)

8.26 (a) Influence of (a) raw material content, (b) weave, and (c) finishing, as a main effect on the general static friction coefficient m_s.

friction coefficients for fabrics made of rotor yarn and the other fabric variants.

The weave also influences the value of the static friction coefficient (Fig. 8.26(b)). The value of μ_s for plain fabrics is significantly higher than for fabrics of canvas and twill; the value of μ_s for both canvas and twill is similar.

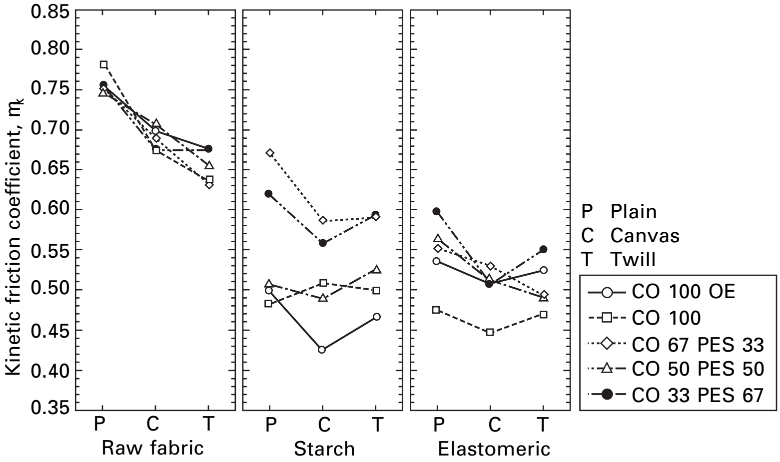
Fabric finishing causes a significant drop in the value of μ_s from its value for raw fabrics (Fig. 8.26(c)). This results from the nature of the finishing process, the aim of which is an improvement of fabric properties (including surface properties) and greater fabric smoothness.

Starch finishing causes fabric fulfillment and rigidity from gluing the pores between warp and weft threads. The final mechanical operations such as calendering and ironing cause the fabric to be smooth and decrease the friction coefficient. Elastomeric finishing assures better smoothness of the fabric surface than starch finishing, because of the specifics of this type of finishing already described in previous sections of this chapter.

Kinetic friction coefficient, μ_k

No universal tendency was noted for the kinetic friction coefficient μ_k to change depending on the raw material used. In comparison with the static friction coefficient, the values of the kinetic friction coefficient are more differentiated.

The relationships between μ_k, weave and type of finishing are analogous to those observed for μ_s. In both cases the influence of raw material is modified by type of finishing (Fig. 8.27).



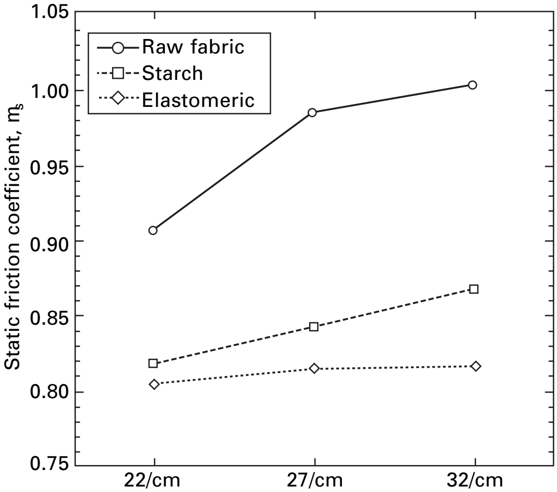
8.27 Influence of raw material content, weave and finishing on the general value of the kinetic friction coefficient μ_k.

Only for raw fabrics were noted very clear differences between the values of m_k for plain fabrics and for other weaves (i.e., canvas and twill). In the case of fabrics finished both by starch and by elastomer, the values of the static and kinetic friction coefficients are similar, since fulfillment of pores by finishing smoothes the fabric surface and levels the differences in surface resulting from applying the different weaves.

Influence of raw material content, weft density and type of finishing

Static friction coefficient, m_s

The value of the static friction coefficient m_s increases with the increase of the weft density of plain fabrics (Fig. 8.28). The biggest variation with weft density is noted for raw fabrics. In the case of finished fabrics there is an analogous tendency, i.e., static friction coefficient increases with weft density, but the observed differences are less than for raw fabrics.

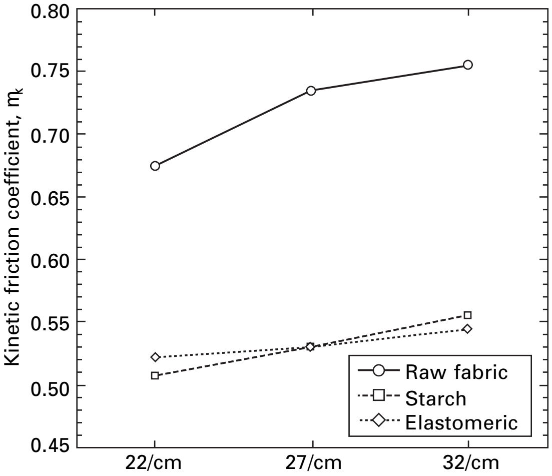


8.28 Influence of weft density and finishing on general static friction coefficient m_s.

Kinetic friction coefficient, m_k

Analogously to fabrics of different weaves, fabrics with a share of PES fibers are characterized by much higher values of the kinetic friction coefficient m_k than for cotton fabrics. As in the case of m_s, the value of m_k increases with increase of weft density (Fig. 8.29).

Raw fabrics are characterized by much higher values of m_k than finished ones. There was no statistically significant difference between the general values of m_k for fabrics with starch and elastomeric finishing.



8.29 Influence of weft density and finishing on general kinetic friction coefficient η_k.

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Part III

Effect of processing on fabric hand

9

Effect of wet processing and chemical finishing on fabric hand

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9.1 Introduction

Hand or handle is an elusive quality of fabric that is usually defined as the subjective assessment of a textile material obtained from the sense of touch. For subjective assessments, the terms silky, soft and smooth are the most frequently used descriptors. Among other descriptors are scroopy, beefy, bouncy, lively and dead. These subjective descriptors have evolved from people's attempts to describe the feel of the fabric on their hand. Techniques for objectively quantifying hand have been developed from measurement of an array of physical properties and correlation of these objective measurements with human subjective assessments. These techniques are discussed in detail in other chapters of this book. Many factors contribute to hand, for example the influence of fiber, yarn and fabric construction, and dyeing and finishing. The fiber, yarn and fabric construction factors are covered in other chapters, so the effect of dyeing and finishing will be the focus of this chapter.

The hand of most greige woven and knitted fabrics will not resemble the final hand of the dyed and finished end product; they must be wet processed before they are suitable for their intended use. The hand of greige fabric is the product of the woven or knitted construction plus the presence of non-fibrous materials. Subsequent wet processing steps remove the non-fibrous materials and alter the construction. The basic steps in wet processing are preparation, dyeing and finishing. The sum total of all wet processing steps will impact the final hand of the fabric. In many cases, process conditions are chosen to achieve the desired final hand.

9.2 Dyeing and finishing

Wet processing is the term used to describe the post web formation steps required to produce finished fabrics. The term dyeing and finishing is synonymous with wet processing and incorporates fabric preparation under its umbrella.

9.2.1 Fabric preparation

Preparation is the wet processing steps that ready a fabric for dyeing and finishing. The purpose is to remove all of the non-fiber materials that interfere with dyeing and finishing. The contaminates range from fiber spin lubricants, waxes, pectin, and wool grease to warp size, machine lubricants and mill dirt. Inadequate removal will adversely affect the quality of dyeing and finishing. In many cases, the cause of poor quality dyed goods can be traced back to poor preparation.

Desizing, scouring, and bleaching are the steps used to prepare most woven fabrics. The desizing step is designed to remove the polymeric warp size. Many woven fabrics, especially those made from spun yarns, require a warp size for efficient weaving. The size is a protective coating applied to the warp yarns and is a usually a combination of film forming polymers and waxes. The most commonly used film formers are starch and/or polyvinyl alcohol. Desizing is accomplished in three stages: apply the appropriate chemicals, provide time and temperature to promote chemical reaction, and finally, wash away the soluble by-products.

Scouring removes waxes, oils, grease and dirt. Cotton yarns contain waxes and pectin, wool yarns contain wool grease, and synthetic yarns contain fiber spin finishes. Additionally the rolls of fabric may be soiled by the way they are handled in the mill. The scouring step involves applying a detergent composition, providing time and temperature to loosen the soil, and finally washing away the contamination.

The bleaching step is designed to chemically degrade color bodies inherent in the fiber. Bleach chemicals can also cause fiber degradation so the choice of bleach, time and temperature will be a balance between desired whiteness and minimizing fabric strength loss. The most widely used bleach is hydrogen peroxide because it is much milder to both wool and cellulosic fibers. Full bleach is the goal for fabrics to be sold as white goods. For dyeing pastel shades, partial bleaching is often enough because it is important to have a consistent white base, to minimize shade variations between dye lots.

Knitted fabrics differ from woven fabrics in that they do not contain warp size, therefore scouring and bleaching alone will be sufficient. Fiber spin lubricants, knitting machine oils and mill dirt are the major components of the contamination to be dealt with.

Fabric handling

The way fabrics are handled in wet processing will have an effect on fabric hand. There are batch machines and continuous ranges that are used to prepare and/or dye fabrics. Additionally, these machines are specifically designed to process the fabric in open-width or rope form. Lot size, final fabric properties and costs are some of the criteria used to decide which method to use. In terms of fabric properties, fabrics processed open-width are under tension in both the warp and filling directions, so shrinking is minimized. Fabrics processed in rope form, especially in batch machines, are more relaxed, so shrinking can occur. This phenomenon is used to develop bulk in fabrics made from textured yarns and in certain woolen fabrics.

9.2.2 Dyeing

There are two ways of coloring textiles – dyeing (getting the colorant into the interior of the fiber) or pigment dyeing (anchoring the colorant onto the fiber surface). There are many technical details to consider when deciding how to dye a fabric. Some of these are the fiber(s) to be dyed, shade, fastness properties, reproducibility and cost. This chapter will focus on only those details affecting fabric hand. In general, the dyestuffs and auxiliaries used in conventional dyeing have little or no impact on fabric hand. These dyes penetrate the fiber cross-section and the auxiliaries are rinsed away. However, colorants used in pigment dyeing or printing require a binder for fixing them onto the fiber surface. The binder will stiffen the hand. For conventional dyeing, the biggest impact on hand is brought about by how the fabrics are handled during the dyeing process.

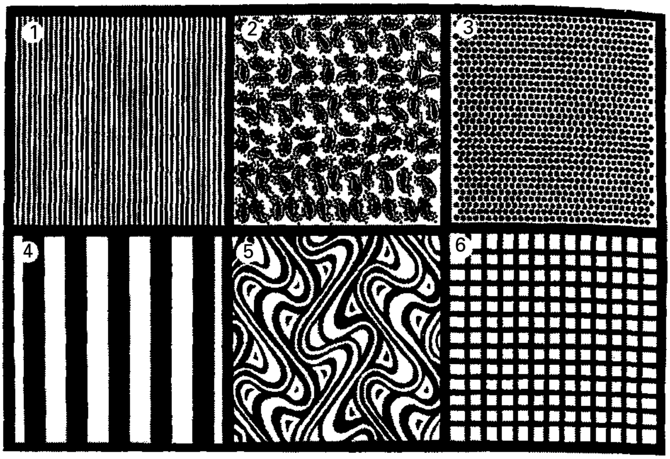
Robinson *et al.* [1] studied the effect of pattern design and fabric type on the hand characteristics of pigment prints. The study was conducted on two cotton fabrics printed with two pigment types in six designs. The analyses of the hand characteristics were evaluated by a trained descriptive panel to evaluate the effects of pattern design, color, and fabric type.

Fabrics used in the study

Two bleached 100% cotton fabrics were selected for this study – an Egyptian shirting fabric and an interlock knit. The shirting had a fabric count of 78 ends ¥ 72 picks per 2.5 cm (or 25 mm), a thickness of 0.188 mm (0.0094 in), and a weight of 111.53 g/m^2 (3.29 oz/yd^2). The knit fabric had 36 wale and course loops per 2.5 cm, a thickness of 0.656 mm (0.0328 in), and a weight of 195.93 g/m^2 (5.78 oz/yd^2). Samples of the shirting and knit fabrics were cut to 35 cm ¥ 67.5 cm with the long dimension parallel to the warp direction.

Pattern design

The six 25 cm ¥ 25 cm pattern designs we developed for this study are shown in Fig. 9.1. All patterns had 50% coverage of the printed area, except for the paisley design, which had 40% coverage. Flatbed screens containing



9.1 Patterns (25 ¥ 25 cm) used in study: (1) 3.2 mm wide stripes, (2) paisley, (3) 6.4 mm diameter dots, (4) 25.4 mm wide stripes, (5) swirl, and (6) checks with 6.4 mm wide crossed stripes. *Source:* 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Galewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

a 109-mesh polyester fabric were prepared for each of the designs using Ulano® water resistant screen emulsion coating.

Print paste preparation, printing, and curing

Preliminary experiments with a variety of pigment print pastes led to the selection of two print paste formulations containing either C.I. Pigment Blue 15:3 or C.I. Pigment White 6 (see Table 9.1). White and blue print pastes were selected to examine the influence of print color on the panelists' evaluation of hand. C.I. Pigment White 6 contained dioxide (TiO_2), which is a harder, more crystalline compound than C.I. Pigment Blue 15:3, a commercially important phthalocyanine pigment. Compared to the blue pigment, a higher concentration of the white print pigment was needed to obtain adequate cover.

The print pastes were prepared by placing water in a 600 ml beaker and slowly adding the thickener while mixing with a high speed mechanical mixer for 10 minutes. Next, the auxiliary crosslinker was slowly added, followed by the binder and pigment, with a 10-minute mixing period after each addition, giving a total mixing time of 40 minutes. The viscosities of the white and blue print pastes ranged from 23,120 to 23,360 cps and from 20,240 to 20,400 cps, respectively.

The cotton fabric specimens were printed on a flatbed machine, using one

Table 9.1 Print paste formulation

	Amount (g)	
Components	Print paste 1 (white)	Print paste 2 (blue)
Distilled water	419.80	426.00
Highfast carrier 06-59287[a] (thickener)	25.00	25.00
Highfast fixative 06-50251[a] (binder)	22.50	22.50
Inmount auxiliary binder 06-50627[a] (crosslinker)	4.00	4.00
Tiona TiO_2[b] (C.I. Pigment White 6)	28.70	
Highfast n. conc. Blue 3GB-61460[a] (C.I. Pigment Blue 15:3)		11.25
Total	500.00	488.75

[a] BASF Corporation
[b] SCM Chemicals.

Source: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Gatewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

pass with a 1.0 cm (width) ¥ 50 cm (length) magnetic squeegee. Fifteen prints were made with each screen before washing to prevent screen logging. The printed fabrics were air dried at ambient temperature (~21°C), then assigned randomly to groups of 30 for curing. The samples were sewn together in a continuous chain with the warp in the lengthwise direction, attached to a leader fabric, then cured with dry heat at 160°C for 3 minutes. The printed fabrics were cut into 25 cm squares with the design in the center and conditioned in a standard atmosphere for textile testing (21 ± 1°C and 65 ± 2% RH).

Panel selection and orientation

In preparation for this study, the panelists received four hours of orientation to reacquaint them with the hand analysis procedures and fabric types. Orientation samples were taken from preliminary print paste experiments. During orientation, the panel members examined two unprinted fabrics and established consensus intensities for the measured attributes to be used as internal reference samples that provided panelists with a basis for consistent and reproducible evaluations. A complete set of previously evaluated fabric standards representing the realm of fabric types was also available to the panelists as a reference for attribute intensities requiring further delineation.

The 17 hand attributes evaluated in this study are given in Table 9.2. The definitions, methods of evaluating the attributes (except surface texture), and attribute categories were developed by Civille and Dus [2]. Geometric

Table 9.2 Definition of fabric hand attributes by Civille and Dus [2]

Attributes	Definition
Geometric characteristics	
Fuzziness	Amount of pile, fiber, fuzz on the surface
Graininess	Amount of small, rounded particles in the sample
Grittiness	Amount of small abrasive picky particles in the surface of the sample
Surface texture [a]	Impact of tactile awareness of a random or non-random pattern
Thickness	Perceived distance between thumb and fingers
Mechanical characteristics	
Force to gather	Amount of force required to collect/gather the sample in the palm
Force to compress	Amount of force to compress the gathered sample into the palm
Stiffness	Degree to which the sample feels pointed, ridged, and cracked, not pliable, round, and curved
Depression depth	Amount the sample depresses when downward force is applied
Fullness	Amount of material felt in the hand during manipulation
Compression resilience	Force with which the sample presses against cupped hands
Springiness	Rate at which the sample returns to its original position after depression is removed
Tensile stretch	Degree to which the sample stretches from its original shape
Hand friction	Force required to move the hand across the surface
Fabric friction	Force required to move the fabric over itself
Sound characteristics	
Noise intensity	Loudness of the noise
Noise pitch	Sound frequency of the noise

[a] Developed by The Sensory Analysis Center Panelists Kansas State University
Source: 'Development of terminology to describe the hand-feel properties of paper and fabrics', by G.V. Civille and C.A. Dos, from *Textile Research Journal* vol. 5, pp. 10–32+319, 1990. Reproduced with permission from *Textile Research Journal.*

characteristics included four attributes related to the feel of the fabric surface (fuzzy, grainy, gritty, and surface texture) and fabric thickness. Surface texture was measured by positioning the hand flat on the fabric and moving the hand back and forth over the surface, focusing awareness on the first three fingers.

The mechanical characteristics included 10 attributes related to compressibility (force to gather, force to compress, stiffness, and depression depth), fullness, resiliency (compression resilience and springiness), stretchability, and frictional properties of the fabrics. The third attribute category was sound properties and included the intensity and pitch of the noise made when rotating the sample gently in the palm held next to the ear. More extensive descriptions of the techniques for assessing each of the attributes are given by Civille and Dus [2]. A ballot containing 17 attributes was developed and the trained panelists were instructed to rate the degree to which each attribute was present in the printed fabric specimens on a scale from 0 (none) to 15 (high).

Results and discussion

The mean intensity scores for the 17 attributes on each of the six designs for the pigment printed cotton knit and shirting fabrics are shown in Tables 9.3 and 9.4, respectively. Figures 9.2–9.5 show the grand means for the four fabric–pigment combinations within each of the attributes. Overall, fabric type had a significant influence on the intensity scores for the 17 hand attributes; it also influenced the differences in the intensity scores among the six pattern designs and two print pastes.

Influence of geometric characteristics

Fabric type followed by print paste composition (pigment type) appeared to have a greater influence on the intensity ratings for the geometric characteristics of the printed specimens than did the design of the print. These findings agree with a previous study [2], which showed that the kind of fabric used in hand evaluations can have a tremendous influence on perceived differences due to treatments.

Overall, the knit fabric was perceived as being fuzzier (grand means = 5.79 (knit) versus 2.18 (shirting) and thicker (means = 7.45 (knit) and 3.18 (shirting) than the shirting fabric. This was expected because the knit was almost twice as thick as the shirting, and in addition it had a lofty appearance in contrast to the flat, smooth shirting fabric. All the fabric–print paste combinations had similar and fairly low intensity values for graininess (small, rounded particles) and surface texture (tactile awareness). The particles on the knitted and woven fabrics were too small to be considered grainy. Conversely, the pigment prints had higher intensity scores for grittiness (small abrasion pick particles), especially on the woven fabrics (means = 9.25 (white prints) and 6.70 (blue prints)). For both fabric types, the intensity values for grittiness were significantly higher on the white pigment prints than on the blue. This was attributed to the higher solids contents and larger,

Table 9.3 Mean scores for hand attributes of cotton shirting

	Intensity based on scale from 0 to15						
Hand attribute	Pattern 1 (small stripe)	Pattern 2 (paisley)	Pattern 3 (dots)	Pattern 4 (large stripe)	Pattern 5 (swirl)	Pattern 6 (checks)	*p* value[a]
White pigment print							
Geometric characteristics							
Fuzziness	1.98	2.03	2.11	2.07	2.15	2.12	ns
Graininess	2.11	2.54	2.55	2.51	2.45	2.30	ns
Grittiness	9.93	8.76	9.68	8.98	9.63	8.49	ns
Surface texture	2.33	1.48	1.94	2.98	2.03	2.45	ns
Thickness	3.17	3.37	3.19	3.11	3.11	3.13	ns
Mechanical characteristics							
Force to gather	6.00	5.89	6.33	5.58	5.93	5.85	ns
Force to compress	6.43	6.47	6.59	6.17	6.41	6.39	ns
Stiffness	8.80a	8.09b	8.79a	7.93b	8.13b	8.03b	<0.05
Depression depth	1.56	1.53	1.61	1.49	1.48	1.49	ns
Fullness	5.49	5.46	5.67	5.69	5.49	5.51	ns
Compression resilience	6.39	6.16	6.64	5.81	6.34	6.17	ns
Springiness	1.47	1.53	1.57	1.51	1.49	1.51	ns
Tensile stretch	1.21	1.18	1.21	1.21	1.17	1.21	ns
Hand friction	8.61	7.85	8.10	8.19	8.57	7.94	ns
Fabric friction	13.59a	12.74ab	12.65abc	9.81d	12.02bc	11.37c	<0.01
Sound characteristics							
Noise intensity	4.55a	4.48ab	4.54a	4.34b	4.41ab	4.39b	<0.05
Noise pitch	4.54ab	4.50abc	4.56a	4.37c	4.43abc	4.41bc	<0.05
Blue pigment print							
Geometric characteristics							
Fuzziness	2.13	2.17	2.33	2.39	2.59	2.11	ns

Table 9.3 Continued

Hand attribute	Intensity based on scale from 0 to15						
	Pattern 1 (small stripe)	Pattern 2 (paisley)	Pattern 3 (dots)	Pattern 4 (large stripe)	Pattern 5 (swirl)	Pattern 6 (checks)	*p* value[a]
Graininess	2.29	2.31	2.54	2.15	2.56	2.14	ns
Grittiness	6.24	7.23	7.89	6.10	6.73	6.04	ns
Surface texture	3.12a	1.07c	1.27c	1.85bc	1.12c	2.19b	<0.01
Thickness	3.31a	3.09bc	3.29ab	3.05c	3.21abc	3.12abc	<0.05
Mechanical characteristics							
Force to gather	5.33b	5.45b	5.90a	5.09b	5.35b	5.10b	<0.001
Force to compress	5.70bc	5.79bc	6.15a	5.49c	5.84ab	5.67bc	<0.01
Stiffness	7.21	7.18	7.51	6.65	7.13	6.91	ns
Depression depth	1.52	1.45	1.54	1.39	1.45	1.48	ns
Fullness	5.05	5.20	5.38	4.97	5.37	5.03	ns
Compression resilience	5.79	5.78	5.91	5.31	6.13	5.81	ns
Springiness	1.53	1.51	1.56	1.43	1.66	1.52	ns
Tensile stretch	1.19	1.16	1.18	1.19	1.16	1.17	ns
Hand friction	6.80	6.97	7.99	7.00	7.01	6.69	ns
Fabric friction	10.57ab	9.24a	11.27a	9.15c	9.82bc	9.47bc	<0.05
Sound characteristics							
Noise intensity	4.11	4.20	4.20	4.16	4.23	4.14	ns
Noise pitch	4.13	4.22	4.22	4.18	4.26	4.16	ns

[a] Within a significant attribute only, means with the same letter are not significantly different.

Source: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Gatewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

Table 9.4 Mean scores for hand attributes of cotton knit

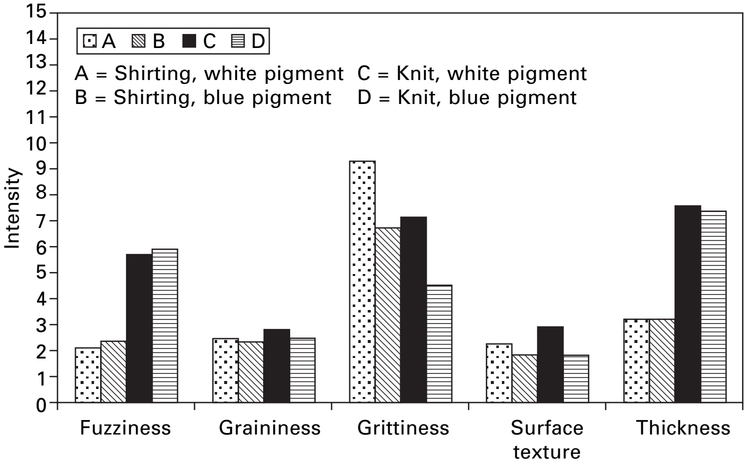
Hand attribute	Intensity based on scale from 0 to 15						
	Pattern 1 (small stripe)	Pattern 2 (paisley)	Pattern 3 (dots)	Pattern 4 (large stripe)	Pattern 5 (swirl)	Pattern 6 (checks)	*p* value[a]
White pigment print							
Geometric characteristics							
Fuzziness	5.57	5.21	5.73	5.87	5.72	5.95	ns
Graininess	2.97	2.83	2.93	2.46	2.68	2.68	ns
Grittiness	7.81a	7.50a	7.77a	5.71b	6.92a	6.97a	<0.05
Surface texture	2.72bc	2.65bc	2.14c	4.15a	3.11b	2.47bc	<0.01
Thickness	7.61	7.75	7.59	7.45	7.55	7.35	ns
Mechanical characteristics							
Force to gather	5.69a	5.68a	5.46a	5.15b	5.59a	5.15b	<0.01
Force to compress	6.36a	6.31a	6.22a	5.80b	6.16a	5.83b	<0.01
Stiffness	5.78	5.89	5.91	5.63	5.77	5.51	ns
Depression depth	7.10	7.28	7.11	6.99	7.09	6.96	ns
Fullness	8.50	8.59	8.56	8.37	8.53	8.35	ns
Compression resilience	4.48	4.53	4.65	4.44	4.62	4.35	ns
Springiness	5.27	5.27	5.38	5.22	5.17	5.19	ns
Tensile stretch	14.24	14.22	14.22	14.25	14.15	14.20	ns
Hand friction	8.50	8.21	8.20	7.74	8.15	7.81	ns
Fabric friction	14.70a	14.74a	14.74a	13.88b	17.37a	14.55a	<0.05
Sound characteristics							
Noise intensity	2.94	2.88	2.92	2.80	2.85	2.73	ns
Noise pitch	2.94	2.88	2.92	2.80	2.85	2.73	ns
Blue pigment print							
Geometric characteristics							
Fuzziness	5.82	5.88	5.95	5.96	5.72	6.09	ns

Table 9.4 Continued

Hand attribute	Intensity based on scale from 0 to 15						
	Pattern 1 (small stripe)	Pattern 2 (paisley)	Pattern 3 (dots)	Pattern 4 (large stripe)	Pattern 5 (swirl)	Pattern 6 (checks)	*p* value[a]
Graininess	2.49	2.38	2.65	2.34	2.64	2.50	ns
Grittiness	4.88	4.27	4.77	4.15	4.58	4.69	ns
Surface texture	2.06ab	1.58bc	1.07c	2.71a	1.75bc	1.38bc	<0.01
Thickness	7.43	7.32	7.43	7.20	7.42	7.29	ns
Mechanical characteristics							
Force to gather	4.95	4.96	5.08	4.98	4.92	4.91	ns
Force to compress	5.53	5.59	5.55	5.47	5.53	5.51	ns
Stiffness	4.97	5.05	5.17	4.95	5.03	5.01	ns
Depression depth	6.98	6.99	6.97	6.93	6.94	6.96	ns
Fullness	8.19	8.18	8.26	8.23	8.19	8.25	ns
Compression resilience	4.03	4.29	4.32	4.21	4.29	4.14	ns
Springiness	5.11	5.18	5.14	5.07	5.21	5.11	ns
Tensile stretch	14.29	14.21	14.26	14.21	14.19	14.22	ns
Hand friction	7.29	7.19	7.07	7.22	7.24	7.00	ns
Fabric friction	14.17	12.56	13.55	13.63	13.23	13.57	ns
Sound characteristics							
Noise intensity	2.72	2.76	2.69	2.67	2.72	2.69	ns
Noise pitch	2.72	2.75	2.71	2.67	2.72	2.69	ns

[a] Within a significant attribute only, means with the same letter are not significantly different.

Source: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Gatewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.



9.2 Mean scores for geometric attributes. *Source*: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Galewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

more crystalline particle size of the TiO_2. The panelists may have perceived the blue prints as being less harsh because a blue color is often associated with softness; however, the panelists are trained to disregard color.

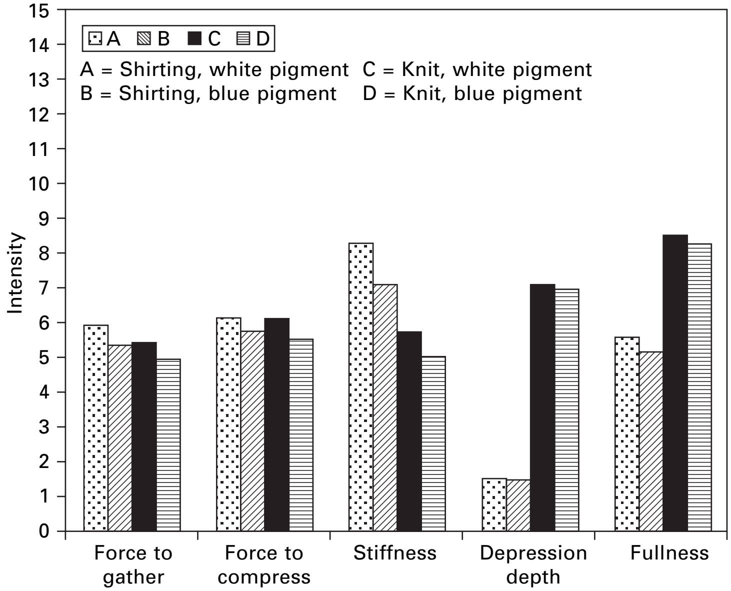
The pattern designs had some influence on the intensity ratings for the five geometric attributes, but their effects were often confounded by fabric and pigment type. Overall, the designs appeared to have little influence on the panelists' perception of fuzziness and graininess. On the cotton shirting fabrics printed with the white pigment, there were no significant differences in the intensity scores for any of the geometric attributes within the six designs. However, there were some differences in the six designs for the shirting fabric printed with the blue pigment. Specifically, design had an influence on the surface texture and thickness scores for the shirting fabric printed with the blue pigment.

The shirting fabric with the small stripe design was perceived as having more surface texture than the other white prints. Conversely, the larger stripe had the highest value for surface texture overall, and on the knits printed with both pigments and the shirting fabric with the white print. The wider stripe enables one to feel the pigmented and non-pigmented areas more distinctly as the fingers move across the surface, whereas with the smaller pattern, the fingers are constantly touching both the pigmented and non-pigmented areas.

On the knit fabrics, unlike the woven fabrics, the pattern design also had a significant influence on the intensity rating for grittiness (small abrasive picky particles). The large stripe was rated as being significantly less gritty compared to the other designs. Grittiness and surface texture seem to be closely related attributes, but the intensity ratings assigned by the panelists differed considerably, as did the influence of the design on these geometric characteristics. This implies that surface texture is a composite of many textural sensations, including grittiness.

Effect of mechanical characteristics

Figure 9.3 shows the mean intensity scores of the four fabric–pigment combinations for the mechanical attributes of hand related to compressibility (force to gather, force to compress, stiffness, depression depth) and fullness. In general, both fabric type and pigment type had a greater influence on most of these attributes than print design. Within a specific print paste type, the shirting fabric had a slightly higher force to gather and force to compress and was significantly stiffer, whereas the knit fabric had a significantly higher depression depth and fullness, which was expected based on the inherent characteristics of the two fabrics. For both fabric types, the white pigment prints were perceived as having a lightly greater force to gather, force to



9.3 Mean scores for mechanical attributes related to compressibility and fullness. *Source*: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Galewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

compress, stiffness, depression depth, and fullness, which coincided with the results obtained for the geometric attributes. The fabric type had the greatest influence on the intensity values for stiffness, depression depth, and fullness, whereas it had only a slight influence on force to gather and force to compress.

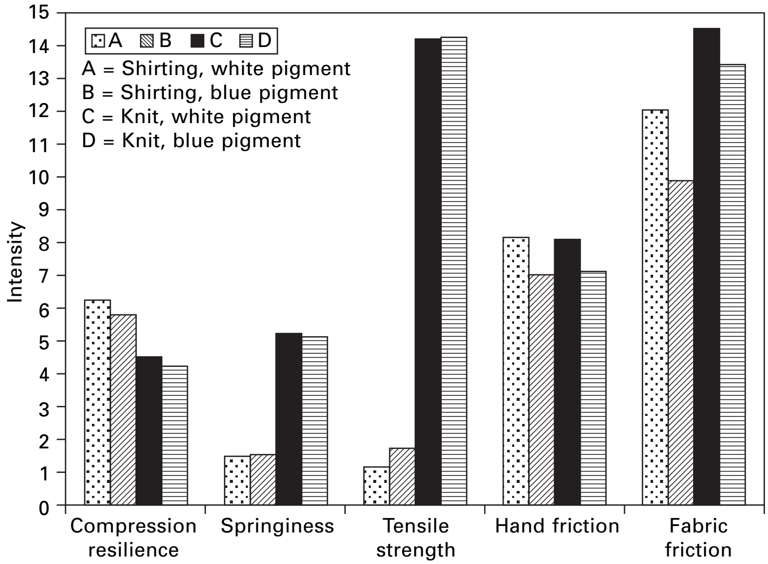
As mentioned before, the influence of pattern design on the compressibility/ fullness mechanical characteristics was confounded by the fabric–print paste combination (see Tables 9.3 and 9.4). For example, pattern design had a significant influence on the intensity ratings for the white pigment on the cotton knit and the blue pigment on the shirting, but not on the blue pigment on the knit or the white pigment on the shirting.

In addition, there were few consistencies between the fabric-print paste combinations in terms of the rank order of the intensity values associated with the size designs, except for the large stripe and dotted patterns. Furthermore, the range of values was quite small, even though some of the differences were significant based on the statistical tests. In general, the dotted design (pattern 3) had the highest intensity rating, and the larger stripes (pattern 4) had the lowest overall, and within most of the fabric–print paste combinations for force to gather, force to compress, and stiffness. Therefore, the design of a print, such as small discontinuous dots versus wide continuous stripes, may influence the bending ability of the fabrics, thus influencing the stiffness-related attributes that are important in evaluating the quality of pigment prints.

Similar results were obtained for the hand attributes related to resiliency, stretchability, and frictional properties, in that fabric type and pigment paste formulation had a greater influence on intensity values assigned by the trained panelists than did the design of the print (see Fig. 9.4). Overall, the knit fabrics had significantly greater springiness (rate at which the sample returns to the original position after the depression is removed), tensile stretch, and fabric friction, whereas the shirting fabric had significantly higher compression resilience (force with which the compressed sample presses against the hand). No appreciable differences were detected in hand friction due to fabric type.

Within a fabric type, differences were also seen in the intensity values between pigment types; e.g., the white pigment had slightly higher compression resilience and hand and frictional properties. However, the white prints were perceived as having a slightly lower tensile stretch. The pigment type had no appreciable effect on springiness.

The pattern designs had no significant effects on the resiliency, stretchability, or frictional properties of the fabrics, except fabric friction. For most of the fabric–print paste combinations, the larger stripes had the lowest intensity values for fabric friction (force required to move the fabric over itself). Perhaps the larger stripe was perceived as being more efficient in reducing fabric friction, especially on the fuzzier knits.



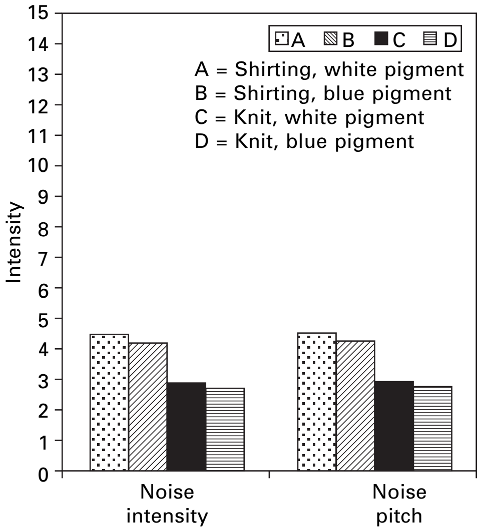
9.4 Mean scores for mechanical attributes related to resilience, stretchability, and frictional properties. *Source*: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Galewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

Influence of noise characteristics

As shown in Fig. 9.5 fabric type had an influence on the sound characteristics of the printed fabrics, with the woven fabric exhibiting higher noise intensity (loudness) and noise pitch (frequency) values. This was expected because a smooth, woven fabric usually makes more noise than a softer knit when rotated in the palm of the hand. The trained panelists also detected slightly higher noise values for the white pigment print with the TiO_2 particles compared to blue phthalocyanine pigment. The pattern design had no significant effect on the sound characteristics of the fabric, except for white print on the cotton shirting, but the ranges in the intensity values for noise intensity and pitch for the six designs were so small they would have little practical value.

Conclusions

The results of this study on the hand attributes of pigment prints show that fabric type has a greater influence on the geometric, mechanical, and sound properties than pigment type or pattern design. Overall, the printed knitted fabrics were fuzzier, thicker, softer, fuller, springier, and stretchier and had more surface texture and fabric friction than the shirting fabrics. These findings



9.5 Mean scores for sound properties. *Source*: 'Influence of pattern design and fabric type on the hand characteristics of pigment prints', by K.J. Robinson, E. Chambers and B.M. Galewood, from *Textile Research Journal,* vol. 67, no. 11, p. 837, 1997. Copyright Sage Publications.

parallel typical characteristics of cotton knits and flat, plain, woven shirting fabrics. Likewise, the woven cotton shirting fabric was stiffer and had a slightly higher force to gather, force to compress, compression resilience, and noise intensity and pitch. Hence the panelists were able to detect differences between the two fabrics in the 17 hand attributes, based on the terms, definitions, and techniques developed by Civille and Dus [2].

The print paste composition had some influence on the perceived hand of the printed fabrics, but the results were often confounded by fabric type and the attribute being evaluated. Differences between the print pastes were slightly more apparent on the knit fabric, whereas differences between designs were slightly more apparent on the woven fabrics. Pigment type had the greatest influence on grittiness, hand and fabric friction, surface texture, stiffness, force to gather, and force to compress for the woven and knit fabrics, and on the tensile stretch of the knit. For most of the other attributes, there were few differences between the two print paste formulations. This was not unexpected because the print pastes differed only in pigment type. Changes in binders, crosslinkers, thickeners, viscosities, add-ons, and curing conditions would have a greater influence on the geometric, mechanical, and sound properties than pigment type alone.

Pattern design had a significant effect on nine of the 17 hand attributes evaluated in this study, i.e., grittiness, surface texture, thickness, force to gather, force to compress, stiffness, fabric friction, noise intensity, and noise pitch. However, its influence was often confounded by pigment and fabric type, and the range in values was often quite small, thus limiting their practical value. For many of the attributes, no one design had intensity ratings that were significantly higher or lower than the others for all fabrics and print paste formulations. Among the geometric attributes, however, the larger stripe had the lowest graininess and grittiness values but the highest surface texture values compared to the other designs. There were also some consistencies in the panelists' ratings of the six designs on mechanical characteristics. The dotted design had the highest mean intensity values overall for force to gather, force to compress, stiffness, depression depth, fullness, compressional resiliency, and springiness, whereas the 2.54 cm stripe had the lowest mean intensity values for most of these attributes. Differences between print patterns were often more apparent on the shirting fabrics. Conversely, the knit fabrics showed greater differences between the print pases. Therefore, this research indicates that more than one pattern, print paste, and fabric construction should be included in studies on the influence of pigment print pastes on fabric hand. All these factors may have an impact on the hand of pigment prints, so each must be considered when assessing the overall hand characteristics of any print.

How the dyeing process affects the hand

The wet process encountered in fabric preparation holds true during the dyeing process. As an example of how the dyeing process affects the hand, consider polyester fabrics. Polyester fibers are dyed with disperse dyes requiring thermal energy to transfer the molecules into the fiber cross-section. The fabric can be dyed either in a pressure beck which supplies the thermal energy in the presence of water, or by the thermosol process. The thermosol process relies on dry heat to activate the dye molecules to the energy level needed for diffusion into the fiber cross-section. The thermosol process is carried out on a tenter frame to maintain the desired width. Either process can obtain the same shade, but the fabric hand will be noticeably different. The beck-dyed fabric will be soft and supple whereas the thermosol-dyed fabric will be stiffer. Post-dyeing finishing treatments may alter this stiffness, but the hands of the two will never approach each other.

9.2.3 Functional finishes

Finishing can be defined as any operation that imparts the final qualities to a fabric. It can encompass drying, applying chemical auxiliaries, or mechanical finishing. The latter will be covered in more detail in Chapter 10. Two categories of functional finishes, softeners and hand builders, are specifically aimed at modifying the fabric hand. For sake of simplicity, each category will be discussed as a stand-alone subject. In practice however, all of the required chemical auxiliaries are mixed into a single bath and applied simultaneously.

Wrinkle-free finishes

Wrinkle-free finishes, also known as crease resistant finishes, durable-press finishes, permanent press finishes, no-iron finishes, and shrink resist finishes, are reactants applied to cellulosic fabrics that chemically cross-link the cellulose polymer chains. In so doing, the fiber becomes more hydrophobic and resilient, resulting in a fabric that is wrinkle resistant, shrink resistant and smooth drying, and in garments with better shape retention.

Glyoxal based resins (DMDHEU) have become the resin of choice and the newer resins have dramatically reduced problems associated with formaldehyde release. The desired properties (DP rating, shrinkage reduction, etc.) are improved with increasing resin add-on, hence greater cross-linking of the cellulose polymer chains. However, cross-linking is responsible for reducing tensile strength, tear strength and abrasion resistance. As the add-on (cross-linking) increases, the greater will be the losses of these physical properties. In practice, a compromise is reached by balancing the degree of improved performance against the loss of physical properties. In terms of effect on fabric hand, cross-linking stiffens the fiber so the fabric becomes less limp.

Water repellent finishes

Repellent finishes fall into two categories: water repellent and anti-stain finishes. Chemical auxiliaries capable of accomplishing these goals fall into three categories: hydrocarbon waxes, silicones and fluorochemicals. As hydrophobes, all three will function as water repellents. The wax types give good initial repellency, are the least expensive and are the least durable to washing. They are not durable to dry-cleaning. The silicones also give good initial repellency. They are more durable to washing and dry-cleaning but are slightly more expensive than the wax types. The fluorochemicals give excellent initial repellency, are the most durable to washing, dry-cleaning and physical abrasion.

As chemical auxiliaries, they are the most expensive. Fortunately, less add-on is required so the added cost is not prohibitive. All three are effective in resisting water-borne stains but only the fluorochemicals have the added feature of holding out oil-borne stains.

Durable water repellent (DWR) finishes are formulations that combine resin wax water repellents with fluorochemical repellents. This combination was developed by the Army Quartermaster Corp. and is often referred to as Quarpel. It has proven to be effective for use on protective outerwear and foul weather gear and is durable to multiple field laundering cycles.

Water resistant fabrics are also known as 'water repellent' or 'waterproof' and it is important to distinguish between these terms. The term water repellent is used to describe a water resistant fabric where water droplets bounce off without clinging to the surface. AATCC Test Method 22 is used to rate this quality. The better the spray rating, the less water clings to the fabric surface. When the term waterproof is used, the fabric must also resist the passage of water through it. The ability of water to pass through is a function of the number and size of pores and openings. For example, DWR-finished tightly constructed fabrics, such as poplins, are more waterproof than are more open-weave fabrics even though the spray ratings may be the same. Coating the fabric is another way of reducing the openings and pores. As the coating coverage increases, water resistance increases and the greatest resistance is achieved whenever the coating becomes a continuous film. Performance requirement for water resistant fabrics must take into account the force of the water striking the fabric. It is obvious that a raincoat suitable for light to moderate rain will offer little protection in a driving rainstorm. A number of tests address the relationship between the force of the water and the threat level protection. AATCC test methods, ASTM test methods and Mil Spec provide more details.

Stain repellent finishes

Most fabric stains are the result of liquid spills from water-borne or oil-borne soils. Stain repellent finishes offer a degree of protection by resisting the penetration of the liquids into the fabric. Examples of water-borne stains are coffee, wine, tea and colas; oil-borne stains include food oils, fats and greases, and motor oil. The silicone and fluorochemical water repellent finishes also function as stain repellents. The silicones provide protection against water-borne stains but not against oil-borne stains. On the other hand, the fluorochemicals resist both. Water repellency tests are an effective way to assess water-borne stain resistance, but they do not address oily stains. The most widely used method for measuring oil repellency is AATCC Test Method 118. A series of test oils differing in their surface tension makes up the test kit. A drop of each test oil is placed on the fabric surface and allowed to sit for five minutes. The oil repellency rating corresponds to the highest numbered oil that does not penetrate into the fabric. The higher the number, the lower the surface tension and this signifies that the finish is a better barrier to oil stains. The same test is repeated after multiple laundering and dry-cleaning to assess the durability of the finish.

In terms of effect on fabric hand, the fluorochemicals are less likely to alter the finished hand, mainly because of the low add-on. The silicones will impart a slippery feel and some resilience or bounce to the fabric. The wax types, because of the resin plus the higher add-on level, will make the fabric feel 'beefier' and more robust. Since these chemicals are applied with other finish components, the hand will be more affected by the other components.

Soil release finishes

The introduction of polyester fibers into apparel fabrics created a problem in the removal of oil stains by laundering. The polyester fiber tends to tenaciously hold on to the stain. This was especially true for polyester/cotton fabrics finished with DP finishes. The problem is exacerbated by the soil repellent finishes mentioned above because once the soil is ground in, it becomes even more difficult to remove the stain by laundering. To address this, several types of soil release finishes are available. One type is specifically for DP fabrics and another for 100% polyester fabrics. Two different chemistries are available for DP finishes. One is based on copolymers of methacrylic acid and ethyl acrylate and is applied together with the DP resins. This chemical type forms a hydrophilic coating on the surface of the fibers. Under laundering conditions, the coating swells and this swelling action dislodges the soil from the fiber surface and allows the detergents to carry it away. It is quite effective in removing dirty motor oil stains. The amount of finish plus the stiffness of the polymer causes the hand to become stiff and boardy. The second, Dual Action, was developed by 3M and consists of block copolymer containing fluorochemical blocks and hydrophilic blocks along the polymer backbone. This finish in effect combines the features of oil repellency with soil release. When dry, the fluorochemical blocks function as a conventional oil repellent finish; under laundering conditions, the hydrophilic blocks absorb water, causing the polymer backbone to flip. Now the fiber surface is hydrophilic and the coating functions as a soil release agent. It too is applied together with DP resins. The effect on fabric hand is negligible because low add-ons are needed and the cured polymer is not as stiff as the methacrylic acid/ethyl acrylate finish.

A totally hydrophilic family of block copolymer finishes that impart both water wick-ability and soil release is available for 100% polyester fabrics. These finishes can be applied as a part of the dye cycle where they exhaust onto the surface or by padding. They are permanently attached. One segment of the copolymer serves as an anchor while the other provides hydrophilicity. When applied to fabrics made from textured yarns, oily soil release is noticeably enhanced. The soil release property is not as effective on fabrics containing either spun or continuous flat filament yarns. Even though the fiber surfaces are modified, the compactness of fibers in the yarn cross-section interferes with the dislodgement of the soil and its transport out of the fabric.

In terms of effect on fabric hand, the treated fabrics may experience a slightly softer hand as some of these finishes have lubricating qualities.

Moisture management, and comfort finishes

An important property associated with fabric comfort is moisture management. Moisture management deals with the ability of a fabric to transmit moisture away from the body. The mechanism of movement can be either by wicking or by passage of water vapor through the fabric. Breathability is a term often used to describe this property. Hydrophilic fibers such as cotton or wool are perceived to be comfortable because of their breathability. Hydrophobic fibers such as nylon, polyester, polypropylene are not. The ability of soil release finishes to improve water wicking also serves to improve moisture management and is often promoted as finishes for improved comfort.

Flame retardant finishes

Flame retardant finishes are designed to reduce a fabric's ability to sustain combustion. Combustion requires that three elements be present: fuel, oxygen and heat. If any one of these elements is removed, the flame will extinguish. For a solid material to ignite, it must be first heated to a temperature where it is pyrolyzed into flammable gaseous by-products (fuel). The temperature to do this is known as the pyrolysis temperature (T_p) and differs for the various fibers. Hence wool, Nomex and Kevlar are inherently more resistant to ignition than are cellulose, polyester, and acetate. Thermoplastic fibers such as nylon and polyester have low melting points so they are able to melt and withdraw from the flame source. In so doing, the melt temperature does not reach T_p so no flammable gases are produced and ignition does not occur. This is the mechanism that allows 100% polyester fabrics to pass the children sleepwear test. If thermoplastic fibers are blended with cellulosic, wool or even fiberglass, the melt does not recede from the heat source so T_p will be reached and these fabrics will ignite.

Flame retardant finishes are based on chemistries that interrupt the flammability cycle. For example, the elements phosphorus and nitrogen in flame retardants for cellulose fibers alter the combustion chemistry and prevent the formation of flammable fuel. Self-propagation cannot be sustained without flammable gaseous fuel. Another way of dousing the flame is to remove the heat source or reduce the temperature of the burning solid. The obvious way to do this is to pour water on the fire. Another way is to interrupt the chain reactions in the flame. Intercepting any of the exothermic reactions in the sequence reduces the heat output to the point that the solid no longer decomposes into gaseous fuel. Halogens such as chlorine and bromine operate in this manner and flame retardant finishes that operate in this mode are highly brominated or chlorinated compounds. They decompose with heat and release chlorine or bromine radicals. Since this mechanism operates in the flame, these retardants are useful for a broad range of fibers. A fourth method of extinguishing a flame is to suffocate it by keeping oxygen out, much like throwing dirt or a blanket over a fire. Flame retardants that work on this principle contain elements such as boron that form a non-flammable coating on the fiber. This restricts the oxygen supply.

Most flame retardant compositions will stiffen the hand of fabrics. There are a few exceptions. Usually high loading of the finish will be needed because the percentage of the active elements with respect to the total weight of the finish is low. Durability is also an issue. Some of the finishes are polymer formers, some react with the fiber, while others are pigments that are encapsulated in a binder on the fiber surface.

Hand modifiers

Softeners and hand builders are the functional finishes that have the greatest impact on fabric hand. These are the tools available to a finisher to try to tailor a hand. They too will be incorporated in the final finish bath along with all of the other ingredients. Almost all finish formulations will include a softener as a component. Softeners are lubricants that provide functional properties as well as hand qualities. From a physical property point of view, they improve tear strength and abrasion resistance and reduce frictional heat build-up on cutting knives and sewing needles in cutting and sewing operations. Hand builders are applied on limp or fragile fabrics so they can more easily be handled in cutting and sewing.

Hand builders

Hand builders are film-forming polymers that coat fiber surfaces. They add weight, body and stiffness to fabrics. Some are identical to the binders used to durablize pigments as mentioned in a previous section. Hand builders fall into two major categories: non-durable and durable. The durable ones are further divided into thermosetting and thermoplastic polymers. The effect on hand depends on add-on and the inherent stiffness of the polymer film. As can be imagined, the amount of a stiff polymer needed to achieve a certain hand is less than that of a soft polymer. Similarly when added weight and bulk is the target, higher amounts of softer polymers can be used without over-stiffening the fabric. A negative aspect regarding increased stiffness is the corresponding loss of tear strength. Fortunately, tensile strength is not affected. The reason for this is that the yarns are immobilized and are not free to slide when the fabric is subjected to tearing stresses. In a stiff fabric, each yarn along the tear line individually bears the entire brunt of the force;

therefore it takes less force to initiate the tear. If the yarns are mobile such as in pliable fabrics, they can slide and can bunch up at the point of stress. The yarns slip and the brunt of the force is met with a greater fiber mass.

Non-durable hand builders

For some fabrics, a crisp, smooth appearance is a desirable attribute. The consumer expects men's dress shirts to have a crisp smooth hand for over-the-counter appeal. Denim jeans traditionally are expected to have weight and body. Quality and toughness attributes have been equated to heavier fabrics so traditionally the weight of the fabric in ounces per square yard has been the barometer of quality. The consumer has come to expect the hand to break down and the color loss that occurs when the garment is laundered. In fact this is a revered quality because the garment becomes softer and more comfortable. The degree of color loss is a visible indicator of wash down, and the more faded and worn the garment becomes, the more comfortable the garment is perceived to be. Pre-washed jeans have become a hot fashion item and the topic will be discussed in greater detail later in this chapter. Non-durable or hand builders with limited durability are used for these applications and water-soluble polymers such as starch, carboxymethyl cellulose and polyvinyl alcohol make up this category.

Durable hand-builders

Durable hand-builders fall into two major categories: thermosetting and thermoplastic. Melamine resins are the most widely used thermosetting hand-builders and are the reaction product of melamine and formaldehyde. The resins are water soluble and stable for a period of time. When formulated with a catalyst, they cure into a three-dimensional cross-linked polymer with some reactivity to cellulose fibers. The cured resin holds up well to multiple washing and can be used on a wide range of fibers. Fabrics made from cellulose, polyester, nylon, acrylic and wool fibers are candidates for this finish. They are also used on blended fabrics.

Thermoplastic polymers are another type of durable hand builders. A wide range of latex polymers is available, made from monomers like vinyl acetate, acrylates, methacrylates, styrene, butadiene and urethanes. This array exists because latexes are used for a broad range of coating applications other than textiles. The physical nature of cured latex films is reflected by its glass transition temperature (T_g). This is the temperature at which a polymer transforms from the glassy state to the rubbery state and is a measure of the stiffness of the film. The lower the T_g, the softer the coating; conversely the higher the T_g, the stiffer the coating. The monomers selected to make the polymer largely control the T_g so the polymer chemist has a wide range at his or her disposal. In addition to T_g considerations, reactive monomers can be incorporated in the composition to provide secondary reactive sites capable of cross-linking the polymer chains after the film is formed. Cross-linking improves the durability of the coating. This wide range of products allows the textile chemist to tailor the hand of the fabric to match a given target.

Softeners

Softeners are the most important class of functional finishes that impact fabric hand. Nearly every finished fabric will have a softener in the finish formulation. Softeners improve tear strength and abrasion resistance and improve the efficiency of cutting and sewing in addition to providing tactile qualities. Softeners are lubricants and the purpose of a lubricant is to lower friction between mating objects, for example fibers against fibers, yarns against guides, fabric against sliding objects, and fabric against skin. Lubricants accomplish their goal by reducing the coefficient of friction and a lubricant's ability to do this depends on two qualities – the polar nature of the molecules and the viscosity. Non-polar compounds such as hydrocarbons and silicones are more effective than polar compounds. Within a given class, for example hydrocarbons, low viscosity fluids give a lower coefficient of friction than paraffin wax. From a practical point of view, the lower hydrocarbons are volatile so their effectiveness as a softener is negated. Mineral oil and paraffin waxes, on the other hand, can be used as softeners. Some other important factors in softener selection are color, dye lightfastness, odor, smoke point and water dispersability. Some potential softeners are dark in color or discolor with heat and age. These would not be suitable on white or pastel shades. Others will alter the dye shade and/or affect the dye's light fastness. Still others have a characteristic unpleasant odor or develop odor on aging. Smoke point is related to volatile components that vaporize as smoke during drying and condense to drip back on the fabric as grease spots downgrading the quality of the finished fabric. Water dispersability is important because softeners are applied from a water bath along with all the other finishing components. Some surfactants also function as softeners and are desirable because they readily disperse in water. Others like silicones, polyethylene and paraffin waxes must be emulsified before they can be used.

Anionic softeners

Anionic softeners are surfactants derived from fatty acids that come from the hydrolysis of triglycerides. Triglycerides are naturally occurring esters found in animal fats and vegetable oils. Fatty acids are the starting materials for making anionic, cationic and non-ionic surfactants. Because of the long hydrocarbon chain, they also serve as softeners. Anionic surfactants contain water-loving groups such as carboxylic acid, sulfonic acid and phosphoric acid. When in contact with water, these groups ionize and develop a negative charge, which is why they are termed anionic. Similarly, most fibers in contact with water will develop a negative zeta potential on the surface. The net effect is that the charged species act to repel each other so there is no attraction between the fiber surface and anionic surfactants. Nonetheless, these materials can be applied from water and will remain on the surface after the water evaporates. As a softener, anionic surfactants require higher add-on because the repulsive forces on the fiber surface must be overcome. The hand developed with anionic softeners is a greasy feel with little or no improvement in fabric suppleness. Anionic softeners are used as napping and Sanforizing lubricants to protect the fabric against the rigors of the machine surfaces. A good napping lubricant will offer the fabric some protection against the napping wires, while at the same time not being so lubricious as to allow the wires to completely pull fibers out of the yarn. While most softeners are hydrophobic and resist water, anionic softeners retain their hydrophilicity and become the softener of choice for applications such as bath towels or moisture management fabrics where water wicking is important.

Cationic softeners

Excluding the silicones, cationic softeners provide the greatest softening effect unmatched by any of the others. Cationic softeners are molecules that have a positive charge on the hydrophilic end which are amines and quaternary ammonium salts. In contrast with the anionics, the positive end of a cationic softener is attracted to the fiber surface and orients the molecule so that the hydrophobic portion is away from the fiber surface, creating an enriched hydrocarbon outer layer. This attraction is also the reason why cationics exhaust out of the bath onto the fiber. This leads to efficient use of the softener with maximum surface coverage and optimum lubrication. Quaternary ammonium cationic softeners are used as home laundry softeners. Cationic softeners are the ones of choice when a soft, pliable and silk-like hand is the target. Because of the low add-on, softness is achieved without a greasy feel. In addition to softening, a cationic softener renders the fabric hydrophobic. Drawbacks associated with cationic softeners are that some of them will discolor with age and some will have a negative impact on the lightfastness of certain dyes. Aminosilicones can also be considered cationic softeners, but they will be discussed in the section dealing with silicone softeners.

Non-ionic softeners

Polyethylene

There are several classes of materials that fall under the heading of non-ionic softeners. Fatty acid derivatives fall into the surfactant category while polyethylene and silicone do not. Hydrocarbon softeners are based on petroleum and include polyethylene and paraffin wax. They have little effect on fabric hand because they are semisolid materials at ambient temperatures. However, at elevated temperature, they melt and become good lubricants. This condition occurs when fabrics are subjected to frictional heating, so polyethylene is widely used whenever protection against abrasive forces, tearing forces and cutting and sewing is needed.

Ethoxylates

Ethoxylated fatty acid derivatives are the reaction product of a fatty hydrophobe with ethylene oxide. There are a number of hydrophobes that can be ethoxylated, e.g. fatty acids, fatty alcohols, fatty amines and alkylphenols, The degree of ethoxylation can be controlled to give a wide range of products ranging from oils to semisolid waxes. The ethoxylated portion imparts water solubility and remains a neutral molecule when in water, so is non-ionic. The number of different hydrophobes coupled with varying the degree of ethoxylation (moles of e.o.) creates a large menu of products from which to choose. As softeners, the effect on hand will depend on which combination is chosen. The ones that are oils will develop a pliable hand while those that are semisolid waxes will not noticeably affect the hand at all. These softeners are also used when re-wetting is desirable.

Silicones

Silicones as a group are considered the premium softeners. The family of silicone softeners is based on polydimethylsiloxane and includes neutral fluids, fluids with reactive side groups and aminofunctional silicones. The silicone fluids are capped at both ends of the linear chain with non-reactive end groups to provide a series of fluids with viscosity ranging from low viscosity fluids like sewing machine oil to high viscosity fluids like mineral oil. These water-clear fluids are emulsified and come as milk-white dispersions at about 30% solids. They do not discolor on aging and do an excellent job of lubricating as they develop a pliable, luxurious, silky hand. The fabric also becomes water resistant and the finishes are durable through a number of washes. This can present a problem to the finisher when it becomes necessary to rework the fabric. Fabric must be readily wettable to successfully strip, re-dye and finish off quality fabrics.

A more lasting effect can be accomplished by using silicone fluids modified with side reactive groups. Epoxy functionality can be introduced into the polymer backbone and these modified silicones can self cross-link or react with the fiber surface, making them more durable. These softeners are also used to enhance the resilience of wrinkle-free fabrics by adding bounce to the wrinkle recovery process.

A more recent addition to the silicone family softeners is the aminofunctional silicone microemulsions. The amine functionality confers several useful properties. First of all it greatly assists the emulsification process by acting as an internal emulsifier. The amine group acts as an internal emulsifier, making it much easier to produce stable micro emulsions. The emulsions are translucent rather than milky, indicating that the dispersed particles are much smaller, allowing the finish to be more uniformly distributed throughout the fabric structure. Secondly, the polymer molecule will have cationic sites along the backbone. As in the case for the other cationic softeners, these sites are attracted to the surface of the fiber, ensuring better surface coverage and orientation of the non-polar groups to the outer layer. These features are responsible for putting the aminosilicones at the top of the list as hand softeners. One interesting feature is that the cationic nature is neutralized under laundry conditions, making them less water-soluble and thereby improving their durability.

9.3 Special topics

9.3.1 Dryers and ovens

The equipment used to dry and cure fabrics will impact fabric hand. Tenter frames and dry cans are fabric transport mechanisms that use tension to convey the fabric. Fabric is restrained from shrinking so it will have a stiffer hand. Tumbling dryers, loop ovens and relax dryers have mechanisms that move the fabric in a relaxed state and result in a much softer hand. Relax dryers are preferred for knit fabrics as they allow the loops to rearrange into a stable configuration. Stable loop formation is important for controlling the wash shrinkage of knit fabrics.

9.3.2 Heat setting

The purpose of heat setting is to stabilize fabrics containing thermoplastic fibers. Fabrics from polyester and nylon yarns benefit from heat setting because the thermoplastic fibers acquire a new memory after they are fashioned into fabrics. When heated above the fibers’ prior heat history, the geometry of the yarn crimp becomes locked in as the fibers acquire a new memory. This serves to stabilize the fabric by providing a new stable state and resistance to distortion and wrinkling. Polyester, nylon, spandex and blends with cellulose and wool benefit from heat setting. Heat setting can be done on greige fabrics as well as finished fabrics. Greige heat setting is done to stabilize fabric and prevent it from being distorted during wet processing. Greige heat setting becomes necessary for those fabrics where wet wrinkles cannot be pulled out during drying. Final heat setting can be done at any stage of dyeing and finishing but preferably at the end.

Heat setting is usually done on a tenter frame. Time and temperature parameters are selected to achieve the degree of stabilization needed without overstiffening the fabric. The setting process does stiffen fabric hand and the closer the temperature gets to the fiber's melting point, the stiffer the fabric becomes. Because of the fiber mass, heavyweight fabrics require more exposure time than do lightweight fabrics. Another heat setting issue of concern is dyeing. Heat-set fibers are more difficult to dye because they become more crystalline, making it more difficult for dye molecules to penetrate. Ideally, heat setting should be done after the fabric is dyed to the correct shade.

Setting processes are also used at several stages in the production of wool and wool-blend fabrics and garments. Such processes, which induce stress relaxation in the fibres and yarns, result in major modifications to the properties of the fabrics and thereby form the basis of the operations used to develop hand and other characteristics of wool-containing fabrics. The principles of setting wool and synthetic fibers are well understood and a wide range of techniques are available to exploit the more recent advances in setting technology.

Setting is also an important function of the final pressing operations (dry finishing). Final pressing routines are very important in determining the physical and mechanical properties of fabrics which in turn determine fabric hand [3]: luster, making-up characteristics (tailorability) [4] and the appearance of the garment. Traditionally, final pressing has consisted of a series of batch operations designed to impart the required aesthetic properties to the fabrics and render those properties stable to release under mild conditions. More recently, higher costs have necessitated the increased use of continuous or semi-continuous pressing processes [5]. Moreover, the requirements of fabric stability have increased so that more severe setting conditions are needed.

Fabric may also be set after the garment has been manufactured. Pleated skirts or skirt panels are often set in a vacuum autoclave using high temperature saturated steam, whereas skirts and trousers can be set using chemical assistants (e.g. Siroset). Such processes will also modify hand and other characteristics of the fabric.

A number of studies of the effect of setting and pressing operations on the mechanical properties and dimensional stability have been reported. Many of these studies have measured properties important in the assessment of fabric hand, such as fabric thickness and compressibility, ending stiffness, surfae friction, and wrinkle recovery. Measurements of these properties during finishing of wool and wool-blend fabrics demonstrated that many of the changes in mechanical properties of the fabrics can be attributed to changes in frictional effects within the fabric. Such changes are brought about by a reduction in the normal force between adjacent fibers and yarns as a result of stress relaxation of the fibers at constant length or by shrinkage of the fabric. The surface frictional properties of the fabric, however, appeared to vary with each operation: friction increased in operations which the fabric was unconstrained and become smaller in pressing operations.

Several studies of final pressing operations, which include many of the above measurements, have demonstrated that differences in fabric mechanical properties are also achieved by modifying the final pressing conditions. However, few studies have considered whether the changes that occur during setting operations in wet finishing (before, during or after dyeing) are still observable in the finally pressed fabric and whether their effect can be compensated for by suitable modification of the dry-finishng routine.

The results of a study into the effect of set-inducing finishing processes on those mechanical properties of worsted suiting-type fabrics relevant to hand and tailoring properties were reported by DeBoos *et al.* [5], as presented in the following sections.

Experimental

Suiting fabrics

A. Pure-wool, plain-weave, yarn-dyed (~244 g/m^2)
B. 70/30 wool-polyester, plain-weave, undyed (~188 g/m^2)
C. 55/45 wool-polyester, plain weave, undyed (~227 g/m^2)
D. Pure-wool, 2/2 hopsack, undyed (~278 g/m^2)
E. Pure-wool, twill, yarn-dyed (~279 g/m^2)
F. Filament polyester, plain-weave (~197 g/m^2).

All fabrics were obtained in the loom-state and finished as specified below.

Finishing methods

The fabrics were finished using the following methods:

(1) Semidecatizing (loom state). Steamed for 3 minutes in a Bailey machine.
(2) Crabbing. Laboratory beam dyeing machine. 1 hour at the boil. These conditions were selected so as to produce the same amount of set as produced by heat-setting fabric.
(3) Scouring. Open width in a pilot scale dyeing winch, 30 minutes, 50°C (1 g/1 Diadavin DWN (Bayer) and 2 g/1 sodium sulphate).
(4) Heat setting. Benz laboratory stenter, 180°C, 30 seconds. The fabrics were unconstrained during setting.
(5) Dyeing. Open width in a laboratory winch, pH = 4.8, 100°C, 60 minutes.
(6) Semidecatizing (final pressing). Bailey machine for 2 minutes.
(7) Pressure decatizing. Biella KD-matic, 3 minutes, 120°C.

All fabrics were conditioned overnight between operations.

Testing

Duplicate samples of all treated fabrics were tested under the standard conditions recommended for the KES-F instrumentation (Kato-Tekko). All fabrics were aged for at least 28 days prior to testing.

Results: change in properties of pure-wool fabrics in setting

Fabric shrinkage

Fabric shrinkage during processing is one of the most important factors affecting fabric mechanical properties. The amount of shrinkage that occurs during setting depends on both the method used and the amount of set imparted. The pure wool fabrics tested (Table 9.5) shrank little during stress setting (semi- or pressure decatizing) but by a larger amount during crabbing in boiling water (where the dimensions were only partially controlled) and even more during dyeing where the fabric was unconstrained. Overall shrinkage was least when the fabrics were heavily preset under constrained conditions, i.e. crabbing.

Table 9.5 Shrinkage during setting of loom-state wool fabric and subsequent dyeing

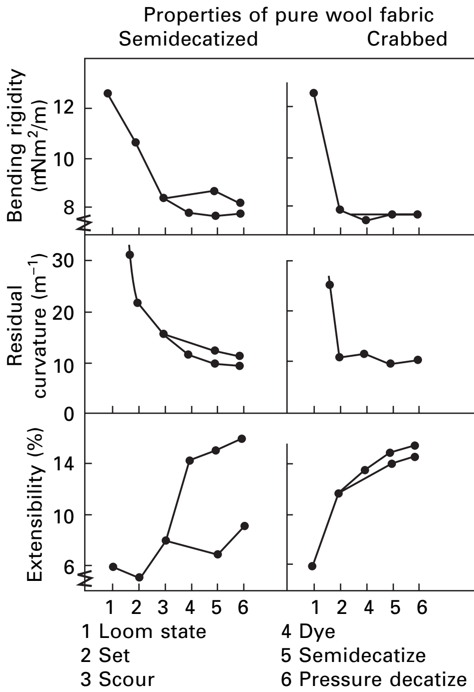
	Area shrinkage (%)[a]		
	Plain weave (A)	Hopsack (D)	Twill (E)
1. Semidecatize	0	1	0.5
2. Pressure decatize	2.2	2.5	1.9
3. Crab	6.9	5.7	6.2
Dyeing of 1	10.8 (14.0)	6.1 (9.6)	7.2 (10.3)
Dyeing of 2	7.3 (12.9)	4.0 (9.4)	5.0 (9.1)
Dyeing of 3	4.0 (11.1)	2.4 (9.0)	2.1 (8.0)

[a] Total shrinkage after dyeing is shown in parentheses.

Source: 'Objective assessment of the effect of setting processes on the properties of wool-containing fabrics', by A.G. DeBoos, F.J. Harigan and M.A. White, from *Proc. 2nd Australian–Japanese Bitaleral Science Tech. Symposium,* p. 318, 1983. Reproduced with permission from the Textile Machinery Society of Japan.

Bending properties

The greatest reduction in bending rigidity and residual curvature of the fabrics occurred in presetting and scouring (Fig. 9.6). Residual curvature depends on the frictional interaction between fibers in a fabric and measures the ability of the fabric to recover from the imposed strain. Treatments which



9.6 Changes in bending properties and extensibility of fabric A (plain weave wool) during processing. *Source*: 'Development of terminology to describe the hand-feel properties of paper and fabrics', by G.V Civille, and C.A Dos, from *Textile Research Journal,* vol. 5, pp. 10–32, 319, 1990. Reproduced with permission from *Textile Research Journal.*

reduce frictional interactions between fibers will reduce residual curvature in bending. The more effective the setting treatment, the greater was the change in bending rigidity and residual curvature. After dyeing, the fabric was completely relaxed whether or not it had been set in the loom state. However, where a mild setting treatment was used on the look-state yarn-dyed fabric (Fabric A), and this was followed by a mild scour and a mild final press, some differences in final bending properties were observed. The differences were minimized if the fabrics were subsequently set more effectively by pressure decatizing, implying that the initial mild treatments did not fully relax the fabric.

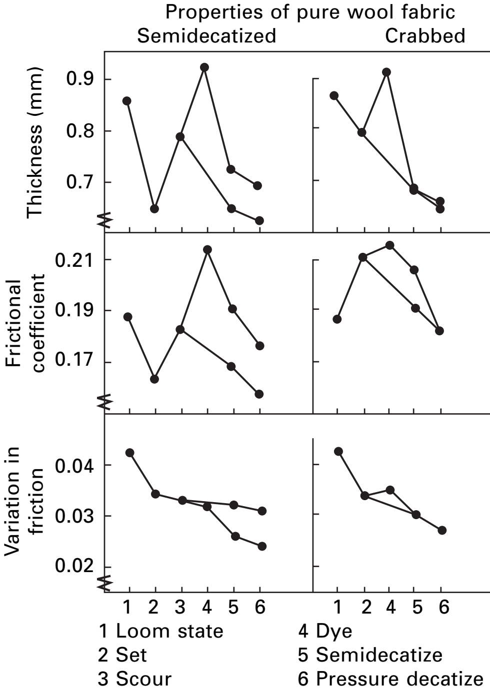
Fabric extensibility

Fabric extensibility is an important determinant of the making-up characteristics of worsted fabrics, particularly for men's suitings. Many garment manufacturers now impose limits on warp and weft extensibility of fabrics. Consequently, the changes in fabric extensibility that occur in finishing should be understood and monitored.

Piece-dyeing caused the greatest increase in the extensibility of the pure wool fabric. In large part, this was the result of the shrinkage that occurred during dyeing.

Fabric thickness

As expected, setting of wool fabrics constrained by a wrapper cloth (e.g. decatizing) reduced fabric thickness, whereas setting of unconstrained wool fabric (e.g. dyeing) increased fabric thickness (Fig. 9.7). Although setting operations during final pressing, including pressure decatizing, tended to reduce the difference in thickness between dyed and undyed fabrics (simulating piece and yarn- or top-dyed fabrics respectively), the latter remained thinner than piece-dyed fabrics. Pressing treatments vary considerably in their effect on fabric thickness but generally the more effective the setting treatments the thinner the resultant fabric.



9.7 Changes in thickness and surface properties of fabric A (plain weave wool) during processing. *Source*: 'Development of terminology to describe the hand-feel properties of paper and fabrics', by G.V Civille, and C.A Dos, from *Textile Research Journal,* vol. 5, pp. 10–32, 319, 1990. Reproduced with permission from *Textile Research Journal.*

Surface properties

When lightly preset wool was set unconstrained (e.g. piece dyeing), the frictional coefficient of the fabric surface increased substantially. Crabbing also increased surface friction but after piece dyeing the frictional coefficient was largely independent of the presetting method. The frictional coefficients of fabrics that were not dyed (as would be the case in yarn-dyed fabrics) were considerably less than those of the piece-dyed fabrics. Setting of wool in pressing operations reduced the coefficient of surface friction of fabrics, the greater reduction resulting from the more effective setting treatments. Previous studies have shown excellent correlation between fabric thickness and the coefficient of surface friction.

The variation in the frictional force is important in determining fabric hand. This property has a large effect on fabric smoothness (*numeri*) [3] which is an important determinant of the overall hand of winter weight fabrics. The variation in surface friction was reduced by steam pressing operations, particularly on piece-dyed fabrics. After final pressing the variability of surface friction of dyed (or crabbed) fabric was significantly less than that of the equivalent undyed fabrics.

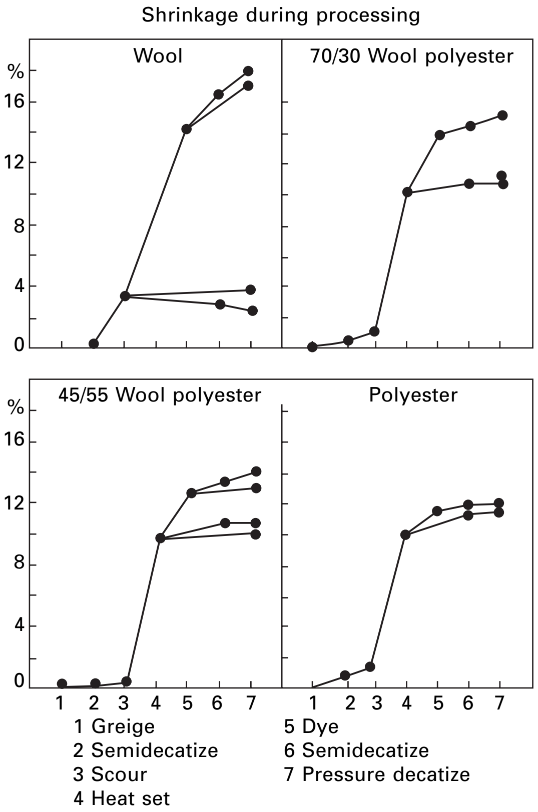
Results: changes in the properties of wool-polyester blends

Unlike pure wool fabrics, wool-polyester blend fabrics are normally heat set, usually before dyeing and sometimes in the loom state. Top- and yarn-dyed fabrics are also heat set and the operation, which sets only the polyester component, improves the wrinkle recovery and flat stability of the blend fabric. Although blend fabrics tend to shrink during heat setting, in a stenter positive dimensional control of the fabric is possible and shrinkage can be controlled or minimized. By controlling shrinkage during heat setting, the finisher can control the weight of the fabric but at the same time will modify the fabric mechanical properties.

The effect of the various setting operations on the shrinkage and mechanical and physical properties of a 70/30 wool-polyester blend fabric is shown in Figs 9.8 and 9.9. Fabric shrinkage occurred primarily in the heat setting operation for the polyester bled fabrics as opposed to dyeing for pure wool cloth. Minimal warp and weft tension was applied to the fabric so that shrinkage was not impeded.

Bending properties

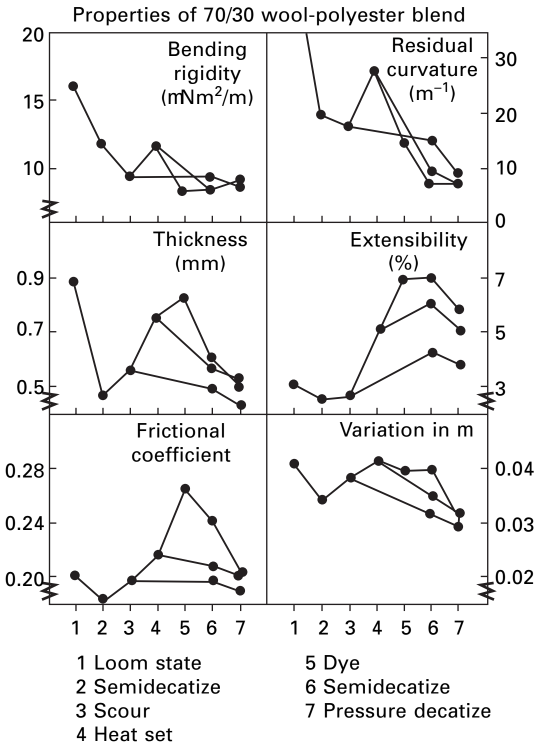
Heat setting increased the fabric bending rigidity and residual curvature in bending (Figure 9.9). This increased stiffness has been attributed to the formation of spot welds between the rubbery surfaces of the fibers. Subsequent



9.8 Shrinkage during processing of wool and blend fabrics (A, B, C, F). *Source*: 'Development of terminology to describe the hand-feel properties of paper and fabrics', by G.V Civille, and C.A Dos, from *Textile Research Journal,* vol. 5, pp. 10–32, 319, 1990. Reproduced with permission from *Textile Research Journal.*

dyeing or pressing removed the effect and it was presumed that the welds are destroyed by mechanical action during dyeing and pressing. However, the increase in stiffness was most readily observed in blend fabrics rather than in a filament polyester fabric. Increased frictional interaction between wool and polyester fibers occurring as result of dimensional changes in the polyester fibers would produce similar effects and may provide a simpler explanation of the observed phenomena. Heat setting had little effect on the ultimate bending rigidity of the pressed fabric, especially after pressure decatizing.

As with pure wool fabrics, the bending properties of wool-polyester blend fabrics may be modified by variations in the final pressing procedure [4]. Again these effects are small compared to the overall changes in bending properties that occur in processing.



9.9 Change in mechanical properties of fabric B (plain weave 70/30 blend) during processing. *Source*: 'Development of terminology to describe the hand-feel properties of paper and fabrics', by G.V Civille, and C.A Dos, from *Textile Research Journal,* vol. 5, pp. 10–32, 319, 1990. Reproduced with permission from *Textile Research Journal.*

Fabric thickness

As in the treatment of pure wool fabrics, setting of constrained fabrics reduced thickness whereas setting of the unconstrained fabric increased thickness. Heat setting under minimal tension had the greatest effect on thickness and, whereas dyeing produced further increases, the additional effect was lost when the fabric was pressed. Omission of both heat setting and dyeing produced a thinner fabric, presumably because shrinkage during processing was reduced.

Fabric extensibility

As with pure wool fabrics, the extensibility of blends is important in determining the tailorability of the fabric. In blends, the behavior of both fibers is important in determining the subsequent extensibility of the fabric.

Heat setting and dyeing both increased the extensibility of the 70/30 wool polyester blend fabrics, again, in part, reflecting the shrinkage that occurred during these setting operations. Where shrinkage was prevented during heat setting, fabric extensibility was not as great.

Surface properties

Heat setting and, more particularly, dyeing increased the coefficient of surface friction in the fabrics. After final pressing the surface friction of fabric that had been heat set and dyed remained greater than that in which both of these operations were omitted (Fig. 9.9). Similarly, heat setting increased the variability of the frictional force. Pressure decatizing in final processing removed the differences between the variously processed fabrics.

9.3.3 Denier reduction

Polyester fibers are subject to hydrolysis in hot caustic solutions. Under severe conditions, the fiber will dissolve. Because the fiber is hydrophobic and resists the penetration of aqueous solution into its structure, the hydrolysis reaction occurs at the fiber surface and works inward toward the core. Under controlled condition, this phenomenon can be used advantageously to impart desirable properties to 100% polyester fabrics. First of all, the hydrolyzed fiber surface will become more hydrophilic and result in a fabric with better wetting characteristics. Secondly, the weight of the fabric is reduced and the diameter of the fiber cross-section becomes smaller, thus the term denier reduction. The net result is finer, more flexible fibers under less physical constraint. This gives rise to more pleasing fabric that has a soft and silky hand. The process conditions are selected to achieve a targeted weight reduction because strength loss will accompany weight loss.

9.3.4 Mercerizing

Mercerizing is the treatment of cotton fabrics with concentrated sodium hydroxide. The treatment usually follows bleaching and profoundly changes fiber properties. The fiber swells and the cross-sectional shape changes from collapsed to round. The round cross-section is retained after the caustic is rinsed away. Mercerized fabrics become more water absorbent and easier to dye and give a greater color yield per unit of dye. Additionally, the round cross-section improves fabric luster, giving it a silk-like sheen. Liquid ammonia mercerization will create similar effects to cotton fibers, but not to the same degree as caustic solutions.

9.3.5 Wool shrink resist

Scales on the surface of wool fibers are the cause of felting shrinkage. The surface scales allow the fibers to slip in only one direction when wool fabrics are washed. Under the mechanical action of washing, this one-way slippage causes the fabric to felt or compact. It shrinks in width and length and grows in thickness. To prevent this, shrink resist treatments alter the scale structure and smooth the surface. This is done either by chemically removing the scales or by covering them with a polymeric coating.

9.3.6 Garment wet processing

Garment wet processing has become a well-established process for creating a wide range of garments with unique and desirable properties. For example, it is ideal for pre-shrinking garments. It can create a washed-down look and produce a garment that is soft and pliable. It can start with undyed garments and end up with dyed, fully finished and shaped garments. Garment processing fits well with the 'just-in-time' delivery concept of supply and is an economical way of producing small lots on a timely basis.

Garment wet processing as a fully fledged manufacturing process blossomed with the introduction of stone-washed denim. Prior to this, it was used to dye and finish items such as full-fashioned sweaters, hosiery and socks. Traditional indigo-dyed denim jeans were one of the staples in work clothing. The qualities of ruggedness, toughness and durability were requirements, and fabric weight, bulk and stiffness were equated to better quality. It was common practice to finish denim with 15% starch and then run it through a Sanforizer to reduce wash shrinkage. The consumer was aware that in use, initial color would fade and the starch hand would soften when the garment was washed repeatedly. The consumer accepted this because the garment became softer and more pliable, therefore more comfortable. Attempts to market jeans with colorfast dyes failed because they did not match the consumer's perception of quality – the worn faded look. In fact, the more faded and worn the garment became, the more the consumer prized its comfort quality.

Historical lore has it that the idea for pre-washed denim arose from a mill trying to salvage rolls of warehoused fabric that had become water damaged and mildewed. Attempts to salvage the goods by wet processing with chlorine bleach effectively removed the mildew; however, it also removed the starch, and the bleach caused the indigo dye to fade in a random, streaky pattern. Samples were shown to the marketplace and the idea became an immediate hit, appealing to both consumers and fashion designers. The original mill wash-down process was difficult to reproduce, so the idea of washing the garments in an industrial washing machine was pursued. Many developments followed in an effort to reproduce the wash-down effect. Among some of the procedures tried were stone wash, acid wash, enzyme wash, chlorine bleach, permanganate bleach and more. Each set of conditions produced uniquely different effects, giving designers a broad menu of washed-down effects from which to choose.

The rise of the casual look, driven by the desire for comfort, extended the range of garments amenable for garment washing. The wrinkled look of pure finished 100% cotton garments became the fashion rage and this quality could only be accomplished by garment laundering. Garments coming out of the dryer were softer, more pliable and somewhat faded in color. Garment wet processing was further broadened to include a dye cycle. As with all fads, public taste changes and the desire for the neat look, i.e. freshly pressed garments, became the next fashion rage. The garment wet processing cycle was eventually expanded to encompass the entire process of desizing, scouring, bleaching, dyeing and finishing by starting with undyed garments. The finishing step required the use of the same finishing chemicals as were applied at the mill, so machine modifications were necessary to control the add-on and to ensure even distribution of chemicals over the entire load. Also the drying step required careful control to prevent finish migration.

How does garment wet processing affect fabric hand? The major contribution is pre-shrinking the garment. This allows the finisher to reduce the amounts of chemicals needed to give shape retention. Less cross-linking equates to better retention of physical properties, therefore bringing 100% cotton into the wrinkle-free arena. The relaxed state of the fabric plus added softeners results in softer, more pliable and more comfortable garments.

9.4 Literature review

9.4.1 Enzyme finishing

Cellulase treatment is commonly used to improve the hand of cotton fabrics and is one of the most important processes in fabric manufacturing.

Cellulase enzymes will hydrolyze cellulose fibers and cause weight loss and alter fabric hand. These treatments also remove surface hairs and pills, making the surface smoother. Mori *et al.* [6] used the KES system to evaluate the effect of cellulase hydrolysis of seven cotton fabrics. The induced weight loss was approximately 5%. This study confirmed that the hydrolysis of the cotton fabric by cellulase took place in the interior of the fibers. Changes in primary hand qualities were the same silk-like trends shown by a polyester filament fabric treated with sodium hydroxide.

Experimental

Commercially available fabrics were scoured and bleached in a conventional technical manner. No differences were detected in the surfaces of the cotton fibers through SEM observation. The amount of damage caused, especially by bleaching, was almost the same for all the cottons used. Additionally, the materials were washed with an aqueous solution of 0.2% nonionic surfactant at 40°C and then rinsed several times with pure water. The original fabric characteristics after washing are summarized in Table 9.6.

Cellulase treatment occurred in a 0.2% (v/v) aqueous solution at a temperature of 40°C, a liquor to-sample ratio of 1:100, and a pH of 4.5. Alkali treatment involved a 10% (w/v) aqueous sodium hydroxide solution at 60°C. Strokes were 3.5 cm at 82 rpm for both treatments. Weight loss was obtained from weights before and after cellulase and alkali treatments. Weight loss and treatment time for each treatment are also shown in Table 9.6.

Fabric properties were measured with a KES-FB instrument (Kato Tech Co.). Property definitions and measurement conditions based on KES are listed in Table 9.7.

Bending rigidity B and shear rigidity G represent the elastic components. In contrast, hysteresis of bending moment 2HB and hysteresis of shear force 2HG and 2HG5 represent the inelastic components of the properties.

Residual curvature is defined as 2HB/B and is the equivalent of deformation at zero fabric bending moment. Also, residual shear strains of 2HG/G and 2HG5/G represent the extent to which a fabric recovers from shear deformation. 2HG at a smaller shear angle than 2HG5, as described in Table 9.7, was also measured.

Results and discussion

Comparing cottons and polyester

Cellulase treatment of the cotton fabrics and alkali treatment of the polyester staple fabric decreased both the bending rigidity and the hysteresis of the bending moment. Figure 9.10 shows that the decrease in residual curvature of the polyester fabric following alkali treatment was more marked than that of the cotton fabrics following cellulase treatment in both warp and weft measurements, ragardless of the cotton weave structures.

Positive changes in residual curvature appeared in the shirting

Change in elongation measured at 5 N/cm based on KES [7] might be a useful indication of fabric relaxation caused by the treatments. Relaxation during the treatments is thought to cause fiber entanglement, which is one factor influencing residual curvature. The average change in elongation of the seven cotton fabrics was 16.7% for the warp measurement and 11.5% for the weft measurement. The average value of the elongation change of the warp in the cottons was much smaller than the warp elongation change in the

Table 9.6 Characteristics of the staple used. Cotton and polyester fabrics were treated with cellulase and sodium chloride, respectively, for treatment times given

No.	Fabric	Fiber	Weave	Weight loss (%)	Treatment time (hours)	Density (cm^{-1})		Count (tex)		Mass/area (g/m^2)
						Ends	Picks	Warp	Weft	
1	Broadcloth (40/1)	Cotton	Plain	6.5	5.00	54	27	14	14	121
2	Broadcloth (100/2)	Cotton	Plain	6.2	4.50	61	30	12	11	118
3	Sateen (1)[a]	Cotton	Satin	4.8	4.50	36	52	14	14	130
4	Sateen (2)[b]	Cotton	Satin	6.7	4.25	70	44	9	10	119
5	Shirting	Cotton	Plain	5.0	1.00	31	26	19	18	108
7	Muslin	Cotton	Plain	6.0	2.38	31	27	17	19	112
8	Sarashi[c]	Cotton	Plain	6.5	3.08	20	20	28	29	118
9	Muslin	Polyester	Plain	4.5	1.50	28	26	30	31	158

[a] 5 Harness (5 picks, base of 2).

[b] Harness (8 picks, base of 3).

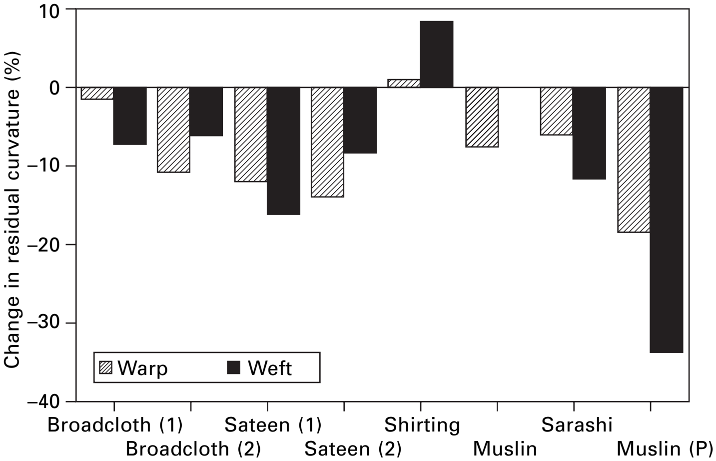
[c] Japanese traditional fabric.

Source: 'Mechanical properties and fabric hand of action fabrics subjected to cellulose treatment', by R. Man, T. Haga and T. Takagishi, from *Journal of the Society of Fiber Science and Technology*, Japan, vol. 55, no. 10, p. 488, 1999. Reproduced with permission from the Society of Fiber Science and Technology, Japan.

Table 9.7 Definition of properties, parameters and measuring conditions based on KES

Property	Abbreviation	Description	Measuring conditions
Bending	B	Bending rigidity obtained from linearity between curvature and bending moment	Pure bending, bending rate, 0.5 cm^{-1}/s
	2HB	hysteresis of bending moment at ± 0.5 cm^{-1} of curvature	Maximum curvature + 2.5 cm, sample size (W ¥ L) 20 ¥ 1 cm
Shear	G	Shear rigidity obtained from linearity between shear deformation and shear force	Shear deformation, shearing rate 0.417 mm/s
	2HG	Hysteresis of shear force at 8.7 mrad	Maximum shear angle ± 40 mrad
	2HG5	Hysteresis of shear force at 87 mrad	Tension on sample 0.1 N/cm, sample size (W ¥ L) 20 ¥ 5 cm

Source: 'Mechanical properties and fabric hand of action fabrics subjected to cellulose treatment', by R. Mari, T. Haga and T. Takagishi, from *Journal of the Society of Fiber Science and Technology*, Japan, vol. 55, no. 10, p. 488, 1999. Reproduced with permission from the Society of Fiber Science and Technology, Japan.



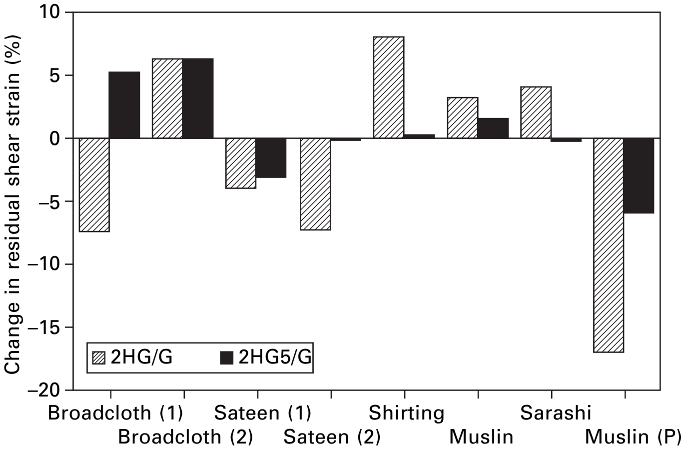
9.10 Percent change in residual curvature for cottons treated with cellulase and polyester staple fabric treated with sodium hydroxide. Muslin (P) means muslin woven of polyester staple fibers (no. 9 in Table 9.6). *Source*: 'Bending and shear properties of cotton fabrics subjected to cellulase treatment', by R. Mori, T. Haga and T. Takagishi, from *Textile Research Journal,* vol. 69, no. 10, 1999. Copyright Sage Publications.

polyester (130%), but the average value of the weft change was comparable to that of the polyester (10.5%). Thus, the work suggests that the residual curvature of the polyester is reduced to a greater extent than that of the cottons as a result of the treatments, especially in the weft direction, as shown in Fig. 9.10.

Shear rigidity and hysteresis of shear force, as well as bending rigidity and hysteresis of bending moment, of all fabrics tested decreased with the respective treatments. Because of the comparable extent of presumed relaxation in the weft direction between the cellulase and alkali treatments, we focused on the residual shear strain of 2HG/G and 2HG5/G in the weft measurements, as displayed in Fig. 9.11. The polyester fabric exhibited the most extensive decrease in residual shear strain of both 2HG/G and 2HG5/G for all fabrics tested. The cotton fabrics displayed positive or small negative changes in residual shear strain.

The reduction in fiber fineness caused by the treatments is thought to have contributed more strongly to the decreased residual shear strain than the decreased residual curvature, because the maximum deformation of the fibers is smaller for the shear measurement than for the bending measurement in KES.

The reduction in frictional force accompanied by the reduction in fiber fineness might enhance recovery from shear deformation and lessen the inelastic shear component of the shear property. Nevertheless an increase in residual shear strain was observed for several cellulase-treated cotton fabrics



9.11 Percent change in residual shear strain in weft measurements for cottons treated with cellulase and polyester treated sodium hydroxide. 2HG/G and 2HG5/G are residual shear strain introduced at 8.7 mrad and 87 mrad, respectively. Muslin (P) means muslin woven of polyester staple fibers (no. 9 in Table 9.6). *Source*: 'Bending and shear properties of cotton fabrics subjected to cellulase treatment', by R. Mori, T. Haga and T. Takagishi, from *Textile Research Journal,* vol. 69, no. 10, 1999. Copyright Sage Publications.

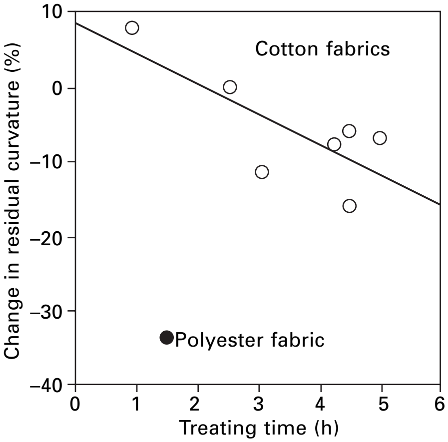
in both 2HG/G and 2HG5/G. The change in residual shear strain was consistent with the fact that the hydrolysis of the cotton fibers took place not only on the fiber surface, but also in the interior of the fibers.

Bending strongly depends on fiber properties. The cellulase treatment weakened the cotton fibers and caused a decrease in both the elastic and inelastic components of bending. However, the inelastic component of hysteresis of the bending moment did not decrease to as great an extent as the elastic component of bending rigidity, due to the degradation within the cotton fibers during cellulase treatment. Because of this internal degradation, the decrease in residual curvature of the cotton fabrics was smaller than that of the polyester fibers, where hydrolysis by alkali treatment took place only on the fiber surface.

Effect of fabric construction on properties

The changes in residual curvature and residual shear strain induced by cellulase treatment are possibly influenced by the original fabric characteristics (Table 9.6). Numerical values were set of 1 and 2 for plain and sateen weaves, respectively, in order to make single correlation analyses for the other quantitative factors. The analyses demonstrated that residual curvature in weft measurement was significantly related to two factors, treatment time and mass/area, at a confidence level of over 95%.

The relationship between residual curvature and treatment time for the cotton fabrics was linear, as shown in Fig. 9.12. In contrast, the relationship between residual curvature and mass/area for the cotton fabrics was described better by an elliptical curve (Fig. 9.13).



9.12 Changes in residual curvature in weft measurements plotted against treatment time for cottons and polyester treated with aqueous cellulase and sodium chloride solutions, respectively. A linear equation is optimized for the plots of the cottons. *Source*: 'Bending and shear properties of cotton fabrics subjected to cellulase treatment', by R. Mori, T. Haga and T. Takagishi, from *Textile Research Journal,* vol. 69, no. 10, 1999. Copyright Sage Publications.

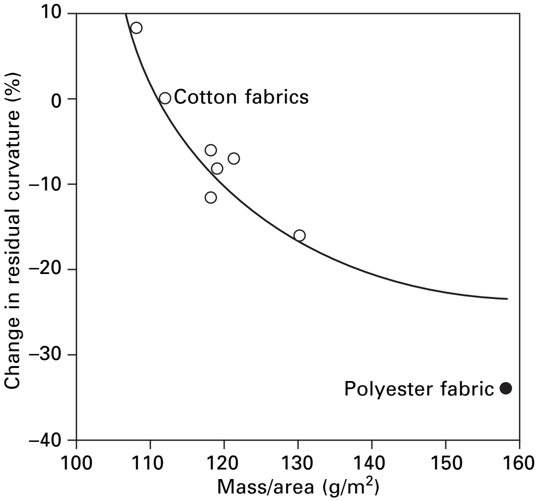
The change in residual curvature in the weft direction for the cottons decreased as expected with both treatment time and mass/area. This was because relaxation increased with treatment time, and larger fiber density worked more efficiently to decrease residual curvature.

Given the treatment time for the polyester fabric, the decrease in residual curvature in the weft measurement was much smaller for the cotton fabrics than for the polyester. In addition, the decrease in residual curvature in the weft direction of the cotton fabrics was definitely smaller compared to that of the polyester at the mass/area given by the polyester.

These results suggest that the reduction in the inelastic component is less marked for the cotton fabrics than for the polyester when considering both bending and shear properties.

Conclusions

The cotton fabrics treated with cellulase have a tendency to decrease to a lesser extent in residual curvature and residual shear strain than does a polyester staple fabric treated with alkali, especially in the weft direction.



9.13 Changes in residual curvature in weft measurements plotted against treatment time for cottons and polyester treated with aqueous cellulase and sodium chloride solutions, respectively. An elliptical equation is optimized for the plots of the cottons.
Source: 'Bending and shear properties of cotton fabrics subjected to cellulase treatment', by R. Mori, T. Haga and T. Takagishi, from *Textile Research Journal,* vol. 69, no. 10, 1999. Copyright Sage Publications.

The inelastic component is reduced less efficiently for the cotton fabrics than for the polyester in bending and shear properties, because the hydrolysis of the cotton fabrics with cellulase takes place, not only on the fiber surface, but also within the fiber. In contrast, the hydrolysis of the polyester fabric takes place only on the fiber surface. Residual curvature in weft direction of the cotton fabrics decreases with increasing treatment time and mass/area less efficiently than that of the polyester. This is consistent with the fact that the inner structure of the cotton fibers is degraded by cellulase treatment.

Karimde *et al.* [8] subjected fabrics made from cuprammonium rayon fabrics to cellulose enzymatic hydrolysis. Variations in time, processing condition (immersion versus pad-roll) and temperature yielded varying degrees of hydrolysis. The physical properties decreased with increase in hydrolysis. A 10% hydrolyzed fabric by the immersion process and a 15% hydrolyzed fabric by the pad-roll process gave the silkiest hand. Kumar and Harnden [9] studied the performance of various cellulase enzymes in garment processing of Tencel and its blend with cotton and linen. Marked differences in hand were observed between whole cellulase and engineered component cellulases and were directly related to the enzyme composition. Mechanical action from the garment processing equipment played a more significant role in removing the fibrillation overriding the effect of the enzyme composition.

Chikkodi and Khan Sand Mehta [10] studied the effect of biofinishing on cotton/wool-blended fabric. Both cellulase and protease enzymes were applied. The enzyme treatment reduced protruding fibers and had a significant effect on physical and aesthetic properties of the blended fabrics. Chattopadhyay *et al.* [11] finished pure jute fabrics with cellulase enzyme and analyzed the changes in fabric hand by the KES system. It was observed that the treatment caused considerable reduction in protruding surface hairs and improvement of fabric hand. The total hand value increased more than 15%.

9.4.2 Bleaching and mercerization

Kotakemori *et al.* [12] evaluated the hand of cotton weaves treated by enzyme bleaching agents. A mixture of horseradish peroxidase and hydrogen peroxide bleaching system reduced hairiness and protected the disordering of intra-yarn, reflecting the high performance of handle values. Wakida *et al.* [13] compared mercerizing desized, scoured ramie fabric with liquid ammonia and sodium hydroxide. Initial dyeing rate was increased with NaOH but greatly decreased with NH_3. As a measure of hand evaluated with KES, shearing modulus and bending modulus were decreased by the NH_3 treatments. Ohshima *et al.* [14] used the KES system to evaluate the effect of high pressure steaming on the hand of cellulose fabrics. Shearing and bending parameters decreased by high pressure steaming except for cotton, concluding that high pressure steaming is effective to improve hand as well as washing shrinkage.

9.4.3 Wool and silk

Marmer *et al.* [15] evaluated the fabric hand of worsted challis fabrics after oxidative/reductive bleaching using the KES system. This study showed greater softness, flexibility and smooth feeling for the two-step process. Karakawa *et al.* [16] compared the hand of fabric made from wool top sliver that had been shrink-resist processed. Ozone verses persulfate oxidation continuous processes were compared. The treated fabric hand and fiber friction were generally the same as for the untreated control fabrics. Jian and Yuan [17] used the KES system to measure the effect of low temperature plasma on the hand of treated wool fabrics. Kim *et al.* [18] investigated the garment performance and mechanical properties of thin worsted fabrics under various wet processing conditions and finishing processes. The effect of rope scouring in wet finishing and pressing and of decatizing in dry finishing on crease recovery, formability, drape and hand were studied. The hand of fabrics processed on semi decators showed better results than on pressing machines. Chopra *et al.* [19] used the KES system to evaluate silk fabrics degummed by different methods. Methods utilizing soap, alkali or triethyl amine scored over acid and enzyme in terms of handle properties.

9.4.4 Finishing

Oh [20] studied various methods to achieve the optimum balance of improved wrinkle recovery of ramie fabrics without losses of mechanical properties and with improved hand. Pre-mercerization and two techniques of applying DP treatment – pad-dry-cure and wet-fixation – were investigated. The contribution of silicone softeners was also explored. The results showed that the wet-fixation process provided a better balance of DP performance versus losses in mechanical properties. This was attributed to the difference in distribution of the resin monomer. Wet fixation promoted better diffusion of the reactant into the fiber interior, resulting in a structure with better stress distribution and a more pliable hand. Furthermore, the inclusion of a silicone softener in the pad-dry-cure method enhanced wrinkle recovery of the ramie fabric with a significant improvement in strength retention as well as a softer hand.

Castelvetro *et al.* [21] evaluated fluorochemical latices such as water and oil-repellent finishes. Three fluoropolymer latices were applied by pad-dry-cure to wool, cotton and polyester fabrics and their performance evaluated for water repellence, oil repellence, fabric hand and mechanical properties. The fluorinated coating did not significantly alter the fabric hand. Czech *et al.* [22] presented data comparing the performance of finish formulations based on fluorocarbon soil release finishes and various types of silicones. The silicone softener contained both amino and hydrophilic moieties and provided substantially improved fabric hand without degrading the soil release properties provided by the fluorochemical treatment. Kim *et al.* [23] evaluated instrumental methods for measuring the surface frictional properties of six fabrics finished with different softeners. Two evaluations were quantitative, based on the KES system, and the third was a human panel evaluation. Statistical analysis of the results showed that the fabric-on-fabric probe provided a superior discrimination in surface frictional behavior compared to the standard probe or the human panel.

Robinson *et al.* [24] reported the influence of pattern design and fabric type on the hand characteristics of pigment prints. Two cotton fabrics printed with two pigment types in six designs were analyzed by a trained descriptive panel to evaluate the effects of pattern design, color and fabric type on 17 hand characteristics. Results showed that fabric and pigment type had a greater influence on hand characteristics than did the design of the print. Pattern design had a significant influence on eight of the 17 hand components. These results were reported earlier in the chapter. Anon [25] investigated the effect of softeners in pigment printing. Two softeners – one based on fatty esters and the other based on silicone microemulsion – were evaluated. The softener based on a silicone microemulsion provided more stable films with improved elasticity, which reflected in fabric hand.

Barndt *et al.* [26] evaluated the effect of silicone finishes on 100% cotton denim for softness using both the KES system and a hand panel. The KES descriptors were capable of distinguishing small changes in fabric hand and the values correlated well with the hand panel ratings. The study showed that only one or two of the 16 KES fabric mechanical properties were necessary to accurately describe the effects of the finishes on fabric. Lautenschlager *et al.* [27] explored the structure activity relationship between the arrangement of pendant aminofunctional side change in silicone finishes and finish response such as hand, whiteness, water absorbency and soil release. Dramatic effects were observed, suggesting that optimizing the aminofunctional side chain could lead to a substantially improved finish.

Beal *et al.* [28] studied the sorption of a cationic surfactant, distearyl dimethyl ammonium bromide onto fabrics made of 100% cotton, 100% polyester, and a 50/50 cotton/polyester blend with and without functional finishes. Finishes chosen were a DMDHEU durable press finish and a polyacrylic acid soil release finish. The results showed that unfinished 100% cotton picked up more softener than did unfinished 100% polyester. DMDHEU finished fabrics picked up less than their corresponding untreated controls. The polyacrylic acid finished fabrics picked up more softener than the unfinished controls. Perceived fabric softness was generally improved for all cationic softened test fabrics. Both 100% cotton and 50/50 cotton/polyester fabrics finished with DMDHEU durable press finish were perceived to be less soft than their unfinished counterparts; however, sorption of the cationic softener onto the DP finished fabrics restored the softness level back to that of the unfinished fabrics. The stiffness of both cotton and polyester fabrics was greatly increased by the acrylic finish. Even the presence of large amounts of softener did not restore the softness ratings to levels comparable to the unfinished controls.

Paek [29] evaluated the fabric hand and absorbency of three types of children's flame-retardant sleepwear fabrics. Fabric hand was determined by measurements of flexural rigidity, coefficient of friction and compactness and subjective hand ratings by a test panel. The analysis of response profile indicated that roughness and openness was preferred to smoothness and compactness for the sleepwear fabrics evaluated. Absorbency was mainly influenced by fiber content and not by the flame retardant finishes or additives. Mukhopadhyay [30] measured the general characteristics of eight fabric groups divided by fiber content, fabric construction and special finishing treatment by the KES-F system. Using silk as a reference, caustic-reduced polyester fabrics exhibited strong silk-like characteristics except in their surface properties. Liquid ammonia-treated cotton fabrics also possessed a certain silky hand. Micro-fiber fabrics are soft and smooth but do not have the high *kishimi* hand typical of silk fabrics. Fabric construction has some influence on fabric stiffness, but not on hysteresis. Polyester lining fabrics have high bending stiffness and polyester/cotton fabrics have very high shear stiffness and hysteresis. These two groups are the least silk-like. Shear properties and bending hysteresis appear to be the most important factors affecting the hand of the fabrics studied. Matsudaira and Matsui [31] followed the changes of mechanical properties and fabric hand of polyester fabrics through wet processing and the finishing stages using the KES system. Relax processing, including desizing, shrinking and denier reduction, softened the polyester fabric in all its mechanical properties and fabric hand. The weight reduction stage, because of the effective gap between fibers, was largely responsible for the increase in softness. However, the effects of dyeing and raising were small.

Csiszár and Somlai [32] characterized the hand and mechanical properties of linen, cotton/linen and polyester/linen blends taken step by step from greige fabric through final finishing. Combinations of chemical–mechanical and enzymatic–chemical–mechanical finishing technologies were used. The most noticeable effect on hand was obtained on 100% linen fabric, which was the stiffest of the three. Physical test results indicated that the major contributor to fabric softness was mainly due to mechanical treatment and not enzymatic or chemical finishing. However subjective assessment indicated that the enzymatic treatment within the applied finishing line resulted in fabrics with better appearance and luxurious hand.

9.5 Future trends

The trend of producing textiles in low-wage-labor countries has changed the responsibilities of the parties along the supply chain. The retailers must assume the responsibility not only for creating new products, but also for sourcing and quality assurance. The technical support once provided by the domestic manufacturers involved in vertical manufacturing is shrinking as jobs flow to low-wage countries. The retailers must now turn to their global suppliers, upgrade their technical staff or contract the work out to a third party. It was one thing when all parties in the vertical chain were in close proximity. Now it is a new game and to work effectively, information must be transmitted in unambiguous terms. When it comes to fabric hand, subjective descriptors are fraught with language translation and individual interpretation, so it becomes important to factor out the human element and develop reliable methods for accurately quantifying hand properties. The information also must be in a universal language and formatted in a form that can be transmitted electronically.

A good example of this is management of fabric color. Traditionally, the human eye was used to evaluate color. All decisions and communications were based on these evaluations. Color science has advanced to the point where the attributes that describe color can be measured by a spectrophotometer.

Software has been developed that allows the use of this information for all aspects of color management, and for communicating this information electronically. It has taken many years to get the technology to this stage; however, it has reached a state of maturity that allows it to be quickly implemented as globalization becomes more widespread.

Another trend on the horizon is the potential rise of businesses aimed at niche markets. Fashion, fads and new products are as important as price in satisfying consumer needs. The void created by the disappearance of the traditional domestic manufacturers creates an opportunity for creative individuals to step in.

9.6 Sources of further information and advice

Additional information regarding the chemistry of the finishes discussed in this chapter can be found in Tomasino [33]. This book provides a review of the chemistry and technology of fabric preparation and finishing. Vigo [34] provides details on textile processing and properties, and Lewin and Sello [35] delve deeply into functional finishes. Product bulletins provided by suppliers of chemical auxiliaries are another good source of information. A compilation of products and suppliers can be found in the annual buyers' guide edition of the *AATCC Review*.

The constant flow of new products to the retailers' shelves is the lifeblood of the textile industry. Fashion designers and product developers are the ones who initiate this flow. Since the hand of the final fabric largely depends on the starting greige fabric, factors discussed in other parts of this book, such as fiber, yarn and fabric construction, have a profound influence on the final hand. Usually fabric designers are concerned with manufacturing the greige fabric and give little or no thought to what happens in wet processing. While the finisher does have some tools at his disposal to fine tune the hand, they may not be enough to satisfy the fashion designer. If there is a specific hand target in mind, the fabric designer and the finisher should work together. Having a greige construction that can accommodate the changes that occur in dyeing and finishing is the best approach. Therefore as advice, the designer, greige manufacturer and finisher must work together at the onset stage rather than in isolation.

Further information can be obtained from References 37–44.

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10

Effect of mechanical finishing on fabric hand

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10.1 Introduction

Mechanical finishing is defined as the use of mechanical devices to manipulate fabrics to enhance their functional and aesthetic properties [1]. Herard [2] has referred to mechanical finishing as 'yesterday's finishing techniques applied to today's fabrics'. It has also been stated [6] that mechanical finishing is not an exact practice, but in many ways an art. It takes skilled operators to control the operating parameters to compensate for equipment wear to produce finished goods with consistent quality. The term 'surface finishing' is also used to describe the effect produced by some of the devices. This chapter will describe the mechanical devices, what they do and how the tactile properties and appearance are altered. Topics included in this chapter are calendering, compacting, napping, sueding, shearing, polishing and pressing.

10.2 Calendering

Calendering by definition is mechanical finishing processes for fabrics or webs to produce special effects such as luster, cover, glaze, moiré, Schreiner and embossed patterns [6]. Fabrics are compressed between two or more rolls under controlled conditions of time, temperature and pressure. A calender is a machine consisting of two or more massive rolls compressed against each other by means of hydraulic cylinders applying pressure at the journals. One roll is considered the pattern roll and is responsible for the finished appearance of the fabric, while the other roll (the filled roll) serves as pressure back-up for the pattern roll and also to transport fabric through the machine.

There are many types of calenders, each designed to impart specific effects to cloth. The composition of the rolls, number of passes, temperature control, moisture control and pressure can vary to fit the desired effect. For example, the pattern roll can be engraved to emboss a three-dimensional pattern into the fabric. The engravings can be shallow or deep depending on the desired effect. The pattern roll can be smooth, made of steel or nylon, to give the fabric a high luster and sheen. The backing rolls can be made from corn husks, kraft paper, or hard or soft rubber, and deform to receive the pressure of the pattern roll. In calendering, the yarns are flattened and become more oval in shape. This causes them to spread in two dimensions, closing up the fabric structure and leaving less open spaces between the yarn crossovers. The surface becomes smoother and more lustrous and the fabric becomes thinner and more compact. The reason fabrics are calendered is to improve aesthetics. The major fabric changes are reduced fabric thickness, increased fabric luster, increased fabric cover, smooth silky surface feel, reduced air porosity and reduced yarn slippage.

10.2.1 Types of calenders

Rolling calender

The function of a rolling calender is to provide a smooth or glossy fabric surface as well as to improve hand. It is used on all types of cloth but is predominately used on woven fabrics or cotton knits. Normally rolling calenders consist of three rolls with alternate steel and filled backing rolls. The filled backing rolls can be of wool felt paper, cotton, resilient wool and cotton blends. There are others that may contain two, four or five rolls to accommodate multiple pressing in a single run through the machine. The nip pressures are very high and can range from 300 to 500 PLI kg per linear cm. When required, the steel roll can be heated by gas, hot oil, electricity or steam up to 210°C.

Silk finishing calender

The main function of a silk finishing calender is to provide a smooth fabric surface with improved hand and light luster. It can be used on all types of fabrics but is used mostly for high content cotton and coated or impregnated webs. The silk finishing calender has a three-roll configuration with a top and bottom filled roll and a steel middle roll. The filled rolls are made from cotton/wool blends. The main steel roll can be heated by gas or steam to a surface temperature of 177°C. The nip pressure is 80–139 kg/cm compared to the 300–500 kg/cm linear for roller calenders. The major difference between the rolling calender and the silk finishing calender is the lower nip pressure. This parameter is responsible for the lighter surface luster and fabric silk-like hand.

Friction calender

The main function of a friction calender is to polish fabric surfaces to a very high gloss or to reduce the porosity of the fabric to the minimum. The ‘down proofness' and 'water resistance' of a fabric are greatly enhanced by friction calendering. Accordingly, the fabric hand becomes stiffer and crisp. The calender is used on woven fabrics of cotton or linen and these fabrics must be very strong to withstand tremendous tension in the calendering nip. The friction calender is a three-roll design with the intermediate roll filled with heat resistant cotton. The top roll is the polishing roll and is driven faster than the support rolls at speed differentials ranging from 5% to 100%. The line speed of the fabric traveling through the calender is determined by the speed of the cotton filled intermediate roll and the bottom support roll. The coefficient of friction between the fabric and these rolls is similar so the fabric sticks to these surfaces. The top roll, because of the nature of the steel surface, can slide by at twice the speed, creating a frictional polishing action. The top roll can be heated to 177–218°C and the bottom roll to a maximum of 66–121°C. Frictioning produces a high degree of luster on one side.

Schreiner calender

The function of a Schreiner calender is to texture the surface of a fabric to obtain controlled opacity, desirable softness, luster and translucency. For knits, a Schreiner calender provides improved hand, surface texture and more cover, while for woven goods it offers more texture and drape. It has also been used to soften latex impregnated non-wovens. The pattern roll has from 100 to 140 lines per cm, etched at 26.5° from the vertical and at a depth of 0.025–0.050 mm. These lines are lightly embossed onto the fabric surface and, being regular, reflect light so as to give the surface a high luster. When mercerized cotton fabrics are Schreiner calendered, the fabrics develop a silk-like luster and brilliance.

The calender is normally a two- or three-roll machine and operates with a nip load at about 214–300 kg/linear cm. The top pattern roll is chrome-plated forged steel and the resilient roll is wool felt paper. In a three-roll calender, the bottom roll is forged steel. Both the top and bottom steel rolls can be heated to 177°C.

Embossing calender

The function of an embossing calender is to impart texture or a three-dimensional pattern to the surface of the fabric. All types of fabrics including woven, non-woven and knitted fabrics can be embossed. Embossing calenders are two-roll machines using a forged steel engraved top roll and a filled bottom roll with filling of wool felt paper, resilient wool/cotton, or in the case of 'Kiss' embossing where a slight glaze or luster is preferred, a higher content cotton filling. A synthetic shelled bottom roll can be used in lieu of a fiber roll. The top roll can be heated by high-pressure steam or hot oil. For natural fibers such as cotton and cotton blends, the roll can be heated to 177°C, while for synthetic woven goods or knits, to 232°C. Engraved pattern rolls range from polished to very deep floral patterns. For example, the moiré effect, a watered appearance that resembles paper after it has been wetted with water, can be obtained by using a moiré pattern embossing roll. Thermoplastic fabrics can be permanently embossed with heated rolls and the effect can withstand repeated laundering. Natural fibers are more difficult to emboss and usually starch is needed for the embossing to take; however, this effect is not durable to laundering. Certain melamine resins can be added prior to embossing and, when properly cured, the embossing effect is more durable.

Cire calender

The Cire calender is used for glazing and glossing fabric surfaces. Some porosity reduction and fabric compaction also occurs but not to the degree obtainable by a friction calender. All types of fabrics can be processed but usually they are 100% synthetic fiber or fabrics with a high synthetic fiber content. The units are operated at 300–600 kg/linear cm and the top roll can be heated to 177–242°C. The filling roll is usually cotton.

10.2.2 Construction of the rolls

Pattern rolls

Pattern rolls are turned from solid steel billets. The pattern is engraved onto the roll surface and the roll is heat treated to harden it and make the pattern more durable. The rolls are chromed which also increases wear resistance and protects them from rusting on storage. The center of these rolls is bored out to accommodate various heating systems. Steam, electrical heaters, natural gas and recirculating hot oil systems have been used to heat these rolls.

Resilient rolls

Resilient rolls are steel cores filled with cotton, or a combination of wool and cotton. The diameter of the steel core is approximately 50% of the final filled roll. Cotton is used to produce very hard, dense surfaces. These are not very resilient and are susceptible to being marked or scarred should hard objects inadvertently pass through with the cloth. Wool or wool/cotton is used because the surface will be more resilient and less likely to be damaged if a seam passes through. A disadvantage of wool is that the scales on the fiber tend to pick certain fabrics and create surface defects. Paper is also used to fill bowls. The latest in bowl design is nylon bowls – a 2.5 cm thick nylon shell fitted over a roll. The advantage of nylon is its resiliency; it is more resistant to being marked than are the other surfaces. Seams and wrinkles can run through without having to refurbish them all the time. Cloth having selvages thicker than the body of the fabric can be run through without problems.

Auxiliary equipment

Other devices are necessary for running the calender. Let-off and take-up rolls geared-in with the calender rolls are important. Proper tensions must be maintained to produce a consistent product. Edge guides and spreader bars are necessary to keep wrinkles from developing and being permanently pressed into the fabric. Seam detectors signaling the machine to prepare to jump the seam are necessary, otherwise the seam will mark the bowl. A marked-up bowl will spoil many yards of cloth.

10.3 Compacting

Compactors are mechanical devices that physically rearrange the geometrical relationship of yarns in a fabric. For example, in woven fabrics, the filling yarns can be forced closer together, thus pre-shrinking the fabric. In knit fabrics, the loops can be rearranged to overcome distortion in the length versus width caused by stretching tensions. Knit compactors balance the length to width loop ratio, thereby stabilizing the residual shrinkage in laundering. Controlled residual shrinkage is an important quality parameter for many fabrics to be made into garments. These fabrics need to meet specifications of less than 2%.

10.3.1 Why fabrics shrink

Woven and knitted goods are three-dimensional arrays of crimped or looped yarns. Fabric forming processes take straight lengths of yarns and force them into three-dimensional arrays. In a woven fabric, the degree of crimp is a function of the yarn size and fabric construction. When fabric is completely relaxed as is the case after washing, the crossing yarns will move around in relation to each other until a stable configuration is reached. This stable arrangement, the point where the relaxed fabric no longer shrinks in width and length, is also related to yarn sizes and fabric construction. When stretching tensions are applied to the fabric, the crimped amplitude decreases and the fabric grows in the direction of the stress. Later when the tensions are relieved and the fabric is allowed to relax, the crimp amplitude returns to its stable configuration and the fabric shrinks. Many fabrics are stretched during wet processing as they are pulled from one operation to another. This is the major cause of fabric shrinkage.

10.3.2 Types of compactors

Sanforizer

The Sanforizer is a fabric compactor developed by Cluett Peabody; the term ‘Sanforized®’ is their registered trademark and is used to market fabrics that meet certain shrinkage specifications. ‘Sanforized’ is now generally accepted to mean a fabric that has low residual shrinkage and the term ‘sanforizing’ is used to describe a particular method of compacting. The process consists of a multi-step operation where the fabric is first moistened with steam, run through a short tenter frame (pup tenter) to straighten and smooth out wrinkles, through the compressive shrinkage head and then through a Palmer drying unit to set the fabric. The fabric is wound into large rolls under minimum winding tensions. Usually, a lubricant is added in preceding operations to facilitate yarn movement. Selection of the proper lubricant is critical.

Compactor head

The compactor head is where force is applied to move parallel yarns closer together, causing the length to shrink. More fabric must be fed in than is taken off. A thick rubber blanket running against a steam-heated cylinder provides the compacting force. The rubber blanket is pre-stretched at the entry end where the fabric enters the compactor. The fabric and blanket together come in contact with a large diameter steam-heated cylinder. At this point, the stretching tensions on the rubber blanket are released, causing it to contract to its original length. Since the fabric is non-elastic, something must happen to the extra length of fabric trapped between the conveyor and the restraining drum. The frictional forces imposed on the fabric cause adjacent yarns to move closer together and the unit length of fabric becomes equal to the unit length of rubber blanket it rests on. If the fabric construction does not allow the yarns to move, the extra fabric will buckle, developing creases and wrinkles. Constant stretching and relaxing of the rubber blanket generates heat, so it is sprayed with water to cool it at the exit end. The degree of shrinkage can be controlled by the thickness of the blanket. The thicker the blanket, the greater is the stretched length at the entry end, allowing more fabric to be fed in and resulting in greater fabric compaction. Conversely if the blanket is thinner, less compacting will occur. Blanket thickness can be adjusted by means of a pinch roll compressing the rubber blanket allowing for ‘dialing in’ the desired degree of compacting. To be effective, the required degree of compacting should be predetermined ahead of time. This is done by first laundering the fabric to determine its shrinkage behavior. The degree of compacting should not exceed the degree determined by laundering, otherwise over-compacting will cause the fabric to grow when relaxed. This is as much a disadvantage as is shrinkage.

Friction calender compactors

Another method of compacting fabrics is with calender rolls. The fabric passes between two metal cylinders, one cylinder rotating faster than the other. Shoes positioned against the cylinders prevent buckling of the fabric. The fabric delivery cylinder rotates faster than the take-off cylinder and the frictional forces against the fabric cause filling yarns to move closer together, thus pre-shrinking it. The degree of compacting can be controlled by the differential speeds of the two calender rolls. Tubular knits fabrics can be calendered by machines designed to operate simultaneously on both layers of the fabric in tube form.

10.4 Raising (napping, sueding)

Raising is the term used to describe the creation of pile surface on a fabric [8]. In napping, single loops of fibers are engaged by wire hooks, lifted and released or lifted, and stressed beyond the loop's tensile strength to break the loop. The surface of the fabric is now populated with raised loops or single fiber ends with a soft surface texture. Napping, sueding and shearing are techniques for developing surface pile. In conjunction with calendering, these processes fall into the category of 'surface finishing'. Surface finishing effects, especially raising, have been used for years to enhance the appearance and hand of fabric. Many of the finest wool and cashmere fabrics are still mechanically finished – not only to improve their hand and appearance but to increase their bulk, to impart the feeling of warmth, to increase the number of fiber ends on the surface of the fabric, to provide improved adhesion for laminating purposes and to improve the profit margin per yard sold. While originally developed for finishing fabrics made from natural fibers (yesterday's technology), the same processes are used to finish today's woven and knitted goods made from synthetic and synthetic blends. Sueding and napping machines are used on both filament and spun constructions, while shears, polishers, calenders and decatizers are used singly or in combination to create specific surface effects.

10.4.1 Sueding (sanding)

The objective of sueding, also known as sanding, is to degrade fiber bundles, allowing exposure of a portion of filament ends. The strategy behind sueding is to expose the surface of the web to an abrasive medium at high velocity, providing a surface populated with extremely short filament ends. No pile effect is desired in this process. The machine consists of one or more rolls covered with an abrasive. Fabrics traveling over these rolls develop a soft hand and the material's surface can be made to feel like suede leather. The hand will depend on the fiber composition, the filament count in the yarn and the intensity with which the fabric is worked. Filament fabrics can be made to feel like a spun fabric and, generally speaking, all fabrics will have a softer hand. Another purpose of sueding is to alter the optical property of the surface by hiding or blending the fabric construction.

Multi-cylinder sueders

Multi-cylinder machines are usually five rotating cylinders, each independently driven. They can be rotated clockwise or counter-clockwise to the travel of the cloth. Cylinder construction can vary between machines made by different manufacturers. Some machines are sandpaper-covered abrasive rolls, either free standing or as rolls mounted around the periphery of a larger rotating cylinder shaft. Other types of abrasives are also used, for example, flexible bristle abrasives (silicon carbide impregnated filaments) or specially treated wires. Ahead and behind each cylinder are adjustable idle rolls that control the pressure of the fabric against the abrasive cylinder. Entry and exit drive rolls transport and control the fabric tension as it progresses through the machine.

Single-cylinder sueder

The single-cylinder sueder has one abrasive-covered metallic roll and one rubber-covered pressure roll. Water is circulated through the cylinder interior to control the heat generated from friction. The pressure roll presses the fabric against the abrasive cylinder and is set by means of a micrometer. The abrasion of the fibers on the surface of the fabric takes place in the nip between the pressure roll and the abrasive cylinder.

Abrasive covered rolls

The quality of sueding will depend on fabric construction and selection of abrasive grit. Over-sanding may weaken woven fabrics or perforate knit fabrics. Abrasive material deteriorates with use so it must be changed on a regular basis to guarantee consistent product.

Advantages and disadvantages

Both machine designs perform very well and produce acceptable products. However, one machine may have advantages over the other on a specific style. For example, fabrics with knots or slubs on their reverse sides, or fabrics with selvages thicker than the body, are best run on a multi-cylinder machine. Knot holes or over-sanded selvages may occur on the single cylinder machine because the fabric is compressed against the abrasive cylinder. A single roll sueder is more effective on fabrics with terry loops on the face that must be broken. Also, difficult styles that require shaving the face to develop a surface effect are more effectively and efficiently sanded on a single cylinder machine. Some fabrics tend to develop a directional pile when sanded on a single cylinder machine. The multi-roll machine may be operated with the cylinders rotating in opposing directions, eliminating this effect.

10.4.2 Napping

Nappers in contrast to sueders change the aesthetics of fabrics by developing pile on the surface of the fabric. The pile can be either raised unbroken loops or raised loops where the filaments are broken in the process. The depth of pile developed on a napper can be significant compared to sueding. Pile finishes such as high-pile fur-like effect, fleece, velour, flannel and bed blanket are produced by napping. Proper fabric construction is a prerequisite to napping. It is important that the yarns acted on by the napper are not the ones responsible for the strength and integrity of the fabric, because the napped yarns are weakened by the napping action. Fabric to be napped should have a napping lubricant or softener applied prior to napping to allow the fibers in the yarn to slide more freely during the napping operation.

Nappers

Wire nappers, known as planetary nappers, are the most common machines in the industry. The basic design of a wire napper is 24 to 36 small pile wire-clad rolls (worker rolls) mounted on the periphery of a large main cylinder. The large napper cylinder rotates in the same direction as the flow of the fabric at a constant speed, while the worker rolls rotate on their own axis in a direction opposite to the rotation of the main cylinder. Cleaning rolls or brushes below the main cylinder remove lint and entangled pile to keep the wires at high efficiency. The speed of the worker rolls, the type of wire and the angled direction of the wire all influence the degree of nap. There are many arrangements of these components, each designed for their individual specialty.

Double acting nappers

The double acting napper is the most commonly used machine in the industry. The main cylinder carries 24, 30, or 36 napper rolls. Every other worker roll (the pile worker roll) has hooked wire points angled in the same direction as the rotation of the cylinder. The alternating worker roll (the counter-pile roll) has hooked wire points angled in the opposite direction. The relative speed between the fabric travel and the speed of the worker rolls determines the amount of napping energy imposed on the fabric. Neutral energy is defined as the point at which the surface speed of counter-rotating worker rolls matches the surface speed of the fabric, so that no napping takes place. The napping action is such that the counter-pile rolls dig into the yarn to pull out fibers while the pile roll felts or tucks the fiber ends into the base of the fabric. The double acting napper develops a dense, tangled nap which is very desirable on many fabrics.

Knit goods napper

Knit goods nappers are designed for use almost exclusively by the knit industry. Machines designed for tubular fabrics as well as open-width fabrics are available. A knit goods napper differs in that the main cylinder rotates on its own axis in a direction opposite to the flow of the cloth. Half of the worker rolls are covered with straight wire called traveler wire, and the other half are covered with hooked wire whose points face the rear of the machine. While it looks like pile wire, it acts like counter-pile wire because of the direction of rotation of the main cylinder. Both sets of worker rolls rotate on their own axis in a direction opposite to the cylinder rotation. Fourteen to 24 worker rolls are mounted on the main cylinder. The hooked wire roll does the napping, and the traveler wire roll speed is adjusted to control the tension of the fabric on the cylinder. Correct speeds prevent wrinkles from forming in tubular goods and longitudinal wrinkles in flat goods.

Single acting napper

While the double acting and knit nappers generally develop a directional nap with parallel fibers that can be lofty or flat, the purpose of the single acting napper is to untangle and comb the fibers parallel. The single acting napper's main cylinder rotates in the same direction as the flow of the cloth. There are 20 to 24 pile worker rolls in the cylinder whose wire points face the rear of the machine. The pile worker rolls rotate in a direction opposite to the main cylinder. A distinguishing feature of this machine is the way the cloth is fed to contact the main cylinder. The cloth is fed over contact rolls that permit two to four tangential contacts. If the cloth hugged the entire cylinder, the wire ends all pointing in the same direction would tear it to shreds.

Napper wire

The characteristics of the napper wire are just as important as the machine design. Most wires have a 45° bend at the knee and are ground needle sharp. The wire protrudes through a tough flexible backing, built up and reinforced to securely hold the wires. The backing and wire are wound spirally over a hollow supporting roll to become the worker roll. For certain fabrics, e.g., tricot warp knits, it has been found that a bumped or mushroomed wire point with tiny barbs underneath will develop a denser nap in fewer runs. As the wire point withdraws from the yarn bundle, the minute barbs will raise more fiber than a single-needle point, producing more fiber coverage per napping run. Wires with less severe knee bends can be used to raise unbroken loops from filament yarns. In this instance, the wire raises the filament from the yarn and drops it off without breaking the filaments.

10.5 Shearing

Shearing is a process where raised fibers are cut to a uniform height [7]. Some spun fabrics are sheared close to the fabric surface as a means of removing the raised hairs, giving the fabric a clear, smooth surface. Shearing can be used as an alternative to singeing. More often, however, shearing follows napping to clear out random lengths of fibers and produce a uniform and level pile. Shearing is used to reduce pilling, to produce a certain hand, to improve color and appearance and to produce sculptured effects. Knitted and woven fabrics with loops on the face or back are not necessarily napped first – they can be sheared directly to cut off the tops of the loop and produce plushy velours such as knit velours and plush towels. Terry looped bath towels can be sheared on one or both faces to produce a plush pile surface.

10.5.1 Shearers

The shearer head consists of a spiral blade revolving on its own axis in contact with a ledger blade. This creates a shearing action similar to that produced by a pair of scissors. When fibers are presented to this cutting head, they will contact the ledger blade and be cut off by the rotating blade. The fabric travels over a cloth rest (bed) in front of the ledger blade and the design is such that the fabric forms an acute angle. This sharp angle causes the pile to stand erect and be more easily cut. The distance between the bed and the ledger blade is adjustable, so the height of the pile can be regulated. Most shearers are equipped with expander rolls to straighten and flatten the fabric as it approaches the bed and a vacuum system to remove the lint produced at the cutter. Specially designed support beds are available for producing sculptured patterns on high-pile fabrics. Variations can produce stripes, zig-zag, checks, etc. Very often the fabric is brushed prior to shearing. The object of brushing is to lay the fibers in one direction and thus facilitate the cutting process.

10.6 Polishing

Polishers are primarily used on synthetic pile fabrics when either an erect lustrous pile or a laid-down pile is required. The machine consists of a fluted heated cylinder driven by a variable speed motor and an endless felt blanket. The fabric passes over the endless blanket that is adjustable and brings the fabric face in contact with the heated cylinder. The serrations on the cylinder draw through the fibers to raise and parallelize them. Heat facilitates the straightening process and sets the fibers. Polished fabrics appear more lustrous because the parallel fibers result in more uniform light reflection. By running the cylinder so that the edges of the serrations revolve against the fabric flow, the pile will be made to stand more erect; however, if the edges of the serrations run in the same direction as the cloth, the pile will lie flat.

10.7 Corduroy cutters

Corduroy fabrics are distinguished from other fabrics by parallel pile ribs running lengthwise in the warp direction. The pile ribs, called wales, are produced by passing the fabric through a cutter that slits specific filling yarns across the face of the fabric. The design of the fabric is such that the filling consists of ground yarns and pile yarns. The ground yarns provide fabric strength and integrity while the pile yarns form the rib or wale when cut and brushed. The principle of raising the pile is relatively simple; the filling yarn is slit in two places, creating two legs anchored by warp yarns. The two legs become erect when the fabric is brushed in the filling direction. The brushing action also causes the individual fibers in the two legs to disentangle and become a single rib.

The cutter is a simple device consisting of circular knife blades positioned over slotted base plates. The slotted base plates resemble thin needles inserted under the floating filling yarns to be cut. Each wale requires two cutters so the number of cutters will depend on the number of wales per inch. Once the fabric is threaded onto each base plate, the fabric is pulled through the machine at an angle. Fine wale fabric requires multiple passes because of physical limitations as to how close the cutters can be placed together. Brushing following the cutting operation is necessary to stand the pile. Some styles require an adhesive back coat to anchor the pile because the pile can be pulled out unless it is bonded to the back.

10.8 Decatizing

Decatizing is a method of steaming fabric between two layers of cotton press cloth and can be the last finishing process for some fabrics. The effect on the fabric is similar to steam pressing garments under a press-cloth. The process is used to improve the hand and drape, to brighten colors and enhance natural luster, to assist in setting the finish, or to refinish fabrics after sponging or cold-water shrinking. Decatizing is a normal finishing step for many wool and wool blend fabrics. Wool fiber from different animals will have varying shrinking characteristics. Fabrics made from wool from different regions of the world will develop a cockled surface appearance when exposed to high humidity. The differential shrinking behavior can be evened out by decatizing the fabric and allowing the high temperature steam pressing to reset the fibers. Decatizing is also an effective mechanical softening treatment resulting in a luxurious, soft, smooth hand. The process can also be used on fabrics containing other fibers such as acetate, acrylic, rayon, spun polyester and other synthetic blends.

10.8.1 Semi-decatizing

Semi-decatizing is a batch process where fabric is wound onto a perforated drum between interleaving cotton blankets. Steam is forced through the roll (inside-out) for several minutes to provide moisture and heat. Compressed air is then blown through the roll to remove some of the moisture and cool it down. The fabric and blanket are rewound onto another perforated drum so that the outside layers become the inside layers and the cycle is repeated to ensure uniformity. At the end of the cycle, the fabric and blanket are separated and wound into individual rolls. Controlling time, pressure, heat, moisture and cooling are prerequisites for quality results.

10.8.2 Continuous decatizing

The continuous decatizer has one steaming cylinder and one cooling cylinder. An endless apron carries the fabric around both the steaming and the cooling cylinders. Fabric continuously moves through, so the exposure time depends on the speed of the machine and is less than in batch semi-decatizing. Nonetheless, excellent results are obtained on many fabrics.

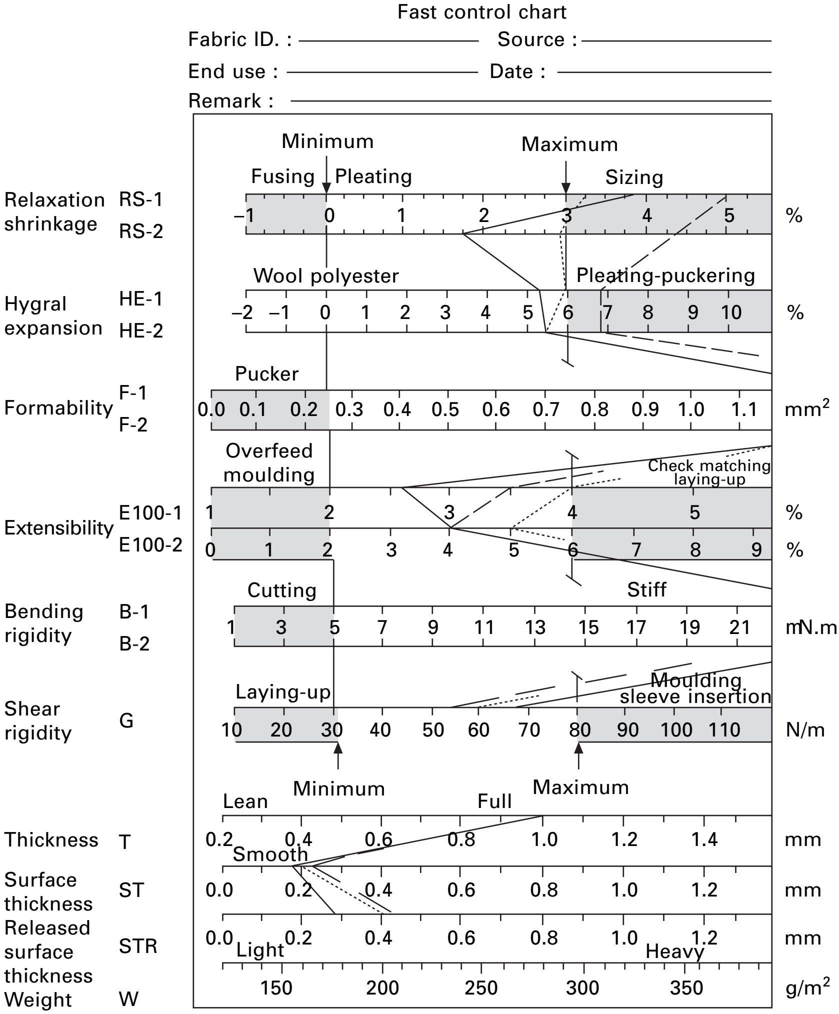
10.8.3 Comparison of alternative decatizing equipment

DeBoos *et al.* [9] reported a study on the comparison of alternative decatizing equipment. The study included conventional decatizing (open blowing) machines with the continuous decatizing equipment. Two types of continuous decatizing machines were evaluated:

A. One that used a wrapper cloth to hold the fabric against a perforated drum and, in sequence, blew steam then sucked cold air through the fabric and wrapper.
B. One that sprayed water onto the fabric (or an interleaved wrapper) and

then used an impermeable belt to hold the cloth against a heated drum and generate the steam during the process.

Samples of cloth were finished using the two types of continuous decatizer and tested using FAST. The data were compared with those obtained from fabric finished using a traditional batch decatizer. Evaluation of the fabric fingerprints obtained using FAST (shown in Fig. 10.1), indicated that fabric



10.1 FAST fingerprints of fabrics decatized in: ——— batch decatizer; – – – continuous decatizer A; ········ continuous decatizer B. *Source*: 'Objective evaluation of wool fabric finishing', by A.G. DeBoos and A.M. Wemyss, from *Journal of the Textile Institute*, vol. 84. no. 4, p. 506, 1993. Reproduced with permission from *Journal of the Textile Institute*.

with the traditional batch-decatized finish and continuous process B had better dimensional stability than fabric finished with continuous process A.

Comparison of the finished thickness of the fabric samples indicated that there was little difference in the amount of press imparted by the different machines; the traditional batch decatizing method was marginally more effective. However, when the overall and surface thickness of the variously decatized fabrics were compared before and after release in steam, it was found that the stability of the finish imparted by the traditional batch process was greater than that imparted by either of the continuous processes (which were approximately equivalent).

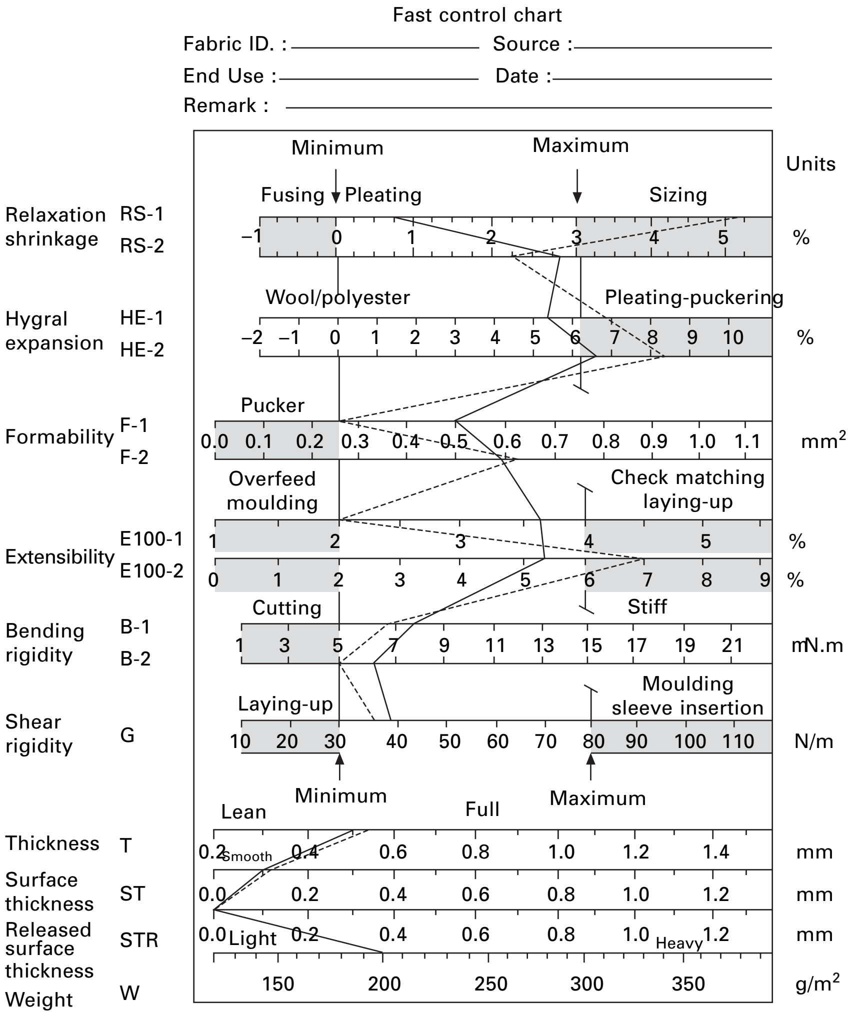
In the particular mill situation, fabric dimensional stability and hand were considered to be of greatest importance. Using these criteria, there was little to choose between the batch and continuous B-decatized fabrics. On the basis of the objective data, the finisher could reject one continuous decatizer in favor of the other and be confident that the economic advantages associated with the new machinery would not be offset by a deterioration in the most important aspects of fabric quality.

In the United States and Japan, sponging is widely used to control the relaxation shrinkage of fabrics and to ensure that fabrics delivered to the garment maker have adequate dimensional stability. In this situation, the criteria of selecting new decatizing machinery would be different from those in the United Kingdom, where sponging is not as widely practiced and finishers are generally required to meet much tighter tolerances on fabric dimensional stability.

The decatizing process could also be used to improve fabric properties as shown in Fig. 10.2. This takes place when faulty pieces are corrected by reversing the crimp interchange that has taken place during the finishing process. The new configuration has to be stabilized by permanent setting in a pressure decatizer.

10.8.4 Effect of finishing stages

In another study, by Dhingra *et al.* [11], the effects of finishing stages, including pressure decatizing in the finished state, were investigated. Three wool and wool/polyester suiting fabrics were sampled after the following stages of a commercial finishing operation: weaving – loom or grey state, heat setting (wool/polyester fabrics only), scouring, blowing and paper pressing (hydraulic flat press), and pressure decatizing in the finished state. The construction and finishing details for these fabrics are given in Table 10.1. Measurements were made on the fabric mechanical and surface properties of the samples taken after each of the finishing stages. The effect of fabric finishing on each of the mechanical properties tested using the KESF instruments is discussed below.



10.2 FAST fingerprint of the original (– – –) and re-finished fabrics (———). *Source*: 'Objective evaluation of wool fabric finishing', by A.G. DeBoos and A.M. Wemyss, from *Journal of the Textile Institute*, vol. 84. no. 4, p. 506, 1993. Reproduced with permission from *Journal of the Textile Institute*.

Fabric properties relating to hand

Tensile properties

Fabric extensibility (EM) after the various finishing stages is shown in Fig. 10.3. For the pure wool fabric, there is a large increase in fabric extensibility after scouring in both principal or thread directions, that is, from 5.6% to 11.6% in the warp and from 3.2% to 6.6% in the weft direction. This is

Table 10.1 Construction and finishing details for the three fabrics used in the fabrics finishing experiment

	Fabric 1	Fabric 2	Fabric 3
Wool fiber diameter, nominal average	22.5 mm	22.5 mm	22.5 mm
Polyester linear density	–	3 denier	3 denier
Yarn count, tex	R44/2	R 40/2	R 52/2
Singles twist, tpm	600	650	550
Folding twist, tpm	560	728	630
Finished fabric sett			
Ends/cm	25	35	17
Picks/cm	21	25	18
Weave	2 ¥ 2 twill	3 ¥ 1 satin	plain
Weight, g/m^2	275	290	212
Finishing	Soap milling – Scour Brush/crop Open decatize Paper press Pressure decatize	Heat set Singe Scour Brush/crop Open decatize Paper press Pressure decatize	

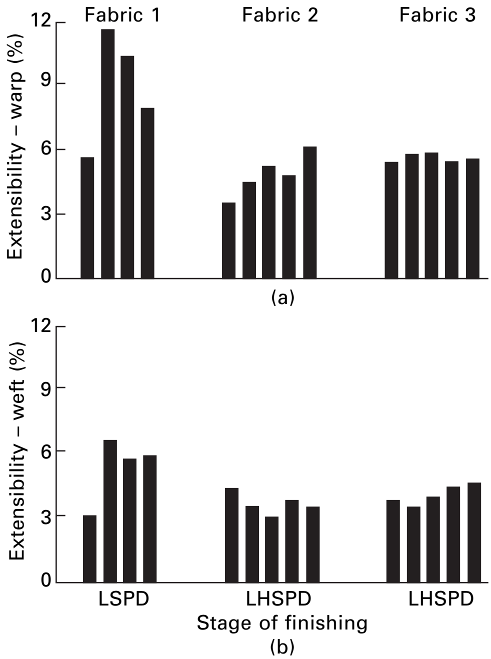
The fabric is lapped between specially glazed cardboard sheets and heated to approximately 40 °C under a pressure of 2800 kPa. The operation is done twice to even out the treatment, especially on the folds.

followed by much smaller decreases in extensibility in subsequent finishing steps. Since the overall increase in extensibility is common to both principal fabric directions, it must be explained in terms of the relaxation shrinkage in both warp and weft directions occurring during scouring rather than a simple interchange of warp and weft yarn crimp.

The increase in extensibility that occurs during finishing of the wool fabrics could improve tailorability, especially from the viewpoint of shaping and sewing. Very high levels of extensibility, however, may result in excessive hygral expansion for the finished wool fabrics, which could result in puckering problems in the tailored garment as a result of changes in ambient relative humidity conditions.

For the wool/polyester satin fabric, the increase in warp extensibility after heat setting and scouring was accompanied by a corresponding decrease in the weft extensibility: this result could be attributed to crimp interchange from the weft to the warp yarns during heat setting and scouring.

Tensile resilience (RT) increases during finishing much more for the two polyester/wool fabrics than for the pure wool fabric. For example, tensile resilience in the warp direction increases from 49% (loom state) to 63% (finished state) for the satin fabric and from 51% (loom state) to 66% (finished

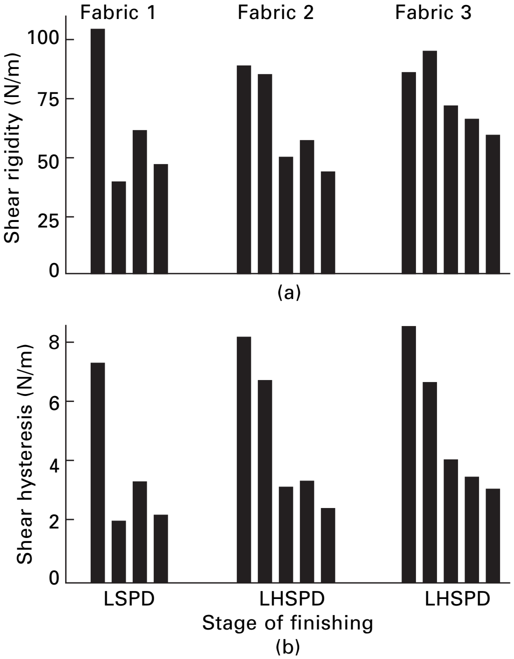


10.3 Fabric extensibility, EM, in (a) the warp and (b) the weft directions after various stages of fabric finishing: L = loom state, H = after heat setting, S = after scouring, P = after pressing, D = after pressure decatizing. *Source*: 'Measuring and interpreting low-stress fabric mechanical and surface properties', by R.C. Dhingra, D. Liu and R. Postle, from *Textile Research Journal*, vol. 59, 1989. Copyright Sage Publications.

state) for the plain weave fabric. The corresponding increase in tensile resilience for the pure wool fabric was from an initial relatively high value of 58% (loom state) to 63% (finished state). Similar results also apply in the weft direction.

Shear properties

Figure 10.4 demonstrates the shear rigidity (G) and shear hysteresis (2HG5) measured with tension applied in the warp direction after the various finishing stages. For the wool fabric, there is a very marked reduction after scouring in both the rigidity and hysteresis in shear. For example, the reduction in shear rigidity is 62% of the original value; the reduction in the shear hysteresis parameter 2HG5 is 76% of the original value. The corresponding reductions in the shear hysteresis 2HG and residual shear strain SG after scouring are 85% and 60%, respectively. Similar results also apply to the shear measurements made with tension applied in the weft direction. These results are indicative



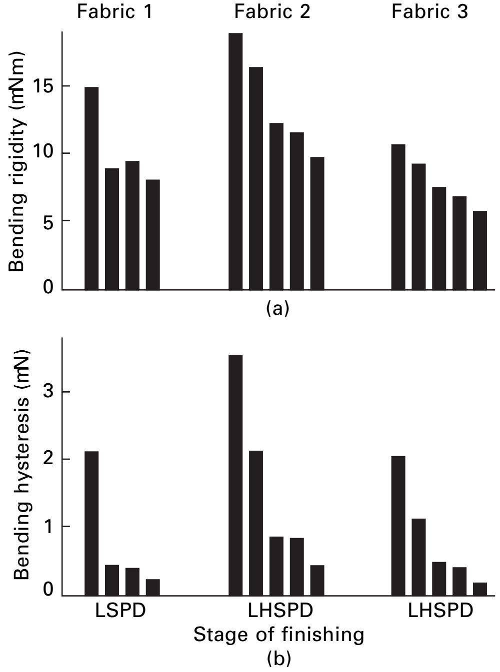
10.4 (a) Fabric shear rigidity, G, and (b) shear hysteresis, 2HG5 in the warp direction after various stages of fabric finishing: L = loom state, H = after heat setting, S = after scouring, P = after pressing, D = after pressure decatizing. *Source*: 'Measuring and interpreting low-stress fabric mechanical and surface properties', by R.C. Dhingra, D. Liu and R. Postle, from *Textile Research Journal*, vol. 59, 1989. Copyright Sage Publications.

of the greatly reduced inter-yarn pressures in wool fabrics after scouring. For the wool/polyester blended fabrics, the effects noted above are almost equally divided between heat setting and scouring.

These very large reductions in fabric shear rigidity and shear hysteresis represent one of the major effects of fabric finishing. The unfinished fabric has very high shear rigidity, which means that draping and three-dimensional forming (as required in tailoring) would be very difficult. Furthermore, the unfinished fabric exhibits a high degree of inelasticity in shear as measured by the large values of shear hysteresis. The unfinished fabric that exhibits this inelastic paper-like behavior is transformed largely by scouring (for pure wool fabrics) or scouring/heat setting (for wool/polyester blend fabrics) into the finished fabric that exhibits the classical three-dimensional elastic draping and fabric forming qualities necessary for successful tailoring and garment wear.

Bending properties

Similar dramatic changes in the values of fabric bending parameters are also evident after scouring (pure wool fabric) or heat setting/scouring (wool/polyester fabrics), as shown in Fig. 10.5. Both the bending rigidity (B) and bending hysteresis (2HB) are greatly reduced during scouring or heat setting/scouring, e.g., the reductions in bending rigidity and bending hysteresis (in both principal directions) after scouring are 42% and 79%, respectively, of the pre-scour values for the pure wool fabric.

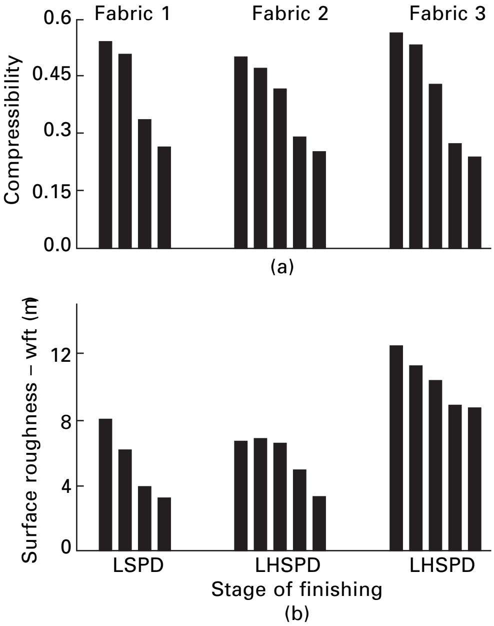


10.5 (a) Fabric bending rigidity, B, and (b) bending hysteresis, 2HB measured in the warp direction after various stages of fabric finishing: L = loom state, H = after heat setting, S = after scouring, P = after pressing, D = after pressure decatizing. *Source*: 'Measuring and interpreting low-stress fabric mechanical and surface properties', by R.C. Dhingra, D. Liu and R. Postle, from *Textile Research Journal*, vol. 59, 1989. Copyright Sage Publications.

The reduction in residual curvature (KB) due to scouring for the pure wool fabric and due to the combined effects of heat setting and scouring for the wool/polyester fabrics is 53–64% in both directions of fabric bending. Again, the finishing processes, especially scouring and heat setting (in the case of wool/polyester blends), greatly increase the fabric flexibility and elastic recovery from bending as required by fabric tailoring, draping, and wear.

Compression properties

The variation in fabric compressibility (CM) with finishing stage is shown in Fig. 10.6(a). The compressibility of each fabric decreases as the fabric progresses through the finishing routine. Figure 10.6(a) shows that the greatest decrease in fabric compressibility occurs during fabric pressing, where we see reductions in compressibility of 32–38% (compared with the post-scoured value) for both wool and wool/polyester fabrics.



10.6 (a) Fabric compressibility and (b) surface roughness in the weft direction after stages of fabric finishing. L: = loom state, H = after heat setting, S = after scouring, P = after pressing, D = after pressure decatizing. *Source*: 'Measuring and interpreting low-stress fabric mechanical and surface properties', by R.C. Dhingra, D. Liu and R. Postle, from *Textile Research Journal*, vol. 59, 1989. Copyright Sage Publications.

The overall reduction in fabric compressibility due to the combined effects of scouring, pressing, and decatizing for the pure wool fabric is 52% of the loom state value. The corresponding reduction in compressibility due to the combined effects of heat setting, scouring, pressing, and decatizing for the two wool/polyester fabrics is 50–58% of the loom state value.

There was also a large increase in compressional resilience (RC) for the pure wool fabric during finishing: the compression resilience increased from 45% for the loom state fabric to 58% for the finished fabric. The compressional resilience for the wool/polyester fabrics was relatively unchanged, varying between 41% and 46% during finishing.

Fabric thickness (T) and specific volume (V) are also greatly affected by pressing for each of the three fabrics. For the pure wool fabric, there was an approximately 20% increase in fabric thickness after scouring, followed by a dramatic decrease (46%) after pressing (compared with the post-scoured value) and a further small decrease after decatizing. The thickness of both wool/polyester fabrics decreased progressively through the finishing routine. Once again, the greatest decrease in fabric thickness occurred during fabric pressing, where we observed a reduction in thickness of 31–35% compared with the value before pressing.

Fabric specific volume decreased progressively through the finishing routine for each of the three fabrics. The greatest decrease occurred during fabric pressing, where reductions were seen in fabric specific volume of 31–45% compared to the corresponding value before pressing. The overall reduction in fabric specific volume due to the combined finishing operations is between 52% and 60% of the loom state value for the three fabrics investigated. The characteristic bulkiness of pure wool fabrics was evident from the slightly higher specific volume of the finished pure wool fabric, 2.7 cm^3/g, compared to the value for the two wool/polyester fabrics, 2.3 cm^3/g in each case. These differences occur despite the different weave construction of each fabric.

Surface properties

The variation in fabric surface roughness along the weft direction is depicted in Fig. 10.6(b). Here again, fabric pressing has the greatest effect when compared to the other finishing operations. These results quantify the effect of pressing on the surface roughness of the three different fabrics. Figure 10.6(b) also highlights the much greater surface roughness of the finished plain weave fabric, 8.9 μm, compared with 3.3 μm for the 2/2 twill and 3.5 μm for the 3/1 satin. Results were similar in the warp direction, too. The geometrical roughness of the finished plain weave wool/polyester fabric was 9.9 μm compared with 3.8 μm for the 2/2 twill wool fabric and 2.3 μm for 3/1 satin fabric. These results are attributable to the larger number of yarn interlacings for the plain weave fabric compared to the twill and stain constructions.

General remarks

The remarkably large influence of finishing on the low-stress fabric mechanical and surface properties can be specified quantitatively by the objective mechanical data obtained using the KESF instruments.

For the wool fabrics, there is a marked reduction after scouring in both the rigidity and hysteresis in shear and bending properties. For the wool/polyester blended fabrics, these effects are almost equally divided between scouring and heat setting. There was an overall increase in both warp and weft fabric extensibilities during finishing for the wool fabric, arising entirely from the scouring operation (after which there was a small reduction in extensibility for subsequent finishing operations). For the wool/polyester blended fabrics, however, a crimp interchange process from weft to warp during heat setting/scouring operations resulted in increasing warp extensibility and decreasing weft extensibility. The tensile resilience of the unfinished wool fabric was relatively high compared with that of the unfinished wool/polyester materials, but after finishing, the tensile resilience of all fabrics increased to a similar value of approximately 63–66%. Furthermore, there was a marked reduction after paper pressing in compressibility, thickness, and surface roughness for both wool and wool/polyester blended fabrics.

The overall effect of these changes in mechanical/surface properties due to finishing results in a progressive improvement of elastic recovery properties, surface hand feeling, and the desirable fabric aesthetic attributes. This study demonstrates the scope of applying the principles of engineering design (using low-stress fabric mechanical/surface property measurements) to the production of apparel fabrics with aesthetic properties acceptable for particular markets and end products.

10.9 Mechanical hand breaking (softening)

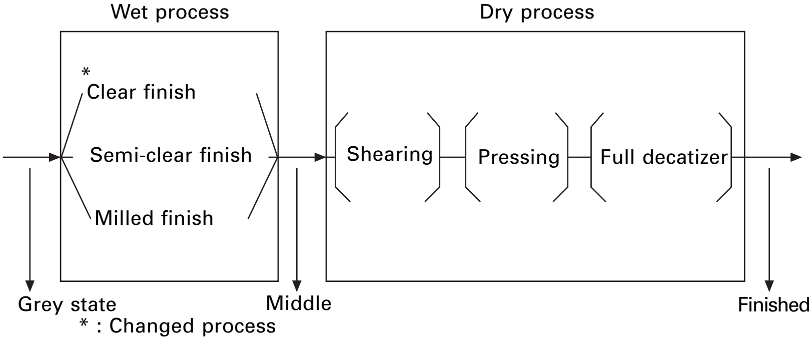
When a fabric is mechanically manipulated the hand will break down and become soft. Physical manipulation will disrupt cohesive forces between fibers and yarns and the fabric becomes more flexible. There are many causes of fabric stiffness; for example, line-dried towels are boardy and stiff compared to tumble-dried towels. However, this stiffness can be overcome by flexing or tumbling them. Similarly, starched fabrics and certain chemical finishes also cause fabric stiffness. They too can be softened by physical manipulation.

There are several machines that can be used to break down the hand of roll goods. The compressive shrinking machine discussed earlier is one. There are also several machines designed specifically for the purpose of mechanically working the fabric. A button breaker is one. The button breaker is a mechanical device where a number of paired rotating rolls studded with protruding buttons are positioned on a non-rotating cylinder. The fabric is pulled through under tension and the force of the buttons working against the fabric causes the hand to break down. Another version utilizes scroll rolls arranged in pairs of opposing helical spirals. The action of the opposing spirals applies stresses to the fabric, resulting in a softer fabric.

10.10 Interrelation between fabric mechanical properties and finishing process

There are different combinations of finishing processes for fabric finishing. A study was conducted by Matsui [10] using the most representative processes to investigate changes in the fabric mechanical properties by finishing processes, using the KES-FB system.

The finishing process of worsted weaves was divided into two stages: wet process and dry process. The wet process was changed by three methods called clear, semi-clear, and milled, as shown in Fig. 10.7.



10.7 A most representative sequence of the finishing process; the wet process is changed in three ways. *Source*: 'Fabric finishing on the basis of objective measurement of fabric mechanical properties by cooperation with apparel company engineers', by Y. Matsui, from *Objective Evaluation of Apparel Fabrics*, (ed. R. Postle, S. Kawabata and M. Niwa). Reproduced with permission of the Textile Machinery Society of Japan.

Samples of fabrics were taken at the grey state, after the wet process (middle) and in finished state for measurement. The mechanical properties of these fabrics were measured for the three finishing methods and the results of fall/winter men's suit fabric are shown in Table 10.2, as well as those of summer men's suit fabrics – at clear finish only. The results are plotted on the HESC Data Chart and shown in Figs 10.8(a)–(d).

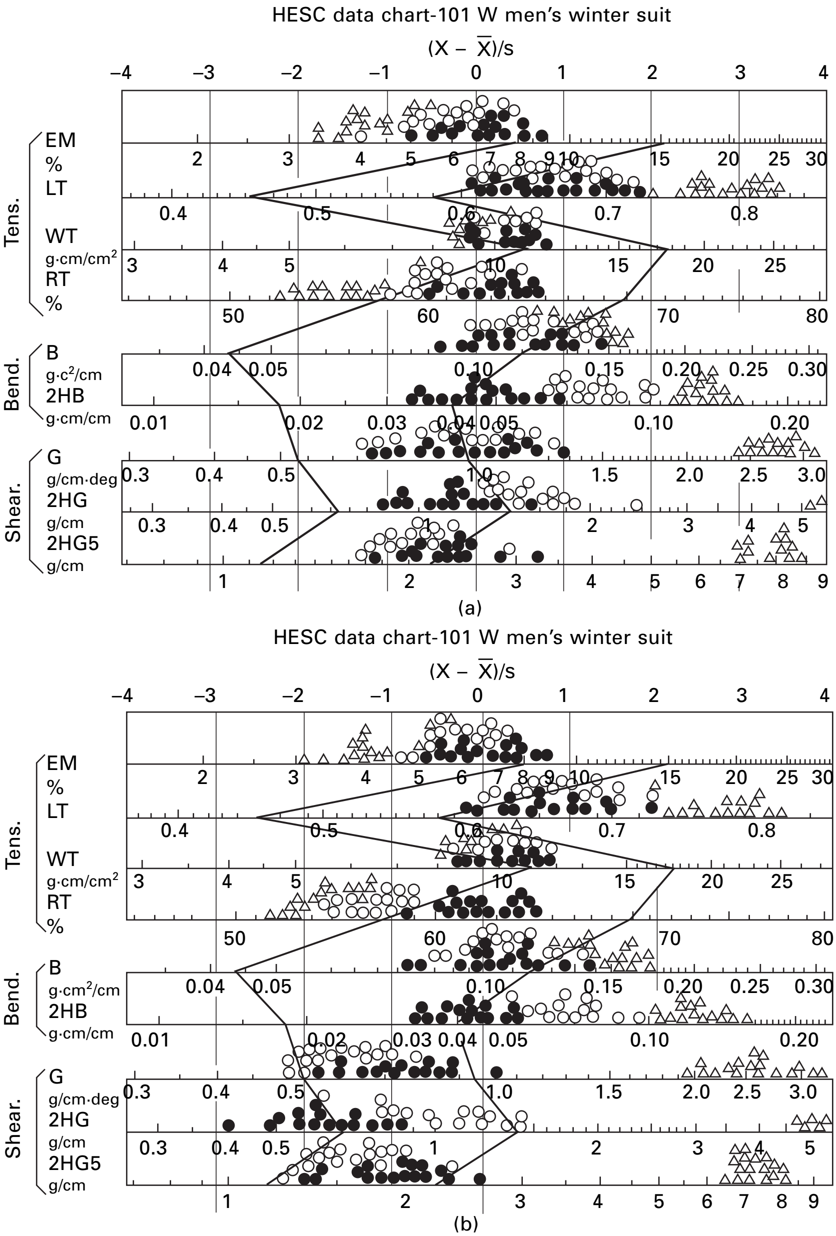
The following general conclusions were made for fall/winter men's suit fabrics regardless of finishing methods:

- Tensile property:
  - LT, WT: no difference through the finishing process.
  - RT, EMT (weft): increase in order of grey, middle and finished states. That is, fabrics become stretchable and springy with the progress of the finishing process.

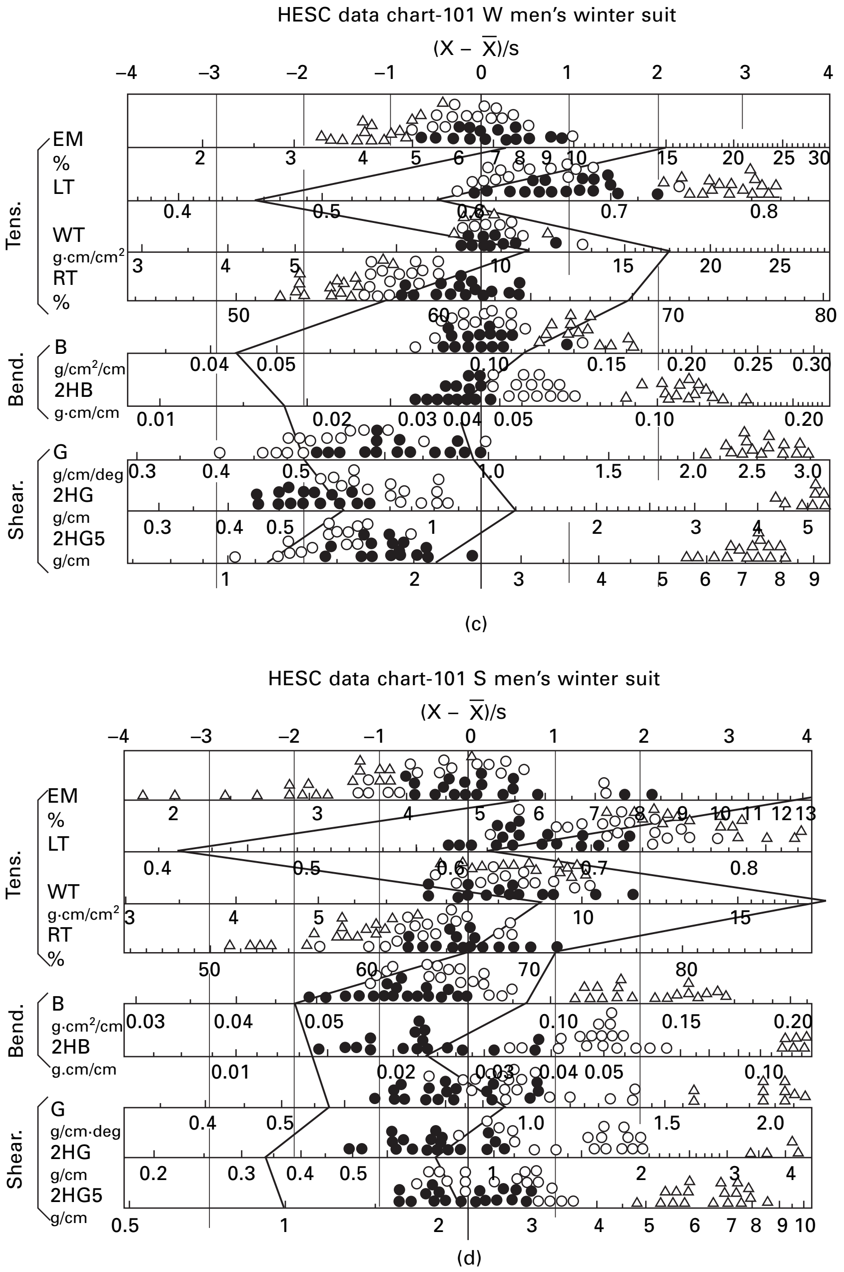
Table 10.2 Mechanical properties of fabrics obtained from various finishing methods and finishing states

		Fall/winter men's suit fabric									Summer		
		Clear finish			Semi-clear finish			Milled finish			Clear finish		
		Grey	Middle	Finished	Grey	Middle	Finished	Grey	Middle	Finished	Grey	Middle	Finished
LT	Mean	0.783	0.669	0.668	0.783	0.656	0.676	0.779	0.670	0.665	0.764	0.717	0.668
	S.D.	0.028	0.029	0.034	0.021	0.036	0.027	0.025	0.032	0.035	0.035	0.033	0.030
WT	Mean	9.36	10.41	10.47	9.45	9.86	9.52	9.49	10.04	9.95	8.53	8.05	8.03
	S.D.	0.57	0.78	0.78	0.77	1.05	0.84	0.79	1.06	0.98	0.86	1.03	1.29
RT	Mean	55.7	60.8	63.4	55.2	58.3	61.6	54.8	56.9	61.8	58.1	64.1	65.9
	S.D.	1.8	1.8	1.6	1.5	1.2	1.9	1.7	1.4	1.9	3.4	3.1	3.2
EMT[a]	Mean	4.21	6.32	6.85	4.37	6.48	6.59	4.23	5.95	6.58	3.15	4.77	5.06
	S.D.	0.59	1.01	0.84	0.65	1.20	0.91	0.69	0.73	0.82	0.73	1.08	1.11
B	Mean	0.143	0.123	0.116	0.140	0.103	0.101	0.149	0.115	0.108	0.134	0.074	0.065
	S.D.	0.012	0.016	0.018	0.012	0.021	0.011	0.014	0.020	0.017	0.019	0.009	0.008
2HB	Mean	0.136	0.081	0.049	0.122	0.063	0.041	0.128	0.073	0.044	0.143	0.049	0.023
	S.D.	0.011	0.012	0.009	0.017	0.015	0.004	0.016	0.014	0.010	0.039	0.009	0.006
G	Mean	2.83	1.00	0.98	2.56	0.61	0.75	2.55	0.62	0.75	2.28	1.02	0.82
	S.D.	0.38	0.21	0.21	0.25	0.14	0.13	0.32	0.08	0.13	0.35	0.17	0.12
2HG	Mean	6.21	1.57	1.09	5.49	0.83	0.55	5.59	1.07	0.62	5.40	1.51	0.76
	S.D.	0.89	0.30	0.19	0.56	0.15	0.09	0.43	0.25	0.12	1.14	0.38	0.16
2HG5	Mean	8.06	2.17	2.34	7.05	1.45	1.85	7.21	1.57	1.89	6.64	2.71	2.29
	S.D.	0.92	0.28	0.36	0.76	0.22	0.27	0.44	0.28	0.35	1.03	0.56	0.43

[a] All the data are means of 20 samples and averaged value of warp and weft direction deformation mode except for EMT which is only weft direction.



10.8 Mechanical properties of fabric, effects of various finishings. (a) Clear finish of men's winter suit; (b) semi-clear finish of men's winter suit; (c) milled finish of men's winter suit; (d) clear finish of men's summer suit. In all diagrams, △ grey state, ○ middle, ● finished. *Source*: 'Fabric finishing on the basis of objective measurement of fabric mechanical properties by cooperation with apparel company engineers', by Y. Matsui, from *Objective Evaluation of Apparel Fabrics*, (ed. R. Postle, S. Kawabata and M. Niwa). Reproduced with permission of the Textile Machinery Society of Japan.



HESC data chart-101 W men's winter suit

(c)

HESC data chart-101 S men's winter suit

(d)

10.8 Continued

- Bending property:
  - B: no difference between middle and finished states.
  - 2HB: smaller in the finished than in the middle state of fabrics.
- Shearing property:
  - G, 2HG5: larger in the finished than in the middle state.
  - 2HG: smaller in the finished than in the middle state.
  - Mechanical characteristics of shearing obtained by the clear finish are larger than those obtained by the semi-clear or milled finish.

Results for summer men's suit fabrics are as follows:

- Tensile property:
  - LT: approaches the good zone (becomes smaller) in order of grey, middle and finished state of fabrics.
  - WT: no large difference through the finishing process.
  - RT: becomes springy in order of grey, middle and finished.
- Bending property:
  - B: very bad (large) in grey state of fabrics, but becomes smaller (approaches the good zone) as middle and finished.
  - 2HB: very bad (large) in grey, but very good (small) in middle and finished, a little better in finished state of fabrics than middle.

10.10.1 Changes of mechanical properties of fall/winter men's suit fabrics with various decatizing processes

Mechanical properties of fall/winter men's suit fabrics were measured for three decatizing processes after the same wet process. The results are shown in Table 10.3 and Fig. 10.9. It is clear that fabrics processed through the full decatizer after paper pressing show the best properties.

10.11 Future trends

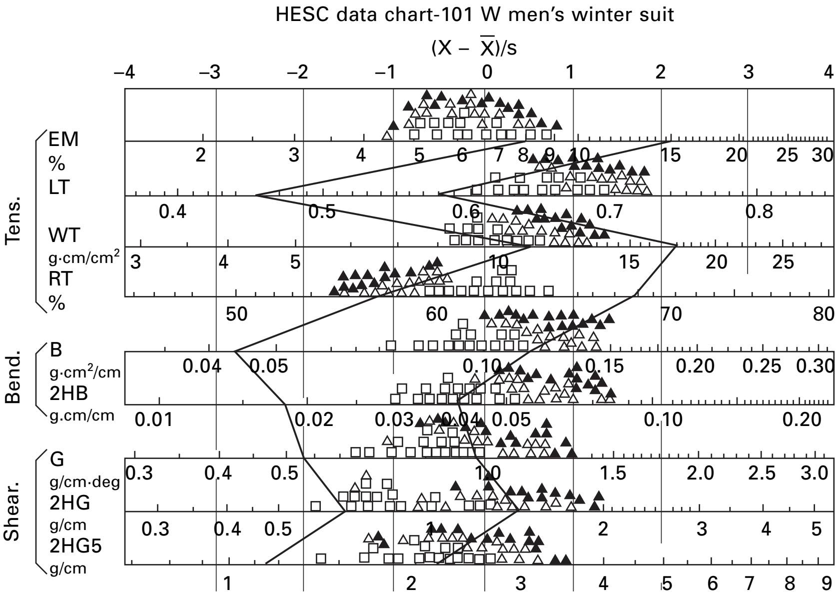
The basic principles of mechanical finishing are quite old and have been known for a long time. Modern machines utilize the same principles; however, they incorporate the latest technology for monitoring and controlling the operating parameters. These controls improve the overall quality of the finish by accurately measuring the speed, pressure and temperature of the various components working on the fabric. This trend will continue in the future as newer, more reliable instrumentation is developed. As the trend of producing textiles in low wage countries continues, the need to generate novel fabrics should take into account the qualities that can be generated by mechanical finishing, either as a single process or in combination. It will be up to the imagination of the designers as to how to incorporate these qualities into their designs.

Table 10.3 Mechanical properties of fall/winter men's suit fabrics obtained from various decatizing proceses

Process[a]		LT	WT	RT	EMT[b]	B	2HB	G	2HG	2HG5
D	Mean	0.684	11.95	57.7	6.66	0.124	0.063	1.07	1.51	2.55
	S.D.	0.018	1.03	1.8	1.03	0.010	0.009	0.06	0.30	0.60
S	Mean	0.700	11.26	59.9	6.29	0.126	0.059	1.00	1.24	2.43
	S.D.	0.022	0.85	1.7	0.94	0.009	0.007	0.19	0.32	0.67
K	Mean	0.658	9.66	63.0	6.37	0.094	0.040	0.80	0.78	2.00
	S.D.	0.023	0.60	1.8	0.85	0.010	0.006	0.08	0.16	0.40

[a] D: Weak decatizing after paper press; S: strong decatizing after paper press; K: full decatizing after paper press.

[b] All the data are means of 18 samples and averaged values of warp and weft direction deformation mode except for EMT which is only weft direction.



10.9 Mechanical properties of fall/winter men's suit fabrics, effects of various decatizing processes: △ weak decatizing, ▲ strong decatizing, □ full decatizing. *Source*: 'Fabric finishing on the basis of objective measurement of fabric mechanical properties by cooperation with apparel company engineers', by Y. Matsui, from *Objective Evaluation of Apparel Fabrics*, (ed. R. Postle, S. Kawabata and M. Niwa). Reproduced with permission of the Textile Machinery Society of Japan.

10.12 Sources of further information

Hall [3] and Midgley [4] are excellent resources dealing with the subject of mechanical finishing, Even though these are old publications, they provide an in-depth discussion of the old machines for each topic. Tomasino [5] devotes a section to a discussion of mechanical finishing. Machinery manufacturers also are a good source of information, not only for describing their equipment but also for providing facts on the quality of fabrics produced on their equipment.

10.13 References

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11

Effect of refurbishment on fabric hand

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11.1 Introduction

Refurbishment processes for apparel is a term generally used to include all operations used in the maintenance and care of apparel and some interior textiles. The term includes dry cleaning, domestic and commercial laundering (aqueous cleaning) and, most importantly, the pressing or ironing operations that are used to restore the smooth, pressed appearance of garments.

The stability of garments to such refurbishment operations has always been considered a key aspect of quality. Quality assurance procedures to measure the stability of a whole range of fabric properties to washing, dry cleaning and pressing are enshrined in standards and tests published by bodies such as the AATCC and ISO. The fabric physical properties considered most important include tensile strength, abrasion resistance, smooth appearance and pilling propensity as well as the fastness of dyestuffs. As key aesthetic features, the stability of the appearance and hand of garments and their component fabrics is an importance determinant of the perceived durability/ quality of apparel.

Considerable effort has been made in recent years into looking at the effect of refurbishment processes on hand. This has been the result of several related lines of study and the availability of objective methods of measuring both hand, or, perhaps more accurately, change in hand and the fabric mechanical properties that determine hand. The objectives of the studies have included:

- Stability of new fabrics (e.g. Shingosen) or the hand imparted by new finishes (e.g. crisp hand) to repeated laundering
- The impact of wash additives on hand (e.g. after-rinse softeners) and their durability
- The stability of functional finishes (and the hand imposed by them) to repeated laundering.

It is anticipated that the more recent development of newer nano-finishes designed to impart new hands to traditional fabrics will also require studies of this type.

11.2 Refurbishment of traditional fabrics

Comparison of the many papers that have reported the effects of dry and wet cleaning on the hand of fabrics indicates that the outcomes are extremely complex. It has been demonstrated that the effects of the refurbishment processes vary with the fabric and fibre type, the refurbishment processes and the conditions used, as well as the history of the fabric and/or garment.

The processes of refurbishment have elements in common with processes used to clean or prepare fabrics in finishing during manufacture. Dry-cleaning has a mirror in solvent scouring, whereas aqueous laundering can be compared with the aqueous scouring and milling processes using to finish fabrics. Finally, a number of processes are used to press fabric in finishing to establish a smooth appearance and hand. In garment manufacture, garment parts can also be pressed a number of times before the garment is finished. These pressing processes are mirrored in the pressing or ironing processes used in refurbishment.

Just as the effect of the above finishing operations on fabric physical properties and hand depends on the prior history of the fabric, so do the effects of refurbishment. The conflicting results obtained by workers often reflect the different properties of the fabrics on which they conducted the study rather than a genuine difference of outcomes or conclusions.

11.2.1 Dry cleaning of worsted suiting

Dry cleaning or solvent washing is widely used to clean delicate fabrics/garments for which the action of water would cause unacceptable changes in appearance (including dye bleeding), hand or physical properties. Dry cleaning normally involves four steps:

- Mechanical action while immersed in a solvent (white spirit or perchlorethylene), which may contain a small amount of water that has been emulsified using detergents
- Spin extraction of the excess solvent
- Tumble dry
- Steam press.

A number of studies have used objective measurement of those low stress mechanical and physical properties of the fabric associated with hand to assess the effect of dry-cleaning on a range of fabric types.[1] These properties have been commonly measured using the KES-F or FAST systems, described in earlier chapters. The hand of wool fabrics can be improved by dry cleaning;

the fabrics become more supple and smoother.[2–4] The extensibility of the fabric is increased, the bending and shear rigidity of the fabrics (controlling stiffness) are reduced, the thickness of the fabrics increases, the bending and shear hysteresis are reduced and the resiliency is improved. Subjectively the fabric becomes more supple, smoother and fuller. Only in the specific instance of Japanese summer-weight suiting are such changes associated with a deterioration in hand.

The magnitude of the changes varied with the fabric and the effect was marginally greater when the temperature of the scouring stage was increased. Observations[3,5] of the independent effect of the pressing operation (without pre-laundering) suggest that the effect was to increase fabric stiffness while reducing thickness. In contrast, Shiomi and Niwa[6] and Dhingra *et al.*[4] observed a reduction in bending and shear rigidity and hysteresis in a full dry cleaning cycle as well as in the pressing cycle (independently applied – Table 11.1).

Table 11.1 Effect of dry cleaning and pressing on fabric mechanical properties

Property	Units	Control	Dry clean and press	Press only
Extensibility	%	6.4	7.2	7.6
Tensile resiliency	%	72	71	71
Bending rigidity (B)	mNm	4.7	4.4	5.0
Bending hysteresis (2HB)	mN	120	90	100
Residual curvature (0.5 ¥ 2HB/B)	m^{-1}	13	10	10
Shear rigidity (G)	N/m	26.7	23.6	20.2
Shear hysteresis (2HG)	N/m	0.39	0.33	0.29
Residual strain (0.5 ¥ 2HG/G)	mrad	7.4	7.4	7.3
Thickness	mm	0.47	0.69	0.60
Work to compress	J/m^2	0.12	0.23	0.18
Compressional resiliency	%	53	48	67

Source: Dhingra *et al.*[4]

It is suggested that the answer to this apparent conflict may lie in the different pressing conditions that can be used and the specific behaviour of wool fibres in steam. The effect of pressing depends not only on the conditions used but also on the moisture content of the wool prior to and during pressing.[7,8] When pressed and steamed for a short time, wool is temporarily set (sometimes called cohesive setting). Provided the fabric is cooled while it is still constrained, a high level of temporary set is imparted but there is no relaxation of the strains built up in the pressing action. The increased fibre–fibre contact resulting from pressing can, without relaxation, restrict the relative movement of adjacent fibres and yarns and thereby increase fabric stiffness. If the fabric is released while still hot and cooled while unconstrained (also a common pressing procedure), the temporary set imparted is less and the increase in stiffness related properties lower. The rate at which these setting and relaxation processes occur depends on the moisture content of the fibres, and therefore the steaming conditions, the amount of 'baking' (as opposed to 'steaming' in the press), and the time between the drying operation and subsequent pressing.

To further complicate the issue, dry cleaning usually has a water load that is suspended using a solvent-soluble surfactant system. This aqueous load aids the removal of water-soluble soils. The water can aid relaxation processes in all fibres, and in the case of wool, promote felting.[9] The overall effect of dry cleaning on hand can thus depend on:

- The solvent and its water load
- The mechanical action in washing
- The solvent temperature
- The extent of drying
- The conditioning time before pressing
- The conditions of pressing (head pressure, steaming, baking and cooling times)
- Any softeners that may be used.[10]

It is not surprising, therefore, that there is some conflict in the literature.

In recent years, the safety problems associated with white spirit and the environmental problems associated with the common chlorinated hydrocarbon solvents (e.g. perchlorethylene) have led to the search for alternative dry cleaning solvents. More recently, machinery has been developed to use supercritical CO_2 for dry cleaning. The machinery is complex and expensive and the technology has yet to be widely adopted. Nevertheless, it is claimed that the process minimises any detrimental effect on garments by the cleaning process, including any deterioration in fabric hand. To date, no objective measurements of properties related to hand have been published on its effect on fabric hand, although it would be expected to be minimal.

Little has been published on the effects of dry cleaning on non-wool fabrics beyond the claims made by manufacturers of dry-cleaning equipment.

11.2.2 Aqueous laundering

Aqueous laundering is the preferred technique for domestic and some industrial applications. The environmental issues of solvent and the simplicity of aqueous systems must be must be balanced by the water pollution and higher energy demand in heating and drying of water-wet garments. For wool and other animal hair products, the natural felting propensity of fabrics is normally overcome by suitable treatment of the fibres, or fabric making aqueous cleaning a viable option for wool garments.

Denim and other cellulosic fabrics

The adverse effects of laundering on cotton fabrics are well recognised by consumers and have been described in a number of studies.[11] In one such study using 100% cotton single piqué knitted fabrics,[12] the changes noted were an increase in stiffness (increased shear rigidity), a reduction in resilience (also seen as an increase in hysteresis in shear deformation), a reduction in extensibility, and an increase in thickness and surface friction. An earlier study on babies' underwear[13] noted similar effects. All these effects are consistent with deterioration in fabric hand, and most particularly in fabric softness. Similar effects were also observed using[14,15] 1 ¥ 1 rib knit fabrics. This study also included subjective evaluations using a range of hand descriptors. After just one cycle some subjective characteristics (e.g. 'bounciness' – resiliency) are changed. Certainly after 50 cycles, significant changes in most characteristics were noted (including reductions in softness and smoothness). An approximately linear relationship between the changes in fabric properties during laundering and the square root of the number of laundering cycles has been reported.[13]

The detergent used and the method of drying both have significant effects on subjective evaluations. Tumble-drying produced a fabric that was rated thicker and less soft and, it has been reported that,[13] contrary to the labelling advice on many garments, tumble-drying can impart less shrinkage and a better hand to laundered garments.

The changes in the subjective hand and mechanical properties of cotton fabrics resulting from laundering are dominated by the increases in shear and bending stiffness and the reduction in extensibility. These changes are entirely consistent with the observed changes in fabric softness and extensibility occurring in washing, and with consumer complaints that cotton knitwear becomes dry and harsh after laundering. The increase in fabric harshness and the changes in fabric mechanical properties have been variously attributed to increased contact between the cotton fibres (the surfaces of which, when untreated, have high friction)[16] and fibrillation of the fibre under mechanical action.

Several authors have noted the excellent correlation between shear hysteresis and subjective softness of cotton fabrics varying from knits through plain weaves to terry towelling[17,18] in a range of applications.

Synthetic fabrics

The hand of acrylic knitwear, unlike that of cotton, can initially improve on laundering[16] giving a softer, warmer and bouncier feel. These subjective changes are associated with a reduction in shear rigidity and hysteresis and an increase in resiliency of the fabric. On acrylics the effect of gentle wash cycles and line drying is small while multiple severe cycles and tumble-drying contribute to a deterioration in hand. This deterioration has been attributed to the loss of texture and bulk in the fibres, observed by the consumer as stretching and a harsh hand.

Wool

The aqueous laundering of wool products is made complex by the tendency of wool to felt in water under mechanical action. Laundering of wool products, especially where this involves tumble-drying, is rarely practicable unless the fibres or fabric have been treated to prevent felting. There are a number of processes used to prevent the felting of wool and the impact of laundering will depend on the process used. In general, however, provided there is no felting, laundering tends to soften the hand of wool. This often-dramatic change in softness is observed as a reduction in the shear and bending rigidities of the fabric, as well as changes in other properties. The changes normally occur in the first laundering cycles after which the hand of the fabric will be stable while there is no felting. A gradual increase in thickness accompanies an increase in the fuzzing of the surface of wool fabrics as laundering continues. Extended laundering of wool products will lead to a subjectively observed reduction in softness, which is consistent with the observed increase in stiffness and reduction in extensibility and resiliency.

Garments

Garments can behave differently from sample fabrics (or more commonly fabric swatches) in laundering. The three-dimensional structure ensures that different forces (both distortive and abrasive) are imposed in the washing and tumble-drying operations. Moreover, many garments require restorative ironing which further changes the properties of the fabric. Differences between the changes in the hand of fabric-in-garments and samples of the same fabric have been reported.[13]

Little has been published on the effects of pressing and restorative ironing on aqueous laundered garments.

11.2.3 After-wash-rinse softeners

Laundering is normally not a simple matter of detergent, water and mechanical action. The application of domestic softeners in the rinse cycle is now common practice in both the domestic and commercial laundering of all garments. A wide range of rinse products is available, the active ingredients of which are commonly cationic surfactants. The subjective and objective effects of softeners used in rinse aids has been described by several authors and measured in a variety of ways[19–22] for cellulosic, wool and synthetic fabrics and their blends (see Table 11.2). The most notable and widely reported effect of rinse aids or softeners is the large reduction in hysteresis of the softened fabric, particularly in shear deformation, as shown in Fig. 11.1 and Table 11.2.

Table 11.2 Effect of softeners on the properties of cotton and polyester fabric

Mechanical property[a]	Cotton		Polyester	
	Control	Softener	Control	Softener
Extensibility (%)	24.5	28.0	8.5	8.9
Bending rigidity (mNm)	0.020	0.022	0.007	0.006
Residual curvature (m^{-1})	17.5	11.5	7.4	5.6
Shear rigidity (N/m)	0.25	0.20	0.68	0.62
Shear hysteresis (N/m)	1.09	0.71	1.59	0.59
Thickness (mm)	1.03	1.03	0.57	0.57
Compressional resiliency (%)	33.6	33.5	50.1	61.5
Surface friction	0.21	0.21	0.20	0.17

[a] Measured using the KES-F instrumentation, from Inoue *et al.*[19]

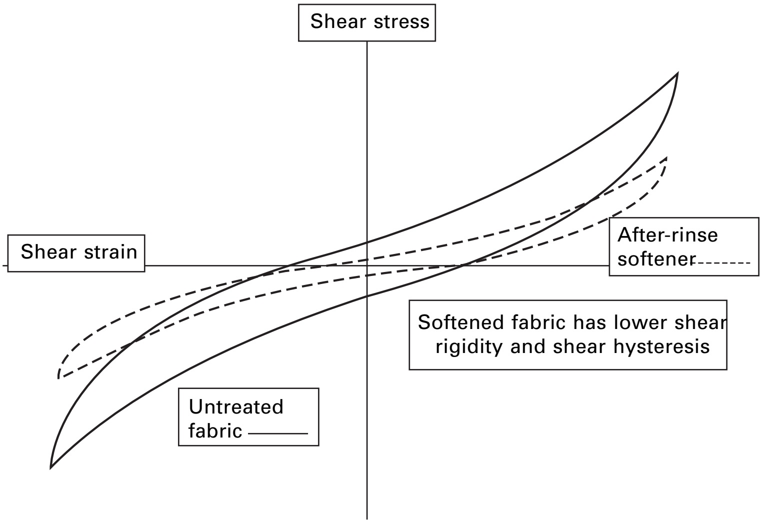

Fig. 11.1 Effect of softeners on fabric deformation in shear.

Inoue *et al.*[19] reported that softeners applied in the final rinse of a laundering process were more effective than those formulated with the detergent, paralleling the situation also reported in the cleaning and conditioning of hair. The absence of less effective detergent–softener complexes and the appropriate orientation of the softener on the fibre surface have been cited as the cause of this widely observed effect (Table 11.3).

The resiliency in compressional deformation has also been shown to be a

Table 11.3 Effect of after-rinse softener and detergent on fabric properties

Property	Units	Untreated	Softener only	Detergent + softener
Shear rigidity (G)	N/m	59.6	46.6	54.0
Shear hysteresis (2HG)	N/m	2.8	1.1	2.0
Residual strain (0.5 ¥ 2HG/G)	mrad	46.6	24.2	37.3
Bending rigidity (B)	mNm	4.0	2.6	3.1
Bending hysteresis (2HB)	mN	367.8	269.7	308.9
Residual curvature (0.5 ¥ 2HB/B)	m^{-1}	45.7	50.9	49.2

From Inone *et al.*[19]

good indicator of softness, especially after laundering. Interestingly, in spite of the subjectively observed improvement in fabric smoothness, changes in surface frictional properties of fabrics have not been consistently observed using the KES-F instrumentation. The reasons for this remain obscure and may reflect differences between the frictional contact of the human hand and the KES-F friction head with the fabric or, alternatively, may reflect the complexity of the relationship between subjective smoothness and fabric properties.

The study on knitwear by Inoue also noted the effect of softener on other aspects of hand. These included 'hydrophobic character', air permeability, thermal conductivity and water vapour transport, all of which are thought to affect hand and ultimately wearer comfort.

11.3 Role of fabric history/finish

Garments rarely arrive at the laundering process without a history. This history includes the finishing of the fabric, the manipulation and pressing of the fabric in garment manufacture and any garment-based processing that may have been undertaken. Garment-based processing of woven products is normally confined to pure cotton garments. It is used in some easycare processes, in the dyeing of some garments and in the achievement of some fashion effects (stone washing).

Apparent inconsistencies in the literature sometimes reflect the history of the fabric used in the study.

11.3.1 Denims

In certain fabrics, notably denims, starches are used to enhanced the stiffness of the fabric to the levels of fashion demands. Laundering softens starched fabrics as does garment finishing operations such as mill or stone washing prior to sale. Similar changes in the stiffness of some denims can also be achieved in laundering processes.

11.3.2 Chemical softeners

Chemical softeners are sometimes used in the finishing of fabrics manufactured from cellulosic fibres (cotton, rayon, etc.) and their blends with polyester.[23] Softeners used in finishing include the wide range of cationic organic compounds used as rinse aids but also include the more expensive aminofunctional silicones that also have wide use as hair conditioners. Softeners applied in finishing modify many of the low stress mechanical properties associated with hand. The large reduction in hysteresis of the softened fabric in shear deformation (2HG, 2HG5) noted previously with laundry softeners and rinse aids has been shown to be a quality control tool for the comparison of softeners[5,19] and for the evaluation of their stability in subsequent laundering.[18]

The effect on laundering of softened fabrics (i.e. treated with softener in the manufacturing process) depends on the stability of the softener. However, as the effects of laundering of cellulosic fabrics are opposite to that of softeners, the response of unsoftened and softened fabrics is more or less ‘in the same direction’. It is anticipated, indeed desirable, that the softener applied in finishing would continue to offset the detrimental effects of laundering for several cycles.

11.3.3 Wrinkle-free fabrics

Durable press resins based on formaldehyde derivatives are widely used in the production of wrinkle-free garments made from cotton, viscose and their blends with polyester. These resins are applied to the fabric and delayed-cured when the garment has been manufactured or applied to the preformed garment. The resins themselves have a significant effect on fabric hand, generally resulting in a stiffening and a loss of fabric extensibility.[24] A wide range of softeners are co-applied with these resins to offset the detrimental effect of the resin on hand. The softeners ameliorate the increase in fabric stiffness (bending and shear rigidity) and increase fabric smoothness, often to a level beyond that of the untreated fabric. The response of wrinkle-free fabrics to laundering can differ from that of the parent fabric in some areas[12] and depends on the resin–softener combinations used. Lau *et al.*[12] reported that the effect of the total wrinkle recovery treatment is to reduce the adverse effects of laundering on many low-stress mechanical properties related to hand. Fabrics with wrinkle-free finishes are more stable to laundering.

11.3.4 Polymer treatments on wool

Woven pure wool fabrics are treated with water-soluble or emulsified polymers to impart shrink resistance. These polymers act by forming interfibre bonds that prevent the relative motion of fibres responsible for felting.

By restricting fibre movement the bonds also stiffen the fabric, an effect associated with a deterioration of the hand of the fabric. Some of these bonds are broken in the first wash, resulting in a partial restoration of hand.[25,26] Indeed, to improve the hand of the fabric prior to sale to garment manufacturers, finishers will wash-off the fabric to duplicate the effects of the first wash. A softener will often be applied in this wash-off. Obviously the changes in the hand of washable wool garments during their first laundering will depend on the procedures adopted in fabric finishing.

11.3.5 The setting of wool

Earlier in this chapter, reference was made to the complexity of the response of wool to refurbishment. The felting propensity of wool and the methods used to prevent the felting of wool garments during laundering are only the first level of this complexity. As wool felts, the fabric becomes subjectively stiffer and thicker, consistent with increases in measured thickness and rigidity (shear and bending). In addition to this, the manner in which the unique setting characteristics of wool fabrics are exploited by finishers and garment makers affect its performance. Like all polymers, wool has a glass transition temperature (T_g) that affects its setting characteristics.[27] Temporary set is imposed by deforming the fibre while it is above the T_g and not releasing it until it is below the T_g. The lower mobility of the protein macromolecules ensures that set is lost slowly while the fibre remains below the T_g but quickly when the fibre is heated or re-wet. Wool is plasticised by water so that the wet fibre is below its T_g while the dry fibre is above T_g.[27,28] This difference is exploited in areas as diverse as the wet–dry waving of hair as well the smooth drying of wool. Other fibres, such as nylon (50–60°C) and polyester (70–80°C) have glass transition temperatures but none is affected by water to the same extent as wool.

Wool has a second apparent transition associated with the permanent setting of the fibre. Unlike other fibres, this setting involves the rearrangement of covalent (disulphide) bonds in the fibre, allowing greater mobility of the macromolecules. The permanent set imparted at high temperatures (around 120°C in the fibre at normal regain), or at lower temperatures using catalysts, is permanent to wetting and heat.

During the finishing of wool fabrics, they are pressed in an operation called decatising. If the decatising is conducted under conditions where the wool is permanently set (high temperature and/or long time) the flattening of the wool will be permanent to laundering. Normally only woven fabrics and a small number of knitted fabrics are pressure decatised to impart permanent set. When temporary setting operations have been used to flatten or press fabrics prior to making up, it is likely that there will be an increase in the thickness and an associated change in hand when the fabric is wet out in the first wash (Table 11.4).

Table 11.4 Stability of the finish/thickness of wool fabric to laundering

Finishing conditions	Thickness (mm)	
	Initial	After wetting and drying
Decatise, 0.5 min, cold release	0.64	0.80
Decatise, 2 min, cold release	0.64	0.77
Decatise, 5 min, cold release	0.66	0.74
Decatise, 10 min, cold release	0.62	0.68
Decatise, 15 min, cold release	0.63	0.68
Decatise, 2 min, hot release	0.73	0.76

11.4 Refurbishment of newer fabric types

As newer fibres are developed (Shingosen, Optim, microfibres[18]), information on their hand and the effects of refurbishment become a key part of the decision to purchase by the consumer and, before that, of the garment maker and retailer.

Matsudaira and Hanyu[29] reported a change in the hand of Shingosen fabrics in the related low-stress mechanical properties after repeated home laundering. Changes in the 'basic mechanical properties are small but their effect of those properties on overall fabric hand is very important'.[29] The extensibility of the fabrics increased as a result of laundering.

11.5 Future trends

The ability to withstand refurbishment without observable deterioration in the aesthetic or functional properties will remain a key aspect of quality in apparel. Although disposable apparel is available, it has specialised uses that have little to do with appearance and perceived quality. Research and development to ensure that fabrics maintain their hand and appearance after refurbishment will continue on a number of fronts:

- Machine makers will continue to produce better, gentler and more environmentally friendly machines for both aqueous laundering and, at least in the short term, dry cleaning.

- Newer techniques for dry cleaning with more environmentally friendly solvents (such as supercritical CO_2) will continue to be developed.
- Detergent makers continue to develop more effective detergents that are less harmful to the fibres and better rinse aids to ensure that garments maintain their soft hand.
- Chemical companies will develop more stable effective auxiliaries to optimise the hand of fabrics and ensure that hand is maintained during any subsequent refurbishment.
- Finally, fabric finishers will seek to ensure that any cloth or garment maintains its excellent appearance in garment manufacture and subsequent use.

It is likely that, in the future and for environmental reasons, the use of dry cleaning will decline and more garments will be required to be stable to aqueous laundering. This will be achievable through the adoption of all the options listed above.

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Part IV

Appendices

Appendix A

The Standardization and Analysis of Hand Evaluation* (second edition)

S KAWABATA, The Textile Machinery Society, Japan

A.1 History of the committee

A.1.1 Publication of the HESC Standard of Hand Evaluation

A confused situation of hand evaluation in Japan when the committee started

There is no doubt that the hand judgement of fabric is one of the important tests of fabric property and has been used widely by many people. We can classify these into two categories, experts in factories and general consumers. The experts in factories, especially in the fabric-finishing factories, have used hand judgement to control the property of their products on a daily basis. Furthermore, each consumer also examines the property of the fabric by his 'hand' to select a good clothing material according to his feeling and experience when he is going to purchase it.

In both cases, fabric hand is judged mainly by the sense of touch on the basis of individual standards of the hand feeling and then the hand feeling is expressed by many words such as 'stiff', 'soft', 'paper-like', etc.

The experts usually use some common terms for the hand expressions although these terms were not clearly defined. Koshi (stiffness), Numeri (smoothness) and Fukurami (fullness and softness) are examples of them. On the other hand, every consumer expresses his feeling of hand in his own language which is not classified. Moreover some consumers confuse hand feeling with colour sense and fashion sense. Such different conceptions on hand have confused every communication about the hand property so we were in a complicated situation.

Everybody says that hand is important and related closely to the quality

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*In memory of Professor Sueo Kawabata (courtesy of the Hand Evaluation and Standardization Committee), The Textile Machinery Society, Japan.

of fabric but the simple question how the hand is defined cannot be answered.

Conversely, many kinds of hand expressions are often used by many people every day and everywhere for business and for reseach of textiles.

The conception of hand

In 1968, Kawabata proposed a conception of the hand by the two following main hypotheses:

(1) One mainly judges the hand by the feeling which comes from the mechanical property of fabric.
(2) Criteria for hand judgement are based on whether or not the fabric possesses suitable properties for its use as a clothing material.

These hypotheses were established after many discussions with many experts on hand judgement in factories in Japan.

For the second hypothesis, the problem is who can judge whether the fabric is suitable for its intended use. Kawabata's idea about this was as follows.

Consumer judgement is essentially important and the source of the criterion of hand judgement. But each consumer has not enough experience of wearing many kinds of fabric in general, but it is certainly true that each opinion has been noted over a long time. And the opinions of the consumers were fed back to the fabric producers, especially to the engineers of the finishing process, because they had to know whether or not their fabric products were of good quality. Thus, Kawabata considered that these experts in the finishing process must be the most appropriate people to judge the hand based on the hypotheses given above, and began to consult them in 1970, together with his coworker, Dr M. Niwa.

As mentioned before, the experts use some common expressions for hand evaluation. But it has been found that these expressions are not classified and not defined yet, and sometimes they have some different connotations for the feeling of each of these expressions.

The organizing of the committee

As a result of the situation outlined above, Kawabata organized the 'Hand Evaluation and Standardization Committee' as one of the research committees which belongs to the Textile Machinery Society of Japan.

The subjects of this committee's activity were as follows.

(1) Selection of the important hand expressions from a number of these expressions.

(2) Definition of the feeling with respect to each of these important expressions.
(3) Establishment of the standard samples which indicate the feeling with respect to each of the expressions and its intensity by numerical value.
(4) Analysis of experts' hand feeling and establishment of the translation formulae that can translate the mechanical properties of fabric into experts' hand.

For the subjects (1), (2) and (3) above, ten experts from the leading textile companies in Japan gathered together as committee members and continued discussions about the above items for three years.

The mechanical measurement of fabric properties

On the other hand, Kawabata continued his fundamental research on the mechanical properties of fabrics at that time with his coworker, Dr M. Niwa.

This work was very helpful for the research on subject (4), that is, for the scientific analysis of the hand evaluation.

Being based on the fundamental research, the author designed a system of instrumentation for measuring the fundamental mechanical properties of fabric and constructed the system which was named KES-F.

After that, 12 people who were engineers or scientists from companies and universities, joined with this committee to help the research on subject (4) mainly. A number of fabrics were measured by the measuring system KES-F and the data from it were analyzed using a computer by Kawabata and Dr M. Niwa.

The main purpose of the activity of this committee covered subjects (1), (2) and (3), that is, the establishment of the standard of hand evaluation.

Members of the committee who contributed to the establishment of the standard of hand evaluation

The following members of the committee contributed to the establishment of this standard for hand evaluation.

Chairman:

Dr Sueo Kawabata	Department of Polymer Chemistry, Kyoto University, Kyoto, 606

Secretary:

Dr Masako Niwa	Department of Clothing Science, Nara Women's University.

Committee members: (*: executive member)

Sub-committee-A (Hand Evaluation Group. All of them are experts in the factories).

T. Adachi*	Miyuki Woollen Textile Co., Ltd
K. Furuichi	Seiren Co., Ltd
H. Hatakama*	Daido Worsted Mills Ltd
M. Kondo*	Kanebo Co., Ltd. Ogaki Mill
S. Kurihara*	Mitsuboshi Sensei Co., Ltd
S. Miyamoto	Gisen Co., Ltd
Masao Mori*	Tokai Senko K.K. Those experts, T. Kato, H. Mugikawa, T. Murasawa and T. Ryochi who are engineers of the Tokai Senko K.K. assisted Mr Mori at the evaluation.
Masuichi Mori*	Tsuyakin Kogyo Co., Ltd
M. Morioka*	The Japan Wool Textile Co., Ltd
T. Nakai	Crown Finishing Co., Ltd
S. Nakano	Toa Wool Spinning and Weaving Co., Ltd Mr Matsuzaki, engineer of Toa Wool Spinning and Weaving Co., Ltd. assisted Mr Nakano at the evaluation.
M. Okada	Gisen Co., Ltd
K. Saito*	Kurabo Industries Ltd. Tsu Mill
K. Tamada*	Unitika Ltd T. Suzuki, engineer of Unitika Ltd. Miyagawa Mill, assisted Mr Tamada at the evaluation.
Y. Tamura*	Miyuki Woollen Textile Co., Ltd
E. Tanita*	Crown Finishing Co., Ltd
Y. Watanabe	Toyobo Co., Ltd Those experts, M. Takada and R. Toriyama who are engineers of the Toyobo Co., Ltd. assisted Mr Watanabe at the evaluation.

Sub-committee-C (contributed to the measurement of the mechanical properties of the fabrics and the arrangement of the data.)

T. Karakawa*	Kurabo Industries Ltd, Tsu Mill
Y. Kawai	Aichi Syukutoku Junior College
S. Kawase*	Kanebo Co., Ltd
M. Kiriyama	Chori Co., Ltd
K. Kita*	Toray Industries, Inc.
K. Kusunose*	Nara Women's University
H. Morooka	Osaka Seikei Women's Junior College
M. Sakamura	Kuraray Co., Ltd
T. Sato	Kao Soap Co., Ltd
Y. Shibata*	International Wool Secretariat, Japan Branch, Inchinomiya Technical Center
R. Sugishita	Nara Women's University

I. Tabayashi*	Toray Industries Inc.
S. Yamaguchi*	Kuraray Co., Ltd

The following people, who were students of Nara Women's University, assisted the activity of sub-committee-C:

A. Akamatsu, Y. Kikuchi, S. Murata and R. Nagasawa.

Contribution from the companies for the publication of The HESC standard of hand evaluation, first edition

The following companies offered samples for publishing the reproduced standard samples of the *HESC Standard of Hand Evaluation*.

Daido Worsted Mills Ltd
Daitobo Co., Ltd
Fukaki Woollen Textile Co., Ltd
Gisen Co., Ltd
International Wool Secretariat, Japan Branch
Kanebo Co., Ltd
Kurabo Industries Ltd
Kuraray Co., Ltd
Mitsuboshi Sensei Co., Ltd
Miyuki Woollen Textile Co., Ltd
Ootsuka K.K.
Seiren Co., Ltd
The Japan Wool Textile Co., Ltd
Toa Wool Spinning and Weaving Co., Ltd
Tokai Senko K.K.
Toray Industries, Inc.
Toyobo Co., Ltd
Tsuyakin Kogyo Co., Ltd
Unitika Ltd.

A.1.2 Publication of *The HESC Standard of Hand Evaluation* (second edition)

Since the first edition of the *HESC Standard of Hand Evaluation* was published, five years have passed, and there are almost no copies left. Under these circumstances, the publication of the second edition was planned in 1979.

In the same manner as the publication of the first edition, the publication committee was organized. The members of the committee consist of nine experts on hand evaluation, all of them are HESC committee members and six of them were the publication committee members of the first edition.

Careful work has been carried out by the publication committee in order to reproduce the copies of the standards.

A small change in the situation from the time of the first edition is that we have the formulae by which hand values can be estimated from the basic mechanical properties of fabric with considerably higher accuracy.

Firstly, the samples collected were measured, their basic mechanical properties and the hand values were estimated by calculation, then the experts decided the samples to be used for the reproduced standard by their hand judgement. This procedure has considerably reduced the labour of the experts.

The members of the editorial committee are as follows:

Editor:
Sueo Kawabata, Kyoto University
Secretary of the editorial committee:
Masako Niwa, Nara Women's University

Editorial committee members:

S. Kurihara,	Mitsuboshi Sensei Co., Ltd
M. Kondo,	Kanebo Co., Ltd
K. Saito,	Kurabo Co., Ltd
S. Sōma,	Unitika Ltd (present, Durban, Inc.)
E. Tanita,	Crown Finishing Co., Ltd
H. Fujiwara,	The Japan Wool Textile Co., Ltd
M. Mori,	Sumi Sōgōkenkyusho
M. Morioka,	

K. Nakajima (publication business officer), The Textile Machinery Society of Japan

Some of the samples used for the reproduced standards were contributed by the companies to which the committee members belonged.

The following members of the HESC and students assisted the editorial work.

K. Komatsu,	Nara Women's University, member HESC
Y. Okamoto,	Nara Saho Women's Junior College, member HESC
K. Izumi,	Sakai Women's Junior College, member HESC
Y. Hirata,	Nara Women's University, student
S. Maeda,	Nara Women's University, student

A.1.3 Publication of the standard of hand evaluation for women's thin-dress fabrics

Several years ago, the standard of hand evaluation for women's dress fabrics had been investigated by the HESC and in 1979, the editorial committee was first organized.

Editor:
Sueo Kawabata, Kyoto University
Secretary of the editorial committee:
Masako Niwa, Nara Women's University
Editorial committee:

H. Fujiwara	The Japan Wool Textile Co., Ltd
H. Maeda	Kanebo Synthetic Fibers, Ltd
T. Mizohata	Unitika Ltd
S. Yamaguchi	Kuraray Co., Ltd
O. Wada	Teijin Ltd

K. Nakajima (publication business officer), The Textile Machinery Society of Japan.

Some of the samples used for the reproduced standard were contributed by the companies to which the editorial memebers belonged.

The editorial committee members of the *HESC Standard of Hand Evaluation*, 2nd edition (standards 1–7), which was published at the same time have taken part in the hand evaluation of the samples and in discussions about the standardization.

The following HESC members and students have given great assistance in the editorial work.

K. Izumi	Sakai Women's Junior College, member HESC
Y. Okamoto	Nara Saho Women's Junior College, member HESC
N. Makado	Nara Women's University, student
K. Moro,	Nara Women's University, student
M. Uematsu,	Nara Women's University, student.

A.2 Selection of the standard samples for hand evaluation

A.2.1 Standard of the hand for men's suit fabrics

Selection of important hand expressions

From hypothesis (2) on page 390, the criterion of fabric hand is based on the end-use of the fabric. The committee consisting of the experts accepted that this hypothesis was true, and they limited the object of the discussion to the hand evaluation of the fabric for men's suits. After many discussions, four of the primary hand expressions were selected, and at same time, the proportion of the importance of these terms in the evaluation of quality of fabrics were estimated as shown in Table A.1.

Table A.1 Primary hand expressions and the degree of their importance for quality evaluation

Expressions	Importance in percent	
	Winter suit	Summer suit
Numeri (Smoothness)	30	0
Shari (Crispness)	0	35
Koshi (Stiffness)	25	30
Hari (Spread, anti-drape)*		
Fukurami (Fullness and softness)	20	10
(Appearance of surface)	15	20
(Others)	10	5
Total	100	100

*In the first edition of the HESC Standard, the expression 'Hari' was omitted, and recently, Koshi and Hari were separated.

The coordinated feeling of each of the expressions

All of the expressions shown in Table A.1 are closely related with the mechanical properties except 'appearance of surface'. Thus the committee selected Numeri, Koshi and Fukurami as three primary hand expressions for winter suits and Shari and Koshi as two for summer suits. And recently, the Fukurami and the Hari have been added as the primary hand expressions for summer-suit fabrics. The reason for this new addition is that these two expressions are necessary for quality judgement of summer-suit fabrics. Next, the answers to the following questions were discussed and the coordinated definitions were obtained for each of these expressions.

(a) What kind of feelings are related with its hand expressions?
(b) Which properties of fabric are related to the judgement?

The coordinated answers of the committee are as follows.

Numeri

Answer against questions (a) and (b) are:

(a) A mixed feeling come from smooth, limber and soft feeling. Its typical feeling is given by the fabric woven with cashmere fibre. Experts express this feeling by their professional words which means 'the softness comes from fine and high quality wool fibres'.
(b) Flexibility, smoothness, touch of smooth bending and springy property in bending.

Shari

(a) 'Shari-shari' feeling. This 'shari shari' is the crisp and sharp sound which is made by rubbing the surface of the fabric with itself when the surface is slightly rough and slightly hard just as dry sand. This 'shari' feeling brings us a cool feeling. And this feeling is brought by hard and strongly twisted yarn. For example, woolen plush fabric usually possesses this feeling strongly.
(b) Mainly surface touch. All kinds of hardness of fabric promote this feeling.

Koshi

(a) and (b) A stiff feeling from the bending property and springy property promotes its feeling. High density fabrics made with springy and elastic yarn usually possess this feeling strongly.

Hari

Anti-drape stiffness, no matter whether the fabic is springy or not. This word means 'spread'.

Fukurami

(a) Feeling come from a bulky, rich and well formed feeling.
(b) Springy property in compression and thickness accompanied with warm feeling.

The experts from different companies had not discussed with each other about these definitions before the organizing committee, but they had an almost common understanding about the hand, and there was not so much difference in their conception and understanding of these expressions. The primary hand expression and their definitions are shown in Table A.2.

Determination of the standard samples

In 1973, membership of the committee was increased and a sub-committee which consisted of 20 experts was organized in the committee. On the other hand, 500 samples for men's winter suits had been collected from many textile companies in Japan. All samples were collected randomly from the commercial products for use in men's suits. That is, some of the samples were knitted fabrics and some were polyester fabrics, but all of them are used for 'men's suit'.

After reconfirmation of the definition of each of the primary hands was

Table A.2 Primary hand expressions and their definitions

Men's winter suit fabric

Hand (Japanese)	(English)	Definition
1. Koshi	Stiffness	A feeling related with bending stiffness. Springy property promotes this feeling. The fabric having compact weaving density and woven by springy and elastic yarn makes this feeling strong.
2. Numeri	Smoothness	A mixed feeling come from smooth, limber and soft feeling. The fabric woven from cashmere fibre gives this feeling strongly.
3. Fukurami	Fullness and softness	A feeling come from bulky, rich and well formed feeling. Springy property in compression and thickness accompanied with warm feeling are closely related with this feeling. (Fukurami means 'swelling')

Men's summer suit fabric

Hand (Japanese)	(English)	Definition
1. Koshi	Stiffness	Same as Koshi in Table A.1.
2. Shari	Crispness	A feeling come from crisp and rough surface of fabric. This feeling is brought by hard and strongly twisted yarn. This feeling brings us a cool feeling. (This word means a crisp, dry and sharp sound arisen by rubbing the fabric with itself)
3. Hari[a]	Anti-drape stiffness	Anti-drape stiffness, no matter whether the fabric is springy or not. (This word means 'spreading')
4. Fukurami*	Fullness and softness	Same as Fukurami in Table A.1.

[a]These are recently added to the primary hand group for the summer men's suit fabric.

made by the sub-committee, and a few differences among the understandings with respect to the hand expressions were coordinated, the experts of the sub-committee have judged many samples as follows to set up the standard.

(1) The first step. All samples were divided into three groups according to the intensity of the hand feeling for each of the hand expressions.
Group A: samples having strong feeling-intensity
Group B: samples having medium feeling-intensity
Group C: samples having weak feeling-intensity

(2) The second step. Same procedure as the first step was taken into each of the groups A, B and C, that is, each of these groups was again

divided into three sub-groups. As we have three sub-groups in each of the three main groups, we have nine groups in order of the intensity of the feeling.

(3) The third step. Samples possessing extremely strong feeling were separated from the highest group (A–A) and the samples possessing the extremely weak feeling were also separated from the lowest group (C–C) respectively. Also some adjustments were made between the adjacent two sub-groups each of which belongs to the different main groups (for example, A–C and B–A, and so on).

(4) The final step. Total number of the groups becomes finally 11 as shown in Table A.3. Each of the groups was labeled by a number from 0 to 10 according to the intensity of the feeling. The numbers were called *Hand value*, the largest number denoting the strongest feeling of hand.

Table A.3 Hand values. Samples are divided into three groups A, B and C following the intensity of the hand feeling and then the samples of each of those groups are again divided to three groups. The XH and XL are picked out from A–A and C–C groups respectively. Finally the 11 groups are obtained and labeled by numbers, 10, 9, 8, . . . , 0. This number is named Hand Value (HV) and the highest value corresponds to the strongest feeling of the hand

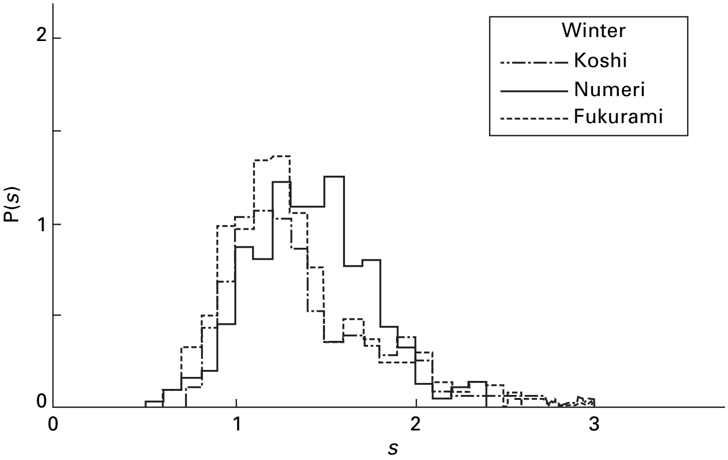
Group	XH	A (strong)			B (medium)			C (weak)			XL
		A–A	A–B	A–C	B–A	B–2	B–C	C–A	C–B	C–C	
HV	10	9	8	7	6	5	4	3	2	1	0

Each of the 20 experts had followed this procedure for all samples and for each of all the primary hand expressions.

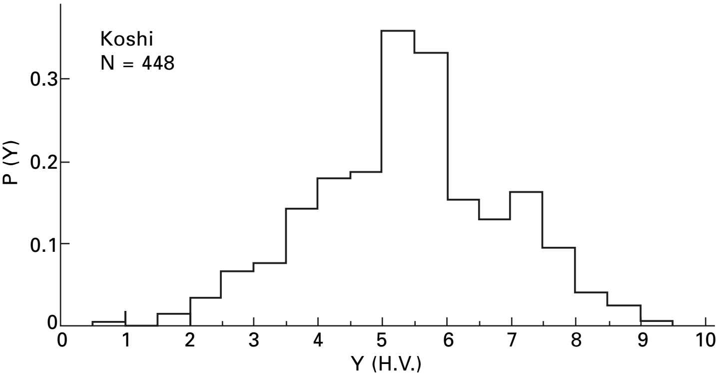
Thus, a sample has 20 hand values evaluated by the 20 experts for each of the primary hand expressions. The mean of these values was taken as the hand value of this sample. Of course, the fluctuation in the evaluated values by the 20 experts was observed for each of the samples so that the standard deviation was calculated as well as the mean value. Figure A.1 is an example of the histogram of the standard deviations observed from each of the 448 samples. The distribution of the standard deviation is narrow and this shows a good agreement among the hand values evaluated by each of the 20 experts.

On the other hand, the histograms of the mean values shown in Figs A.2–A.8 are useful to show the distribution of the hand values of commercially produced fabrics for men's suit in Japan. The mean and the standard deviation of each distribution of hand values is shown numerically in Table A.4.

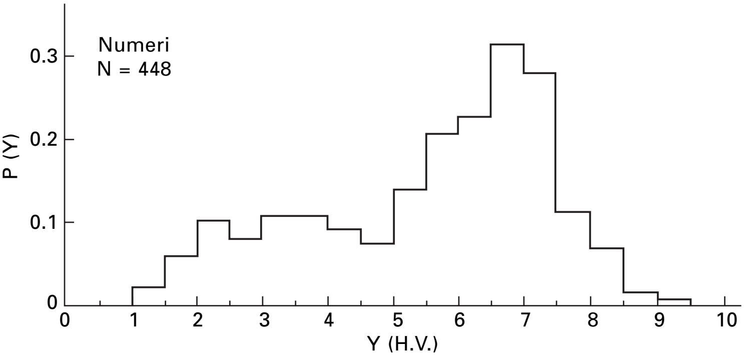
As mentioned before, the 448 samples used here consisted of many kinds of fabrics. But most samples are worsted fabrics, that is, 52% of the samples



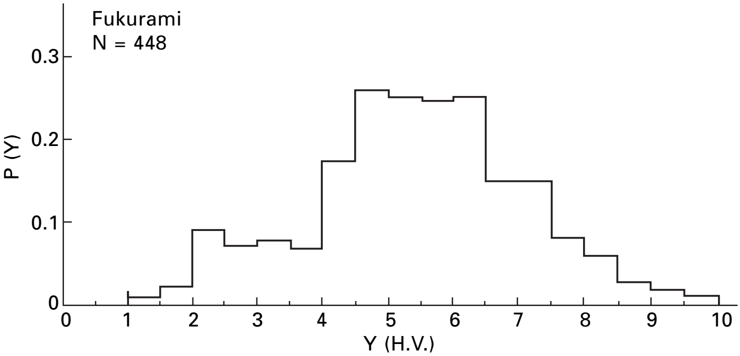
A.1 Distribution of standard deviation of the evaluation hand values by 20 experts.



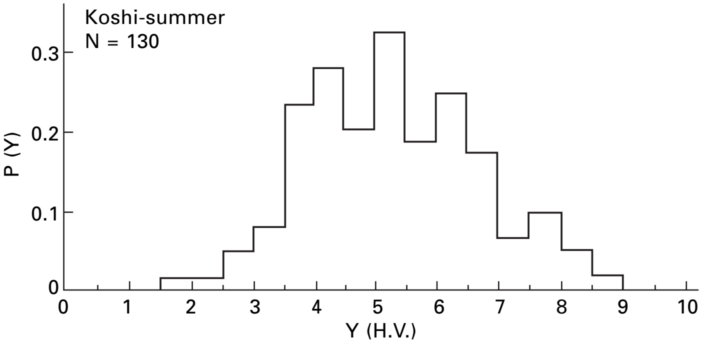
A.2 The distribution of hand values of the fabrics commercially produced in Japan shown by normalized histogram P(Y) – Koshi.



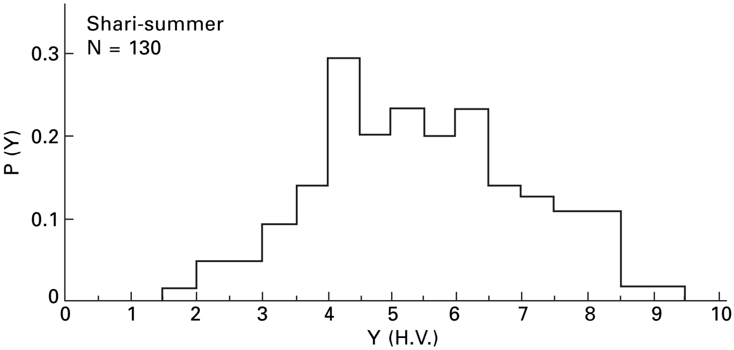
A.3 The distribution of hand values of the fabrics commercially produced in Japan shown by normalized histogram P(Y) – Numeri.



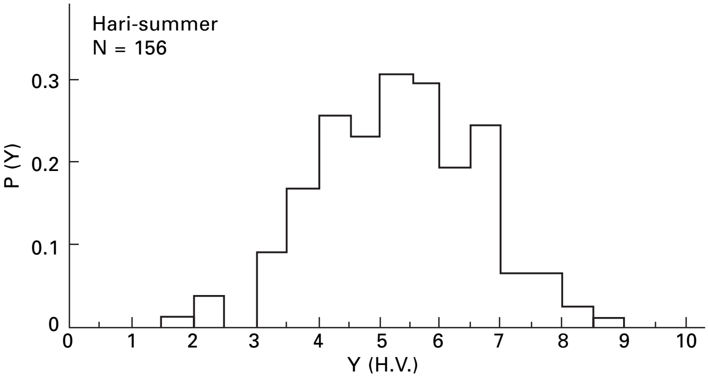
A.4 The distribution of hand values of the fabrics commercially produced in Japan shown by normalized histogram P(Y) – Fukurami.



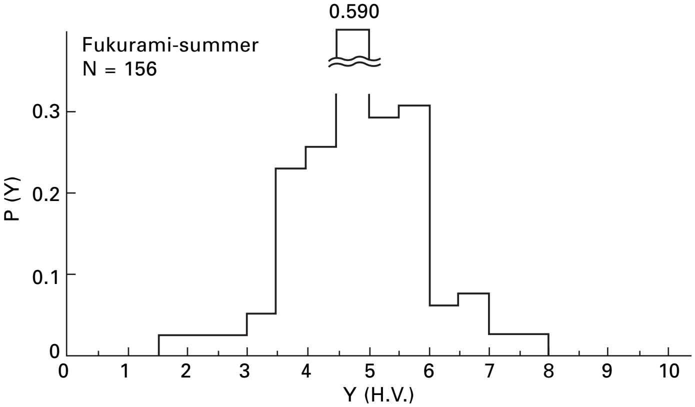
A.5 The distribution of hand values of the fabrics commercially produced in Japan shown by normalized histogram P(Y) – Koshi-summer.



A.6 The distribution of hand values of the fabrics commercially produced in Japan shown by normalized histogram P(Y) – Shari-summer.



A.7 The distribution of hand values of Hari-summer. These data were obtained from the fabrics which were collected for developing the basic mechanical properties–hand value translation formula. The histogram has little deviation from that of randomly collected samples; however, it is considered to be fairly similar to the histogram obtained from the randomly sampled fabrics.



A.8 The distribution of hand values of Fukurami-summer. These data were obtained from the fabrics which have been collected for developing basic mechanical properties–hand value translation formula. The histogram has little deviation from that of randomly collected samples; however, it is considered to be fairly similar to the histogram obtained from the random sampling case.

are worsted, 31% polyester-wool blended, 9% woolen and 6% textured yarn fabrics.

According to the preliminary work described above, all samples were evaluated for their hand and represented by the hand values as shown in Table A.5.

As shown later, this numerical expression of hand became a powerful tool

Table A.4 Mean and standard deviation of the hand values of the fabrics produced in Japan

Hand		Mean value	Standard deviation
Winter	Koshi	4.94	1.46
	Numeri	5.08	1.83
	Fukurami	4.96	1.68
Summer	Koshi	4.81	1.43
	Hari	5.39[a]	1.30[a]
	Shari	4.98	1.61
	Fukurami	4.92[a]	1.02[a]

[a] These data are taken from the samples collected for the development of basic mechanical properties HV translation formula. The values are similar to those of randomly sampled fabrics.

Table A.5 Expression of hand values

Sample no. (Winter)	Hand value		
	Numeri	Koshi	Fukurami
.	.	.	.
.	.	.	.
.	.	.	.
201	6.6	2.1	3.0
202	3.2	3.0	4.0
.	.	.	.
.	.	.	.
.	.	.	.

for the analysis of the relation between the experts' hand and the mechanical properties of fabrics.

Standard samples

All of the samples, each of which was labeled by the hand values, were examined by the committee for the purpose of picking up a set of standard samples for hand evaluation.

At the time of this selection, the following items were considered.

(1) Sample of which standard deviation of the hand values evaluated by the 20 experts is as small as possible.
(2) Sample of which hand value takes the value nearest a round number such as 1 or 2 or 3 and so on.

Table A.6 shows the hand values of the selected samples as the original set of the standard sample for men's suit fabrics.

Table A.6 Original standard

Winter	Hand value								
No. 1 Koshi									
worsted (twill)	1	2	3	4	5	6	7	8	
worsted (plain)		2	3		5	6	7	8	
wool and polyester blended			3	4	5	6	7		9
textured		2	3	4	5	6	7		
woolen	1	2	3	4		6	7		
No. 2 Numeri									
worsted	1.5	2	3.6	4	5	6	7	8	
woolen				4		6			
No. 3 Fukurami									
worsted	1	2	3	4	5	6	7	8	9
textured	1		3		5	6			
Summer									
No. 4 Koshi-summer		2		4	5	6	7	8	
No. 5 Shari-summer	1.6		3	4	5	6	7	8.3	8.6
No. 6 Fukurami-summer[a]		2		4	5	6		8	
No. 7 Hari-summer[a]	1		3		5		7		9

[a] These expressions were added in the 2nd edition of HESC Standard.

As seen from Table A.6, the greater part of the standard samples consisted of worsted fabrics and some woolen and textured yarn fabrics were selected as a supplement to them. This supplement will become useful when these kinds of fabrics are evaluated by using the standard samples.

Reproduction of the standard samples

It is very important that each of many companies and institutes possesses a copy of the set of standard samples for their hand evaluation and for use of the standardized hand values in order to use them in the technical or commercial communications between them.

The committee made a request for contributions from the leading textile companies in Japan for collecting the fabrics for the publication of 200 copies of the duplicated sets of the standard samples.

All of the requested companies whose names are listed on page 394, approved it and about 176 of the samples were collected.

The sub-committee, which is a group of experts, again evaluated all these samples based on the original standard samples, and decided their hand values for each of these samples.

In parallel with this work, another sub-committee was organized also in this committee for the purpose of measuring the mechanical and physical properties of the fabrics. In order to identify the former sub-committee from the new committee were named Sub-committee A for the former and Sub-committee C for the latter committee respectively. Based on the mechanical properties, the calculated hand value (CHV) was obtained by the translation formula (which will be described in Section A.4). These CHVs were used as the reference when sub-committee A picked up the samples for the reproduced set of the standard sample from the 176 samples.

In this duplicate set, the number of the supplement samples was reduced compared with the number in the original set. The reason is as follows. The committee considered that, for example, the hand values of two Koshi obtained from worsted fabric and from textured yarn fabric should be evaluated by essentially the same base and, for this reason, the set of standard samples must be simplified.

Based on this consideration, some of supplement samples were omitted from the set of standard samples. Finally the set shown in Table A.7 was obtained.

Table A.7 Reproduced standard for publication (first edition)

Winter	Hand value								
No. 1 Koshi									
worsted		2	3	4	5	6	7	8	9
textured			3		5		7		
No. 2 Numeri									
worsted	0.5	2	3	4	5	6	7		10
woolen		2	3	4	5.5				
No. 3 Fukurami									
worsted	0	2	3	4	5	6	7	8	9
woolen						6	7	8	9
Summer									
No. 4 Koshi-summer		2	3	4	5	6	7	8.5	
No. 5 Shari-summer		2	3	4	5	6	7	8	9

The second edition of The HESC Standard of Hand Evaluation

The publication of the second edition of *The HESC Standard of Hand Evaluation* was planned in 1979. This is also a faithfully reproduced set of the original of the standard.

A different feature from the first edition is that the layout of the samples is simplified compared with that of the first edition, that is, the layout of the sample is not continuous in order of the hand value but alternative in some portions such as 1, 3, 5 and so on. One reason of this simplification is the difficulty in getting enough samples, but another is that this simplified layout makes for easier understanding of the feeling intensity for many people who are not necessarily in professional positions.

The other different point is that the new standards, Fukurami-summer and Hari-summer, are added in this second edition; these expressions of hand were considered to be important for the quality judgement of summer-suit fabric and added as new standards recently as standard No. 6 and No. 7 respectively. The layout of the samples of the second edition is shown in Table A.8.

Table A.8 Reproduced standard for the second edition

Winter suit	Hand value								
No. 1 Koshi	1		3		5		7		9
No. 2 Numeri	1		3		5	6	7		9
No. 3 Fukurami	1		3		5	6	7		9
Summer suit									
No. 4 Koshi		2		4		6		8	
No. 5 Shari		2		4		6		8	
No. 6 Fukurami		2		4	5	6		8	
No. 7 Hari	1		3		5		7		9

A.2.2 Standard of the hand for women's dress fabrics

Classification of women's dress fabrics

The HESC started discussions on the primary hand expressions for women's dress fabrics for the purpose of standardizing in 1976 based on the HESC standard which had been established at that time.

A distinctive point of women's dresses is the diversity of style of a dress. For example, the thickness of these fabrics varies from about 0.1 mm to 2.5 mm. Therefore, the mechanical properties of these fabrics are also scattered over a very wide range.

The questions we asked were as follows.

(1) Is it possible to find some common expressions of hand for the women's fabric as we found in the men's suit fabric?
(2) Is there any requirement for standardization of these expressions if they exist?
(3) Is it possible to standardize such diverse types of fabrics?

Many discussions were repeated in the HESC, and questionnaires were given frequently to many people who were working at the women's dress manufacturer in Japan. Then we concluded that there were some hand-expressions commonly used; however, the understanding of these expressions was not so clear as in the case of men's suit fabrics. For example, Sofutosa (soft) is an expression used very frequently in fabric manufacturers and markets; however, this expression was not a professional or technical term as, for example, Numeri of men's suit fabric was. In other words, many expressions of hand are used by those people but there are almost no expressions used with clear understanding.

This was a strong reason why the standardization of hand expressions was necessary. This conclusion encouraged the committee members to begin working for standardization.

The first work the committee undertook was the classification of women's dress fabrics and they have been classified as follows.

(1) Thick fabric (overcoat)
(2) Medium thick fabric (suit)
(3) Thin fabric (blouse and one-piece dress)

Apparently, this classification is based on the fabric thickness, but also shows the use of the fabrics as shown in parentheses.

In fact, their thickness is overlapped as seen in Table A.9, in which their thickness ranges are shown as well as some of their mechanical properties. The data shown here were obtained from many samples collected from commercial products and classified by manufacturers for the purpose of hand analysis and standardization working.

Table A.9 Range of thickness and related properties

	Thin fabrics	Medium-thick fabrics
T	0.131~1.460 (0.445)	0.323~2.490 (0.974) mm
W	3.46~25.12 (10.2)	9.38~42.97 (23.6) mg/cm^2
B	0.0012~0.1693 (0.0267)	0.0160~0.3675 (0.1156) gf · cm^2/cm
B/w	1.03~16.91 (2.64)	0.70~25.18 (4.89) cm^3

T: thickness at 0.5 g/cm^2 pressure (mm)
W: weight (mg/cm^2)
B: bending rigidity per 1 cm width (gf · cm^2/cm)
w: weight (g/cm^2)

Reference data

	Summer – men's suit fabrics	Winter – men's suit fabrics
T	0.289~1.060 (0.504)	0.395~2.470 (0.802)
W	13.0~31.1 (19.5)	11.7~38.4 (26.4)
B	0.043~0.251 (0.104)	0.056~0.482 (0.150)
B/w	2.79~10.94 (5.3)	2.17~18.03 (5.6)

Selection of primary hand for women's dress fabric

The 'thick' fabrics were placed out of consideration and the 'medium thick' and the 'thin' fabrics were considered for their hand standardization. The selected hand expressions are shown in Table A.10 for the medium thick fabrics and Table A.11 for the thin fabrics respectively.

Table A.10 Primary hand expressions and their definitions for women's medium-thick fabrics

1.	Koshi	Stiffness	Same as Koshi in Table A.1
2.	Numeri	Smoothness	Same as Numeri in Table A.1
3.	Fukurami	Fullness and softness	Same as Fukurami in Table A.1
4.	Sofutosa[a]	Soft feeling	Soft feeling, a mixed feeling of bulky, flexible and smooth feelings

[a] This is not a primary hand. This expression was added as a semi-primary hand because this feeling was important for ladies' dress fabric.

Table A.11 Primary hand expressions and their definitions for women's thin-dress fabrics

1.	Koshi	Stiffness	Same as Koshi in Table A.1
2.	Hari	Anti-drape stiffness	Same as Hari in Table A.2
3.	Shari	Crispness	Same as Shari in Table A2
4.	Fukurami	Fullness and softness	Same as Fukurami in Table A.1
5.	Kishimi	Scrooping feeling	Scrooping feeling. A kind of silk fabric possesses this feeling strongly
6.	Shinayakasa[a]	Flexibility with soft feeling	Soft, flexible and smooth feeling

[a] This is not a primary hand but semi-primary hand. This hand is added because of its importance for the evaluation of ladies' thin fabrics.

Medium thick fabric

Many people manufacturing women's dresses were asked which expressions of hand were used frequently in their professional activities. Based on the answers from these professional people the expressions shown in Table A.10 were selected.

It is interesting that these expressions are the same as those for men's winter suit fabrics except Sofutosa. The committee discussed Sofutosa and has concluded that it is not a primary hand but a kind of mixed feeling of the other three primary hands. But this hand expression is used very frequently in markets and industries because of its importance as an intense expression.

Generally speaking, the expressions of hand are the same as those for men's suit fabrics, and we have concluded that the standard for men's suit fabrics can be used commonly in the case of the women's medium thin fabrics as their standards of hand evaluation. Only the standard of Sofutosa has been prepared as a reference of the evaluation of this expression.

Thin fabric

The hand expressions for this thin-fabric group are similar to the expressions of hand for men's summer suit fabrics and two expressions are added to the other primary hand expressions common with men's summer suit fabrics:

- Kishimi–scrooping feeling silk fabrics possess this feeling strongly.
- Shinayakasa–soft, flexible and smooth feeling.

These expressions are not a primary hand but a mixed feeling of the other primary hands. Also it is added because of its importance in the evaluation of the fabric properties of this kind of fabric and for its frequent use by professional people. These expressions and their definitions are shown in Table A.11.

These thin fabrics are quite different in mechanical properties and thickness divergency from those of men's summer fabrics. Therefore, it has been considered that the standard for men's summer fabrics cannot be applied to these thin fabrics and a new set of standards is necessary for the evaluation of their primary hand expressions.

The sub-committee C of the HESC has made the selection of fabrics for the standardization with a lot of help from sub-committee A. The layout of the original standard samples of the hand for the women's thin fabric is shown in Table A.12 and the layout of the samples published in the HESC Standard is shown in Table A.13.

Table A.12 The standard samples of the HESC Standard of Hand Evaluation for women's thin-dress fabrics, the original set

Women's thin dress	Hand value									
Koshi	1	2	3	4	5	6	7	8	9	
Hari	1	2	3	4	5	6	7	8	9	10
Shari	1	2	3	4	5	6	7	8	9	
Fukurami	1	2	3	4	5	6	7	8		
Kishimi		2		4		6		8		
Shinayakasa	1	2	3	4	5	6	7	8	9	10

Table A.13 Reproduced standard samples for publication of the HESC Standard of Hand Evaluation for women's thin-dress fabrics

Women's thin dress	Hand value										
No. 8 Koshi		1	2	3		5		7		9	
No. 9 Hari	0		2		4		6		8		10
No. 10 Shari		1		3		5		7		9	
No. 11 Fukurami			2		4		6		8	9	
No. 12 Kishimi		1		3		5		7	8		
No. 13 Shinayakasa		1	2		4		6		8		10

A.3 How to use the HESC Standard of Hand Evaluation

A.3.1 Evaluation of hand values (HV) using the standards

The HESC Standard of Hand Evaluation consists of two volumes; one is the standard for men's suit fabrics and consist of seven sets No. 1–7 and the other is that for women's thin-dress fabrics consists of six sets No. 8–13 as follows.

The sets for men's suit fabrics:

No. 1 Koshi
No. 2 Numeri for winter suit fabrics
No. 3 Fukurami
No. 4 Koshi-summer
No. 5 Shari-summer for summer suit fabrics
No. 6 Fukurami-summer
No. 7 Hari-summer

The sets for women's thin-dress-fabrics:

No. 8 Koshi
No. 9 Hari
No. 10 Shari
No. 11 Fukurami
No. 12 Kishimi
No. 13 Shinayakasa

As described in section A.2, the hand value expresses the intensity of the hand feeling and a large value corresponds to 'strong' feeling. These values are based on the standards established by the Hand Evaluation and Standardization Committee.

If one intends to evaluate the hand value of a given sample, sets 1, 2 and 3 should be used when the sample is the fabric used for men's winter suit, and sets 4 to 7 for summer suit. For example, if 'Numeri' for the sample of the men's winter suit is evaluated, set 2 should be used to compare the sample with those of standard samples by hand touch and decide the hand value.

If the hand value of the sample lies between the values 5 and 6, the judge decides an appropriate value between 5 and 6 by his feeling. The error from this indefinite operation is not so large if the judge learns the intensity-gradient of the standard samples.

As an example, we can evaluate the hand values for a sample of men's winter suit fabric as follows.

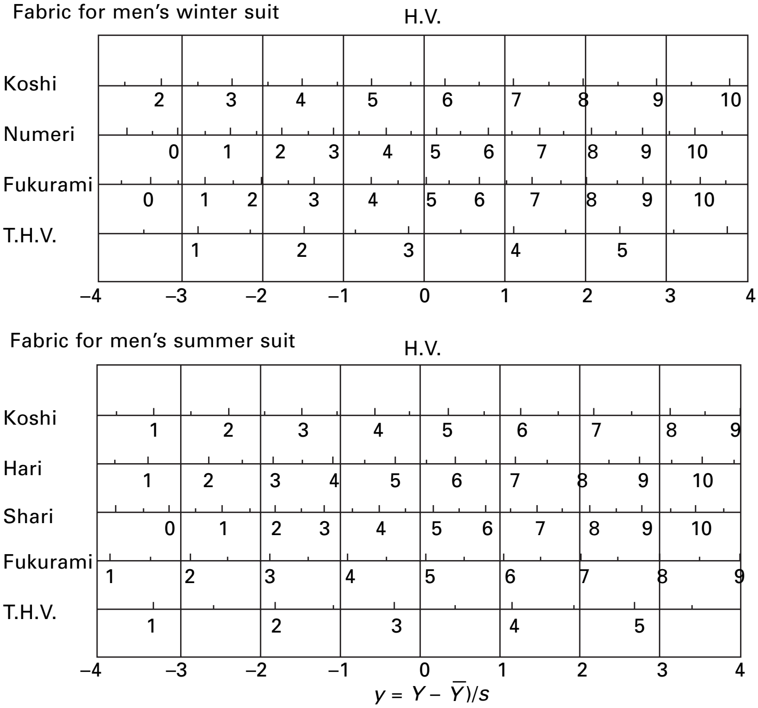
	Numeri	Koshi	Fukurami
Sample # 1	5.5	2	7.5

We recommend the following expression from, for example

HV-Numeri	5.5	
HV-Koshi-summer	3.5	
HV-Koshi-LDY*	5.0	(*LDY means 'for women's thin-dress fabrics')

We have not any specified operation for hand evaluation.

After the evaluation of the hand values, if you want to examine what kind of hand characteristic your sample has, you can plot the hand values on the normalized chart shown in Fig. A.9 or Fig. A10. The values required for this normalization were taken from Table A.3.

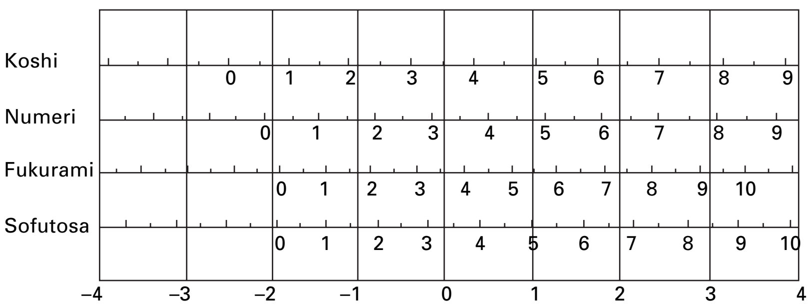


A.9 Charts for plotting the HV of men's suit fabrics. This chart is useful for examining the character of a fabric by plotting its HV on this chart. The common scale is normalized by the standard deviation, that is, $y = (Y - \bar{Y})/s$. This normalizing was carried out by using the mean and the standard deviation of the samples which were collected for the development of the translation formula of basic mechanical properities into hand value, 214 samples of winter and 156 of summer.

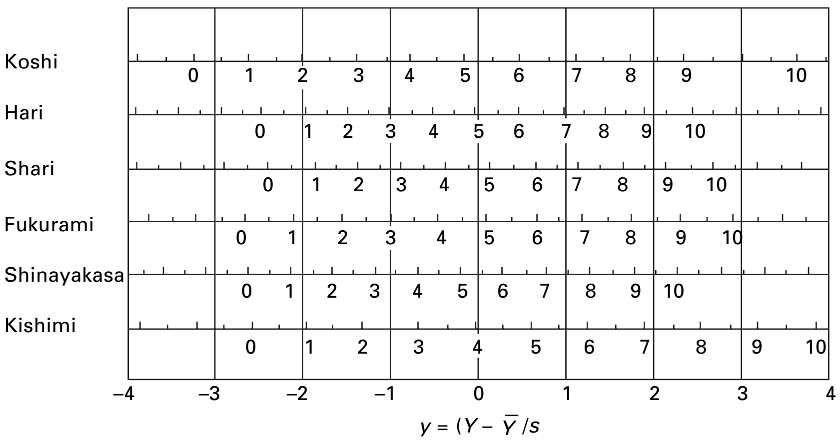
A.3.2 Application of hand values

There are many possibilities of applications of the hand values. Firstly, the numerical expression of hand becomes a powerful tool for improving the

Fabric for women's suit



Fabric for women's thin dress



A.10 Charts for plotting the HV of women's medium-thick fabric (upper) and thin-dress fabric (bottom). The common scale is normalized by the standard deviation such as $y = (Y - \bar{Y})/s$.

fabric quality. For example, if the temperature of a part of the finishing process is changed, its effect on hand of the fabric will be presented by recording the hand values before and after the change. Then we have a numerical correspondence between the temperature and the hand. This will be helpful to improve the process and produce the fabric having prescribed property.

The next example of the application is the communication of information about the hand among engineers and sales engineers. That is, a sales engineer calls his factory by telephone from a long distance and can discuss with an engineer the hand of fabric which is just finished at his factory by using the hand values.

Discussion about the property of a fabric by two engineers who belong to different companies will become possible. In this case, they can discuss the hand of the sample with the same understanding about the fabric hand and by the same scale of its feeling intensity.

Finally, the numerical expressions of hand can be used effectively in research on connecting the mechanical properties of fabrics with the hand evaluation by the experts. This will be shown in the next section.

A.3.3 Relation between the primary hand expressions and the 'good hand feeling'

The simplest but difficult expression of hand for our understanding is the expression 'good' hand or 'poor' hand. This expression, however, expresses the quality of fabric directly. In this case, we have only two expressions, good or poor.

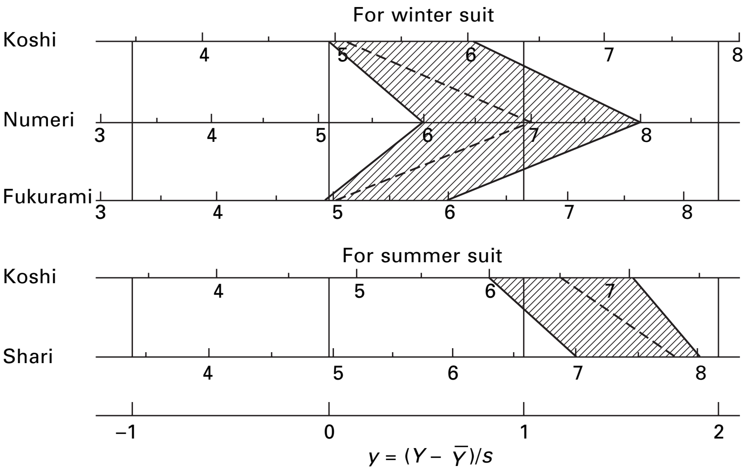
But if we ask an expert why it is said that the hand of that fabric is good, for example, the reply will be that the Numeri of this fabric is high and both the Koshi and the Fukurami are moderate.

This example can explain the relation between our primary hand expressions and the summarized hand expression, good or poor hand. We name this summarized expression 'Total Hand'. It is a very interesting and important problem to find out the relation between the primary hands and this total hand.

Experts on our committee have proposed their opinion based on their experience that the good total hand for men's winter suit is given by a combination of the primary hands such as HV-Numeri 7~8, Koshi 5~6 and Fukurami 5~6 as shown in Fig. A.11 as a 'good' range. The dotted line in this figure is also the combination of hand values which gives the maximum good hand. The combination given by the dotted line was obtained by the mathematical analysis of the data obtained by 20 experts, half of them experts on finishing and the other half in garment-making factories. However, this optimum combination has not been fixed yet.

After the analysis shown in Fig. A.11, a new assessment was carried out using different groups of fabrics which were collected for the development of the translation formula from mechanical properties to hand values. This group contains a relatively wide range of fabric grades, and we have obtained a different result as shown in section A.4.

Cooperation on the assessment of this Total Hand Value is now taking place with Professor R. Postle of the University of New South Wales, Australia and also with Professor S. Backer of MIT in the USA. Recently, Professor Postle obtained a quite different result from ours for summer suit fabrics. The correlation between the result in Australia and that of ours has a negative correlation coefficient, –0.35. This suggests to us that there is a difference between countries with respect to the evaluation of the Total Hand. It is noted that this cooperation was carried out applying the hand value.



A.11 'Good' hand is expressed by the compositions of hand values. Shadowed area is the good hand area based on experts' experience. The dotted line is obtained by the statistical analysis of the judgement of 20 experts. However, a small change of the optimum line has been obtained from the analysis of the new assessment as shown in section A.4.

A.3.4 Total hand value

The degree of 'good' hand has been expressed by the Total Hand Value (THV) as shown in Table A.14.

Table A.14 Total hand value

THV	Evaluation
5	excellent
4	good
3	average
2	below average
1	poor
0	out of use

These properties of fabric such as the resistance against wearing and washing are important; however, there is an essential quality of fabric beside them. This essential quality is expressed by the 'total hand'. Our concept on this quality is as follows.

'Good hand is an evaluation of the primary quality of fabrics, the quality is concerned with comfort and beautiful appearance in the silhouette of suit and is in conformity with function of garment and with human sense. A man who wears a suit made of such a fabric having good hand will become attached to it.'

214 samples of men's winter-suit fabrics and 156 of the summer-suit fabrics have been assesed by the HESC committee members who are experts on fabric finishing and evaluated their THV based on the definition of 'good' as shown before, then the present author and Dr Niwa have analyzed the evaluated data to obtain a translation formula from primary hands to the total hand. The obtained equations are as follows:

For winter-suit fabric:

$$\begin{aligned}\mathrm{THV} = {} & -1.2293 + 0.5904Y_1 - 0.0441\,Y_1^2 - 0.1210Y_2 \\ & + 0.0517\,Y_2^2 + 0.6317Y_3 - 0.0506\,Y_3^2 \end{aligned} \tag{A.1}$$

where

Y_1 = HV of Koshi
Y_2 = HV of Numeri
Y_3 = HV of Fukurami.

For summer-suit fabric:

$$\begin{aligned}\mathrm{THV} = {} & -1.3788 - 0.0004Y_1 + 0.0006\,Y_1^2 + 0.7501Y_2 - 0.0361\,Y_2^2 \\ & + 0.5190Y_3 - 0.0369\,Y_3^2 + 0.2555Y_4 - 0.0352\,Y_4^2 \end{aligned} \tag{A.2}$$

where

Y_1 = HV of Koshi-summer
Y_2 = HV of Shari-summer
Y_3 = HV of Fukurami-summer
Y_4 = HV of Hari-summer.

The contribution of each of the primary hands to the THV is shown graphically in Figs A.19 and A.20 on page 436.

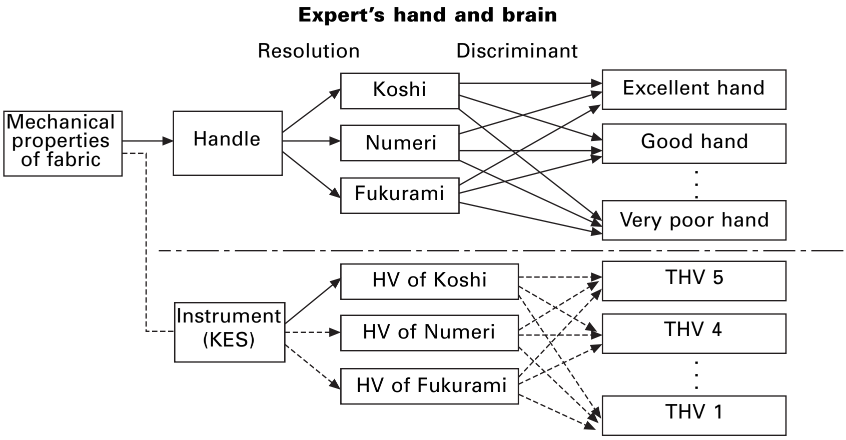
A.4 Analysis of hand evaluation

A.4.1 Translation formula from the characteristic values to the hand values

Preliminary researches

Figure A.12 is a schematic diagram of how experts judge the fabric quality by hand. Firstly, they examine the mechanical properties of fabric by hand to translate the feeling into the intensity of each of the primary hands and then judge the quality by the combination of these intensities of the primary hands. The route shown by a broken line in this figure is a simulation of this process by instrumentational and mathematical means; now we are going to develop this simulation method.

We have already defined the characteristic values of the mechanical properties of fabric and measured their values for each sample by the KES



A.12 The hand evaluation process by experts. The lower process is a simulation route by instrumentation and calculation. HV means the hand value and THV the total hand value.

system. The first problem is how to translate the characteristic values into the hand values. (Note that we have already defined hand value for each of the primary hands.)

The most simple equation predicting the hand value, Y, is the linear equation as follows:

$$Y = C_0' + \sum_{i=1}^{16} C_i' X_i \tag{A.3}$$

where Y = hand value
C_0' and C_i' = constant parameters
X_i = the ith characteristic value or its logarithm.

Equation (A.4) which is a modified form of equation (A.3) is a convenient form because the X_i is normalized by the mean and the standard deviation and, therefore, parameter C_i is proportional to the 'degree of influence' of X_i on the value of Y.

$$Y = C_0 + \sum_{i=1}^{16} C_i x_i \tag{A.4}$$

where

$$x_i \equiv \frac{X_i - \overline{X}_i}{\sigma_i}$$

C_i are constant parameters, $\overline{X}_i$ and σ_i are, respectively, the mean and the standard deviation of the ith characteristic values of the samples which were collected for the development of this translation equation as already mentioned above.

If we get the experimental values of Y of a primary hand and x_i for each of the many samples, we can use the statistical analysis such as regression analysis to determine the parameters C_o and C_i. As the first step of this determination, Kawabata and Niwa began the research to know how many samples were necessary at least for the determination of these parameters by using the multi-variable regression method. We have a set of data of hand values, for example, Numeri, for N samples given by matrix Y such as

$$\mathrm{Y} = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_k \\ \vdots \\ Y_N \end{bmatrix} \tag{A.5}$$

Suffix k means the kth sample of the N samples, and also we have a set of data of the characteristic values corresponding to these Y_k for all samples.

For the N samples, we have a matrix of x_{ki} such that,

$$x = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & \cdots & \cdots & x_{1p} \\ 1 & x_{21} & x_{22} & \cdots & \cdots & \cdots & x_{2p} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k1} & x_{k2} & \cdots & x_{ki} & \cdots & x_{kp} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{N1} & x_{N2} & \cdots & x_{Ni} & \cdots & x_{Np} \end{bmatrix} \tag{A.6}$$

where N is the total number of samples and x_{ki} is the x value of the ith characteristic value of the kth sample, and p is the total number of characteristic values and is equal to 16 in our case. Now, let us consider a model given by equation (A.4) and determine their coefficients. The unknown parameters are also written by a matrix C such as

$$\mathrm{C} = \begin{bmatrix} C_0 \\ C_1 \\ \vdots \\ C_i \\ \vdots \\ C_p \end{bmatrix} \tag{A.7}$$

If we define f as follows, where e is error matrix:

$$f = e^T \cdot e = [\mathrm{Y} - \mathrm{x\ C}]^T\ [\mathrm{Y} - \mathrm{x\ C}] \tag{A.8}$$

and according to the least square method, solve next equation:

$$\frac{\partial f}{\partial \mathrm{C}} = O = -\ 2\mathrm{x}^T\ [\mathrm{Y} - \mathrm{xC}] \tag{A.9}$$

that is,

$$2\mathrm{x}^T\mathrm{Y} = 2\mathrm{x}^T\ \mathrm{xC} \tag{A.10}$$

then we have

$$\mathrm{C} = [\mathrm{x}^T\mathrm{x}]^{-1}\ \mathrm{x}^T\mathrm{Y} \tag{A.11}$$

where T means the transpose and –1, the inverse of the matrix.

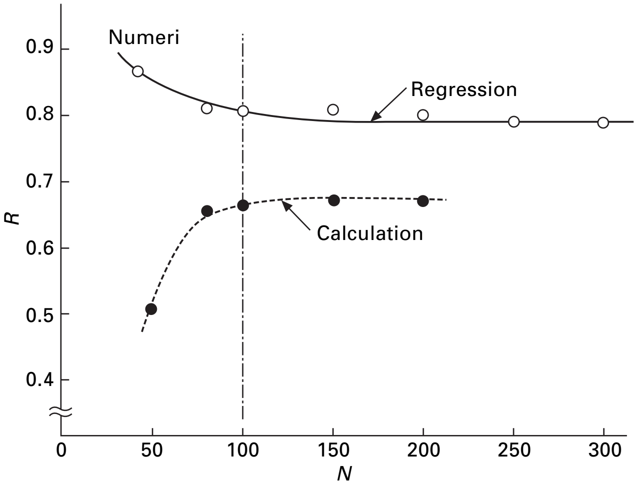
Thus we get the coefficient matrix C and, therefore, the translation equation. If we put $\tilde{Y}$ as the predicted value of Y, we have

$$\tilde{Y} = [1, x_1, x_2, \ldots, x_{16}]\ \mathrm{C},$$

or
$$\tilde{Y} = C_0 + C_1x_1 + C_2x_2 + C_3x_3 + \ldots + C_ix_i + \ldots + C_{16}x_{16} \tag{A.12}$$

If we calculate C from different number of N, the C obtained will be different. If N becomes larger, the accuracy of the regression will be decreased but the accuracy of the prediction by using the C obtained from large N will be increased.

To examine this, the correlation coefficient between the Y and the $\tilde{Y}$ was calculated using the samples which were used for the regression analysis. This correlation coefficient shows the regression accuracy in this case and shown by a solid line in Fig. A.13 as function of N.



A.13 Accuracy of the regression and the prediction.

On the other hand, the formulae were examined again for prediction accuracy by applying this formula to 100 fresh samples which were not included in the samples used for the regression analysis. The correlation coefficient between the Y and the $\tilde{Y}$ in this case is shown by a dotted line in Fig. A.13. The correlation coefficient increases with increasing N. This line will show the true accuracy of this prediction formula. As seen from Fig. A.13, the sufficient number of N for determining the coefficient matrix is about 150 in this case.

Development of the stepwise-block-regression method

Based on preliminary research, the determination of the parameters C_i of equation A.4 was carried out again.

After the research on this determination introduced in the first edition of *The HESC Standard of Hand Evaluation*, an extensive improvement has been carried out by Kawabata and Niwa with the cooperation of the HESC. The samples used for this analysis were selected from the many samples collected from commercially produced fabrics by the HESC. The selection has been made so as to distribute the hand values as widely as possible. Here the case of men's winter-suit fabrics will be introduced as an example.

Let us show the reason why we developed the stepwise-block-regression method. There are relatively high correlations between some pairs of the characteristic values, such as WT and WC, and B and $2HB$, etc. In such cases, the values of the coefficient C_i obtained by equation (A.11) are not necessarily proportional to the degree of importance of the contribution of x_i to the hand value Y.

Let us consider this problem using a simple example. Assume that Y is related with a variable x_1; on the other hand, x_2 is also related to with x_1 with a different category from the relation between Y and x_1. We assume that Y is related essentially with x_1 according to some physical reasons and not related with x_2. Now if we select two variables for predicting Y as follows:

$$\tilde{Y} = C_0 + C_1x_1 + C_2x_2 \tag{A.13}$$

then we may get the result by the multi-variable regression method such that $C_1 \cong C_2$ when x_1 and x_2 are normalized values and related to each other with close correlation. Instead of this multi-variable regession method, the stepwise regression method is adopted as follows. In this method, we examine the correlations between Y and x_1, and Y and x_2 separately. And if Y is directly related with x_1 and indirectly with x_2, the correlation coefficients $R(Y, x_1)$ and $R(Y, x_2)$ will become

$$R(Y, x_1) > R\,(Y, x_2) \tag{A.14}$$

Then we determine the regression equation with respect to x_1 such that

$$\tilde{Y} = \tilde{C}_0 + C_1x_1 \tag{A.15}$$

Next, $\tilde{Y}$ is calculated by this equation for all samples and compared with experimental values, Y_k, in order to obtain the residuals such that

$$e_k = Y_k - \tilde{Y}_k \tag{A.16}$$

Then we determine again the regression equation

$$e = \tilde{\tilde{C}}_0 + C_2x_2 \tag{A.17}$$

then we have

$$Y = \tilde{Y} + e = \tilde{C}_0 + C_1x_1 + \tilde{\tilde{C}}_0 + C_2x_2 \tag{A.18}$$

or

$$Y = C_0 + C_1x_1 + C_2x_2 \tag{A.19}$$

If the x_2 is not truly non-correlated with Y, the value of C_2 should be very small or negligible.

In the case when the variables are more than two, the same procedure may be taken stepwise.[56] We applied this method to determine the translation formula, and developed a modified method, stepwise-block-regression method for this purpose.[57] This method is as follows.

We have already six blocks of the characteristic values as shown in Table A.15.

Table A.15 Six blocks and characteristic values

Block	Property	Characteristic values, X_i
1	Tensile	LT, log WT, RT
2	Bending	log B, log 2HB
3	Surface	log MIU, log MMD, log SMD
4	Shearing	log G, log 2HG, log 2HG5
5	Compression	LC, log WC, RC
6	Weight and thickness	log W, log T_0

First step: By applying multi-variable regression method to each of the blocks, the six regression equations are determined such that:

$$\begin{aligned}
&\text{1st Block:} && \tilde{Y} = \tilde{C}_0 + C_1\,[LT] + C_2\,[WT] + C_3\,[RT] \\
&\text{2nd Block:} && \tilde{Y} = \tilde{C}_0 + C_4\,[B] + C_5\,[2HB] \\
&\text{3rd Block:} && \tilde{Y} = \tilde{C}_0 + C_6\,[MIU] + C_7\,[MMD] + C_8\,[SMD] \\
&\quad\vdots && \vdots
\end{aligned} \tag{A.20}$$

where [] means the normalized value of the characteristic value or of a logarithm of the characteristic value.

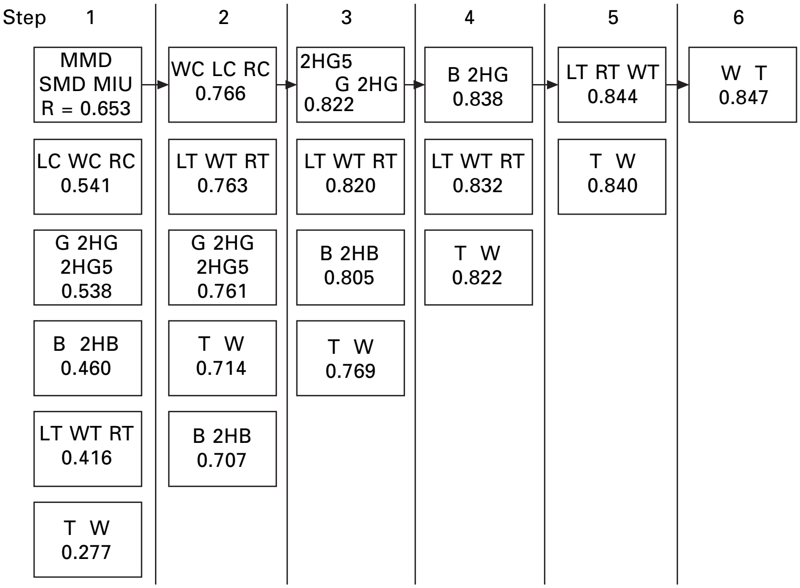
Thus the six equations are obtained with respect to each of the six blocks separately. The $\tilde{Y}$ are calculated using the each of these equations.

Second step: The block which has the highest correlation between the experimental values Y and the calculated $\tilde{Y}$ is picked up and named as the first block.

Third step: The residual $Y-\tilde{Y}$ of this first block are regressed to each of the remaining blocks separately by the same procedure as the first step, and we can determine the second block in the same manner as the second step. Thus, the regressions are continued stepwise. Figure A.14 shows an example of this stepwise-block-regression method.

Fourth step: As shown in Fig. A.14, we obtain an order of the blocks following the stepwise regression. Following this order, the stepwise regression is again repeated for each characteristic value in each of these blocks. The order of the block subjected to this procedure is conserved.

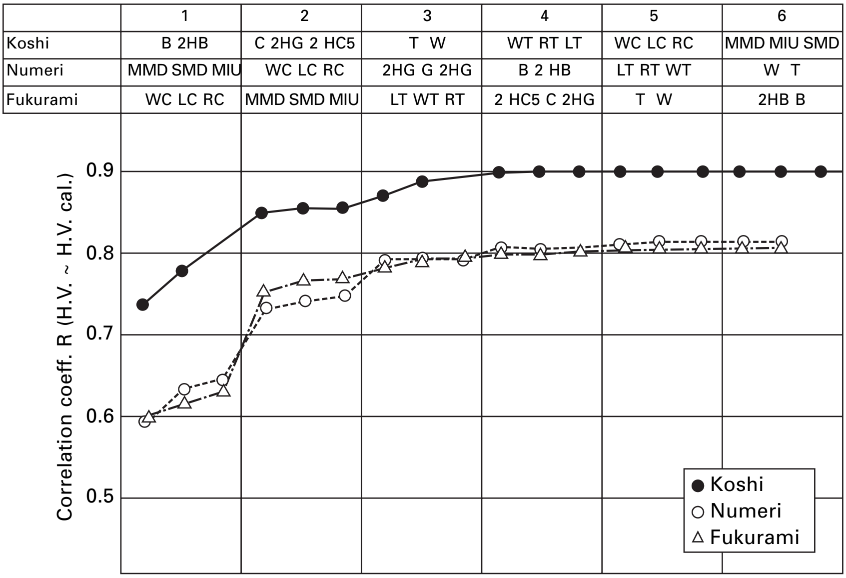
Fifth step: Finally we obtain a linear equation for predicting Y.



A.14 An example of stepwise block-regression applied to the analysis of Numeri.

The strong point of this method is firstly that the order of the blocks indicates the importance of the blocks to hand value Y. This is very useful to analyze the expert's hand feeling and to find out the interrelation between the expert's hand and the physical or the mechanical properties of fabrics.

Secondly, we can use a short equation in which the blocks of no importance can be omitted without injuring the accuracy of the regression equation. Figures A.15 and A.16 show these relations for winter-suit fabrics and for summer-suit fabrics respectively. The correlation coefficient between Y and $\tilde{Y}$ is increased with the increasing number of terms of characteristic value as shown in the figure and also the saturation of R is observed. After the curve is saturated we can omit the blocks or the characteristic values which continue behind for the calculation of Y. Final equations obtained are as follows.



	1	2	3	4	5	6
Koshi	B 2HB	C 2HG 2 HC5	T W	WT RT LT	WC LC RC	MMD MIU SMD
Numeri	MMD SMD MIU	WC LC RC	2HG G 2HG	B 2 HB	LT RT WT	W T
Fukurami	WC LC RC	MMD SMD MIU	LT WT RT	2 HC5 C 2HG	T W	2HB B

A.15 The prediction accuracy with increasing number of characteristic values (winter suit).

The translation equations developed recently are 10 equations, each equation named as shown in Table A.16. The KN is the initials of Kawabata and Niwa who have developed these equations. All equations have the form:

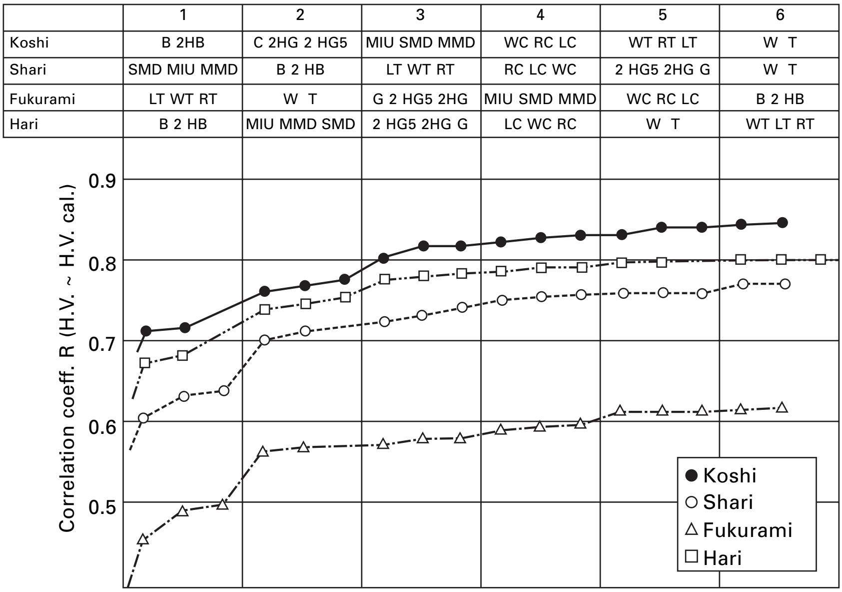
$$Y = C_0 + \sum_{i=1}^{16} C_i \frac{X_i - \overline{X}_i}{\sigma_i} \tag{A.21}$$

where

Y = hand value

X_i = ith characteristic value or its logarithm (refer to Table A.17 to see which characteristic values are taken or their logarithms)

$\overline{X}_i$, σ_i = mean value and the standard deviation of the ith characteristic value. See Table A.17(a) for men's winter suit fabric, Table A.18(a)



	1	2	3	4	5	6
Koshi	B 2HB	C 2HG 2 HG5	MIU SMD MMD	WC RC LC	WT RT LT	W T
Shari	SMD MIU MMD	B 2 HB	LT WT RT	RC LC WC	2 HG5 2HG G	W T
Fukurami	LT WT RT	W T	G 2 HG5 2HG	MIU SMD MMD	WC RC LC	B 2 HB
Hari	B 2 HB	MIU MMD SMD	2 HG5 2HG G	LC WC RC	W T	WT LT RT

A.16 The prediction accuracy with increasing number of characteristic values (summer suit).

Table A.16 Designation of the mechanical properties – hand values translation formulae developed by Kawabata and Niwa[58,60]

Name of equation	Predicted hand	Fabrics
KN-101-Wintr-Koshi	Koshi	Men's winter suit fabrics
KN-101-Winter-Numeri	Numeri	
KN-101-Winter-Fukurami	Fukurami	
KN-101-Summer-Koshi	Koshi	Men's summer suit fabrics
KN-101-Summer-Shari	Shari	
KN-101-Summer-Fukurami	Fukurami	
KN-101-Summer-Hari	Hari	
KN-201-LDY-Koshi	Koshi	Women's thin dress fabrics
KN-201-LDY-Hari	Hari	
KN-2011-LDY-Fukurami	Fukurami	
KN-201-LDY-Shari	Shari	
KN-201-LDY-Kishimi	Kishimi	
KN-201-LDY-Shinayakasa	Shinayakasa	
KN-201-LDYM-Sofutosa	Sofutosa	Women's medium thick fabrics

for men's summer suit fabric and Table A.19(a), for women's thin fabric for the $\overline{X}_i$ and the s_i.

C_0, C_i = parameters (constant coefficient). See Table A.17(b) for women's thin fabric.

The order of X_i corresponding to $i = 1, 2, \ldots$ is not common for all the equations because this follows in order of importance of blocks and also of characteristic values in their blocks to each primary hand. For example, in case of Koshi of men's winter fabric, the KN-101-winter-Koshi is applied. From Table A.17, we can write as follows:

$$Y = 5.7093 + 0.8459 \, \frac{\log B - (-1.0084)}{0.1267} - 0.2104 \, \frac{\log 2HB - (-1.3476)}{0.1801} + \ldots \tag{A.22}$$

In Tables A.17(b), A.18(b) and Table A.19(b), the correlation coefficient between experimental and calculated Y is also shown as R for each stage of calculation. As seen in these tables, R saturates with increasing steps and we can see how many steps are enough for the calculation of Y. In general, three blocks are enough for the actual application. The first three blocks also indicate their importance of these properties to Y value. It is noted that the translation equations for women's medium thick fabrics are not necessary because we can use equations for men's suit fabrics except Sofutosa in this case. For only the Sofutosa, the equation is shown in Table A.20.

As mentioned earlier (page 408), the HESC Committee discussed Sofutosa and concluded that it is not a primary hand, but a kind of mixed feeling of the other primary hands. So it is possible for it to be composed of a combination of primary hands such as Koshi, Numeri and Fukurani. Equation (A.23) is the equation for calculating Sofutosa by this means. The accuracy of this equation is better than the equation calculating it from the characteristic values; the R of regression is 0.945 and the RMS is 0.585.

The Shinayakasa of women's thin fabric is also not a primary hand, and may be calculated from the primary hands as shown in equation (A.24). The R is 0.933 and the RMS is 0.737. This value has higher accuracy than the value of the equation translating the characteristic values.

$$\text{Sofutosa} = 2.1495 - 1.0014Y_1 + 0.0735\,Y_1^2 + 0.5576Y_2 + 0.0111Y_2^2 + 0.5444Y_3 - 0.0167Y_3^2 \tag{A.23}$$

where Y_1 = HV of Koshi (HV means hand value)

Y_2 = HV of Numeri

Y_3 = HV of Fukurami.

$$\text{Shinayakasa} = 10.3921 - 1.1328Y_1 + 0.1277\,Y_1^2 - 0.6043Y_2 - 0.0339\,Y_2^2 + 0.0913Y_3 - 0.0144\,Y_3^2 - 0.4146Y_4 + 0.0373\,Y_4^2 + 0.6539Y_5 - 0.0296\,Y_5^2 \tag{A.24}$$

Table A.17 Parameters of equations KN-101-Winter for translating mechanical values into hand values of men's winter suit fabric

(a) X_i, $\overline{X}_i$, s_i table[a,b]

Block	i		X_i	Winter suit $N = 214$	
				$\overline{X}_i$	s_i
	0				
1	1		LT	0.6082	0.0611
	2	log	WT	0.9621	0.1270
	3		RT	62.1894	4.4380
2	4	log	B	–1.0084	0.1267
	5	log	2HB	–1.3476	0.1801
3	6	log	G	–0.0143	0.1287
	7	log	2HG	0.0807	0.1642
	8	log	2HG5	0.4094	0.1441
4	9		LC	0.3703	0.0745
	10	log	WC	–0.7080	0.1427
	11		RC	56.2709	8.7927
5	12		MIU	0.2085	0.0215
	13	log	MMD	–1.8105	0.1233
	14	log	SMD	0.6037	0.2063
6	15	log	T	–0.1272	0.0797
	16	log	W	1.4208	0.0591

(b) C_i table

Koshi			Numeri			Fukurami		
i	C_i	R	i	C_i	R	i	C_i	R
0	5.7093		0	4.7533		0	4.9799	
4	0.8459	.740	13	–0.9270	.595	10	0.8845	.600
5	–0.2104	.780	14	–0.3031	.633	9	–0.2042	.616
6	0.4268	.849	12	–0.1539	.645	11	0.1879	.630
7	–0.0793	.854	10	0.5278	.734	13	–0.5964	.754
8	0.0625	.854	9	–0.1703	.742	14	–0.1702	.768
15	–0.1714	.868	11	0.0972	.749	12	–0.0569	.770
16	0.2232	.889	8	–0.3702	.794	1	–0.1558	.782
2	–0.1345	.896	6	–0.0263	.794	2	0.2241	.793
3	0.0676	.898	7	0.0667	.792	3	–0.0897	.795
1	–0.0317	.899	4	–0.1658	.807	8	–0.0657	.799
10	–0.646	.900	5	0.1083	.803	6	0.0960	.800
9	0.0073	.900	1	–0.0686	.808	7	–0.0538	.802
11	–0.0041	.901	3	–0.1619	.812	15	–0.0837	.807
13	0.0307	.901	2	0.0735	.813	16	–0.1810	.805
12	–0.0254	.901	16	–0.0122	.813	5	0.0848	.805
14	0.0009	.901	15	–0.1358	.812	4	–0.0337	.806

[a] log means $\log_{10}$.

[b] Each of these characteristic values which belongs to blocks 1, 2, 3 and 5 is the mean value of those of warp and weft directions. After mean value is calculated from the characteristic values of both directions then the mean value is transformed into its logarithm to obtain X_i, for each sample.

where Y_1 = HV of Koshi
Y_2 = HV of Hari
Y_3 = HV of Fukurami
Y_4 = HV of Shari
Y_5 = HV of Kishimi.

A.4.2 Comparison between the calculated and experimental hand values

In order to examine the accuracy of the prediction of these equations, Y and $\tilde{Y}$ are shown in Fig. A.17 for Koshi of men's winter-suit fabric where $\tilde{Y}$ is the predicted value by the translation equation. The predicted $\tilde{Y}$ of the tested samples, all of which are fresh samples and have not been used for the regression analysis, were calculated and compared with the mean value of the Y evaluated by eight experts by hand evaluation.

The examinations for the other hand translation equations are summarized in Table A.21. The correlation coefficient is not always correct for evaluating

Table A.18 Parameters of equations KN-101-Summer for translating mechanical values into hand values of men's summer suit fabrics
(a) X_i, $\overline{X}_i$, s_i table[a]

Block	i	X_i		Winter suit $N = 156$	
				$\overline{X}_i$	s_i
	0				
	1		LT	0.6286	0.0496
1	2	log	WT	0.8713	0.0977
	3		RT	66.4557	5.4242
2	4	log	B	−1.1052	0.1081
	5	log	2HB	−1.5561	0.1635
	6	log	G	−0.0662	0.1079
3	7	log	2HG	−0.0533	0.1769
	8	log	2HG5	0.3536	0.1678
	9		LC	0.3271	0.0660
4	10	log	WC	−0.9552	0.1163
	11		RC	51.5427	8.8275
	12		MIU	0.2033	0.0181
5	13	log	MMD	−1.3923	0.1707
	14	log	SMD	0.9155	0.1208
6	15	log	T	−0.3042	0.0791
	16	log	W	1.2757	0.0615

[a] log means $\log_{10}$.

Table A.18 (b) C_i table

Koshi			Shari			Fukurami			Hari		
i	C_i	R	i	C_i	R	i	C_i	R	i	C_i	R
0	4.6089		0	4.7480		0	4.9217		0	5.3929	
4	0.7727	.712	14	0.9162	.605	1	–0.4652	.455	4	0.8702	.672
5	0.0610	.714	12	–0.2712	.631	2	–0.1793	.489	5	0.1494	.681
6	0.2802	.760	13	0.1304	.637	3	0.0852	.495	12	–0.3662	.738
7	–0.1172	.767	4	0.4260	.702	16	0.2770	.564	13	0.1592	.747
8	0.1110	.774	5	–0.1917	.711	15	–0.0591	.567	14	0.1347	.755
12	–0.2272	.804	1	0.2012	.723	6	0.0567	.570	8	0.2345	.776
14	0.1208	.817	2	0.1632	.731	8	–0.0944	.577	7	–0.0938	.779
13	0.0472	.816	3	0.1385	.739	7	0.0361	.578	6	0.0643	.781
10	–0.1139	.823	11	–0.2252	.751	12	–0.1157	.589	9	–0.1153	.786
11	–0.1164	.828	9	0.0828	.753	14	–0.0560	.592	10	–0.0846	.789
9	–0.0193	.828	10	–0.0486	.754	13	–0.0635	.595	11	–0.0506	.790
2	0.1154	.833	8	0.1237	.757	10	0.1411	.611	16	0.0918	.796
3	0.0955	.839	7	–0.0573	.759	11	0.0440	.612	15	0.0067	.796
1	–0.0031	.839	6	0.0400	.759	9	–0.0388	.613	2	–0.1115	.802
16	0.0549	.844	16	0.0824	.764	4	–0.0209	.614	1	0.0156	.803
15	0.0245	.845	15	0.0001	.764	5	0.0201	.614	3	0.0194	.803

[b] Each of these characteristic values which belong to blocks 1, 2, 3 and 5 is the mean value of those of warp and weft directions. After mean value is calculated from the characteristic values of both directions then the mean value is transformed into its logarithm to obtain X_i, for each sample.

the accuracy, because the range of the hand values of the samples examined influences remarkably the coefficient. The root mean square error, RMS, between experimental and calculated hand values is useful for the evaluation. Agreement between experimental and calculated values is good and, in fact, the calculated value falls in the scatter zone of the data evaluated by experts as seen in Fig. A.17. As seen in Table A.21, the accuracy is not so high in the case of Fukurami of men's summer suit.

This is caused by the difficulty in the experts' judgement for this primary hand. The scatter in the data obtained by the experts is very large in this case. Kishimi is also a problem for the same reason as summer's Fukurami. These are now improving with the cooperation of HESC.

In Japan, many companies have already begun the use of these equations for their research works on quality control and the development of new materials. And recently, the translation equations for the specific use knitted fabrics (outerwear use) have been obtained by the committee with the cooperation of the Wool Knit Association Japan.

Table A.19 Parameters of equations KN-201-LDY for translating mechanical values into hand values of women's thin dress fabrics

(a) X_i, $\overline{X}_i$, s_i table[a]

Block	i		X_i	Ladies dress N = 120	
				$\overline{X}_i$	s_i
	0				
1	1		LT	0.5906	0.0939
	2	log	WT	1.0551	0.2728
	3		RT	43.6828	12.0448
2	4	log	B	–1.7749	0.3592
	5	log	2HB	–2.0351	0.5126
3	6	log	G	–0.3731	0.3044
	7	log	2HG	–0.2733	0.5586
	8	log	2HG5	0.0295	0.4506
4	9		LC	0.4483	0.1109
	10	log	WC	–0.9951	0.3174
	11		RC	49.4168	11.6778
5	12		MIU	0.2258	0.0452
	13	log	MMD	–1.6832	0.2191
	14	log	SMD	0.4892	0.3999
6	15	log	T	–0.4253	0.2209
	16	log	W	0.9623	0.1768

[a] log means $\log_{10}$.

Table A.19 (b) C_i table

Koshi			Hari			Shinayakasa			Fukurami			Shari			Kishimi		
i	C_i	*R*	*i*	C_i	*R*	*i*	C_i	*R*	*i*	C_i	*R*	*i*	C_i	*R*	*i*	C_i	*R*
0	5.1991		0	5.0816		0	5.3474		0	4.7891		0	4.6833		0	4.0158	
4	1.2622	.794	4	1.8527	.906	4	–1.6807	.821	13	–0.6889	.384	13	1.0850	.550	7	–0.8711	.560
5	–0.3961	.870	5	0.0462	.906	5	–0.2870	.839	12	0.5535	.516	14	0.3082	.578	8	0.1120	.570
7	–0.4317	.906	6	0.2238	.914	13	–0.3788	.862	14	–0.1246	.513	12	–0.1014	.577	6	–0.1765	.576
8	0.1781	.920	7	–0.1366	.916	14	0.2827	.869	10	0.4589	.581	6	–1.1854	.832	14	–0.4783	.653
6	–0.0247	.920	8	0.1281	.919	12	0.0648	.869	9	–0.2820	.603	7	–0.0112	.832	13	–0.1089	.659
15	–0.2405	.933	2	–0.2409	.931	6	–0.3688	.895	11	–0.1401	.601	8	0.0012	.832	12	0.0834	.660
16	0.0281	.933	3	0.1212	.933	7	–0.0826	.898	16	0.3154	.616	11	0.2745	.845	2	–0.4831	.738
13	0.1760	.937	1	0.1272	.934	8	0.0784	.896	15	–0.1367	.629	9	0.0674	.846	1	0.0205	.738
14	–0.0537	.940	13	0.0999	.936	1	–0.1810	.898	3	0.1264	.641	10	0.0469	.847	3	–0.0557	.736
12	–0.0596	.940	14	–0.1379	.938	3	0.0795	.899	1	0.0399	.642	2	–0.1181	.848	10	0.1902	.739
1	0.0003	.940	12	–0.0119	.938	2	–0.0263	.899	2	0.1015	.644	3	–0.0982	.849	9	–0.0504	.740
2	–0.3688	.936	15	–0.0990	.938	9	–0.0203	.898	6	–0.0018	.644	1	0.0189	.849	11	0.0314	.741
3	0.0242	.935	16	0.0332	.938	10	0.1411	.898	7	0.0134	.643	16	0.1958	.854	16	–0.0041	.741
10	0.1096	.939	9	0.1163	.938	11	–0.0382	.897	8	0.0104	.642	15	–0.0748	.854	15	0.0044	.741
9	0.0561	.941	11	0.0164	.938	16	0.1019	.897	4	0.0474	.641	4	0.0770	.855	5	0.1018	.743
11	0.0285	.941	10	–0.0361	.938	15	–0.0534	.898	5	0.0199	.639	5	–0.0602	.856	4	–0.0218	.743

[b] Each of these characteristic values which belong to blocks 1, 2, 3 and 5 is the mean value of those of warp and weft directions. After mean value is calculated from the characteristic values of both directions then the mean value is transformed into its logarithm to obtain X_i, for each sample.

Table A.20 Parameters of equation KN-201-LDYM for translating mechanical values into hand values of women's medium thick fabric

(a) X_i, $\overline{X}_i$, s_i table[a]

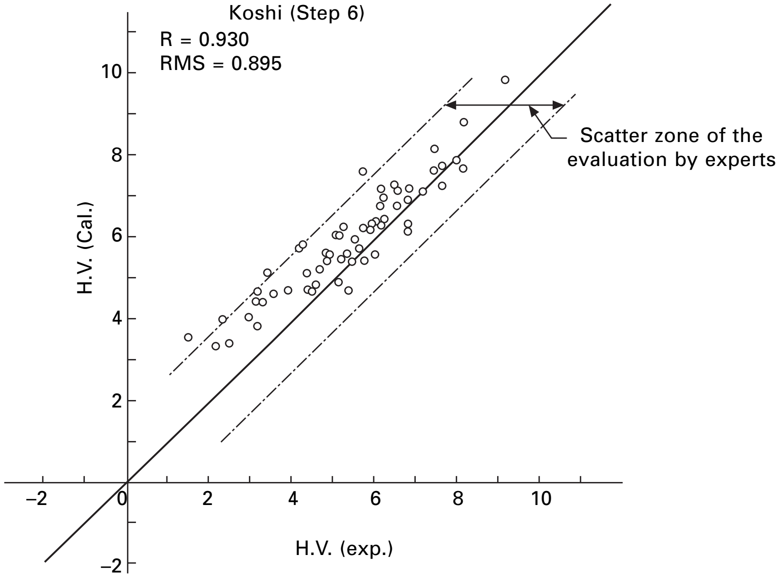
Block	i		X_i	Ladies dress N = 220	
				$\overline{X}_i$	s_i
	0				
1	1		LT	0.6177	0.0823
	2	log	WT	1.1511	0.2166
	3		RT	42.0564	6.9586
2	4	log	B	–1.0133	0.2565
	5	log	2HB	–1.2855	0.3473
3	6	log	G	–0.0745	0.2099
	7	log	2HG	0.1312	0.2966
	8	log	2HG5	0.4217	0.2596
4	9		LC	0.4070	0.1061
	10	log	WC	–0.6211	0.2380
	11		RC	52.2626	9.1288
5	12		MIU	0.2416	0.0431
	13	log	MMD	–1.7248	0.1926
	14	log	SMD	0.5696	0.3521
6	15	log	T	–0.0446	0.1693
	16	log	W	1.3550	0.1270

(b) C_i table

Sofutosa		
i	C_i	R
0	3.2881	
13	–0.9211	.541
14	0.3479	.604
12	–0.2159	.605
10	0.5641	.680
11	0.4741	.734
9	–0.0472	.734
6	–0.4214	.775
8	–0.0326	.775
7	0.0146	.775
3	–0.3573	.803
1	–0.1783	.811
2	0.0102	.811
4	–0.3073	.831
5	0.0159	.831
15	–0.0657	.831
16	0.0340	.831

[a] log means $\log_{10}$.

[b] Each of these characteristic vlaues which belong to blocks 1, 2, 3 and 5 is the mean value of those of warp and weft directions. After mean value is calculated from the characteristic values of both directions then the mean value is transformed into its logarithm to obtain X_i, for each sample.



A.17 Correlation between the hand values of Koshi evaluated by experts (experimental hand value) and those calculated from mechanical properties using the regression equation. Samples used here are the new samples prepared for examination of the accuracy of the regression equation.

Table A.21 Accuracies of the prediction by the translation formulae

(a) Men's winter suit fabrics (*N* = 66)

	Koshi	Numeri	Fukurami
Correlation between experimental and calculated hand values, *R*	0.930	0.793	0.783
Root mean square of errors, RMS	0.895	1.126	1.018

(b) Men's summer suit fabrics (*N* = 44)

	Koshi	Shari	Fukurami	Hari
Correlation between experimental and calculated hand values *R*	0.803	0.716	0.392	0.688
Root mean square of errors, RMS	1.006	0.978	1.328	0.960

Note: The correlation coefficient is sensitive to the distribution of the hand values of the samples selected. The RMS is rather more reliable than the *R* in case of practical-use testing

A.4.3 Analysis of the hand evaluation of the experts

The coefficients obtained by the stepwise-block-regression method give interesting information about the primary hands. The order of the blocks in the equation is considered as a presentation of the extent of the contribution of the block against the hand value. The following conclusions can be obtained. Corresponding to the experts' conception about the hand expressions shown in section A.2, we ask again same questions:

(a) What kind of feeling do you feel for its hand expression?
(b) Which properties are related mainly with its hand feeling?

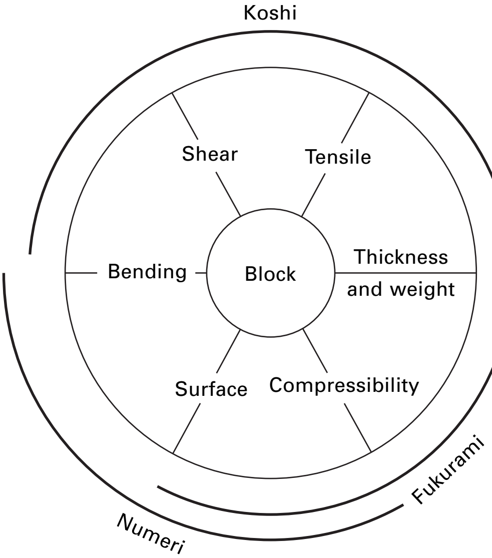
The answers obtained by the mathematical analysis are as follows.

1. Numeri
    (a) Smoothness which comes from smaller variation of frictional force and smooth surface. The bending, shearing and compressional properties have small rigidity and are springy.
    (b) 1st block: surface
    2nd block: compressional
    3rd block: shearing
2. Koshi
    (a) Stiff and springy property in bending. Stiff in the shearing and the compressional properties. Thin fabric in proportion to its weight increases Koshi.
    (b) 1st block: bending
    2nd block: shearing
    3rd block: weight and thickness
3. Fukurami
    (a) Softness in the compressional property. Smooth surface and soft extensibility.
    (b) 1st block: compression
    2nd block: surface
    3rd block: tensile
4. Koshi for summer
    (a) Stiff in bending. Rough surface and high shearing resistance.
    (b) 1st block: bending
    2nd block: shearing
    3rd block: surface
5. Shari for summer
    (a) Rough surface. Stiff and springy in the bending property.
    (b) 2nd block: bending
    3rd block: tensile
6. Hari for summer
    (a) Stiff in bending. Higher hysteresis also increases Hari. Rough surface and high shearing rigidity, especially high 2HG5.

   (b) 1st block: bending
       2nd block: surface
       3rd block; shearing
7. Fukurami for summer
   (a) Extensible, especially in the relatively small tensile strain.
   (b) 1st block: tensile
       2nd block: weight and thickness
       3rd block: shearing.

It is interesting to compare these results with the feelings about the hand by experts, which are shown in section A.2.

As shown in Fig. A.18, these three hands, Koshi, Numeri and Fukurami, cover the blocks of the properties as shown in this figure. And it is seen that Fukurami and Numeri are feelings near each other. Table A.22 gives the correlation coefficients between these three hands. This table also shows this relation. If we compose both Fukurami and Numeri together, then the composed feeling is considered as a soft and smooth feeling, and the Koshi covers the opposite, stiff and springy feeling.



A.18 Relation between the three primary hands and mechanical properties. The related properties are covered by a line of the corresponding hand.

The correlation coefficients between each hand are shown in Tables A.22–A.25, for men's winter suit fabric, men's summer suit fabric, women's thin dress fabric and women's medium thick fabric respectively.

Table A.22 Correlation between three primary hands of men's winter suit fabrics (*N* = 214)

	Koshi	Numeri	Fukurami	T.H.V.
Koshi	1.0000	–0.4390	–0.2515	–0.2237
Numeri	–0.4390	1.0000	0.9040[a]	0.8661
Fukurami	–0.2515	0.9040[a]	1.0000	0.8378
T.H.V.	–0.2237	0.8661	0.8378	1.0000

[a] This value is quite different from the value obtained by the 448 fabrics sampled randomly from commercially produced fabrics in Japan, probably because this new selected fabric assembly shown in this table contains many high grade fabrics compared with the distribution as seen in the randomly sampled fabrics.

Table A.23 Correlation between primary hands of men's summer suit fabrics (*N* = 156)

	Koshi	Hari	Shari	Fukurami	T.H.V.
Koshi	1.0000	0.8488	0.8024	–0.0079	0.5129
Hari	0.8488	1.0000	0.6917	0.0212	0.4328
Shari	0.8024	0.6917	1.0000	–0.0704	0.7360
Fukurami	–0.0079	0.0212	–0.0704	1.0000	0.2495
T.H.V.	0.5129	0.4328	0.7360	0.2495	1.0000

Table A.24 Correlation between primary hands of women's medium thick fabrics (*N* = 220)

	Koshi	Numeri	Fukurami	Sofutosa
Koshi	1.0000	0.1745	0.4435	–0.0869
Numeri	0.1745	1.0000	0.7417	0.8628
Fukurami	0.4435	0.7417	1.0000	0.7297
Sofutosa	–0.0869	0.8628	0.7299	1.0000

Table A.25 Correlation between primary hands of women's thin dress fabrics (*N* = 120)

	Koshi	Hari	Shari	Fukurami	Kishimi	Shinayakasa
Koshi	1.0000	0.8183	0.2051	–0.1849	0.3217	–0.6195
Hari	0.8183	1.0000	–0.0567	–0.0482	0.0042	–0.8790
Shari	0.2051	–0.0567	1.0000	–0.6531	–0.0110	0.0365
Fukurami	–0.1849	–0.0482	–0.6531	1.0000	0.1867	0.1298
Kishimi	0.3217	0.0042	–0.0110	0.1867	1.0000	0.2520
Shinayakasa	–0.6195	–0.8790	0.0365	0.1298	0.2520	1.0000

A.4.4 Calculation of THV

As introduced in section A.3, the translation equation from HV to THV, as seen in Fig. A.12, has been developed for men's suit fabrics.

The equation is as follows.

$$\mathrm{THV} = C_0 + \sum_{i=1}^{k} Z_i$$

where

$$Z_i = C_{i1}\left(\frac{Y_i - M_{i1}}{\sigma_{i1}}\right) + C_{i2}\left(\frac{Y_i^2 - M_{i2}}{\sigma_{i2}}\right) \tag{A.25}$$

Y_i = primary hand values as shown in Table A.26

M_{i1}, M_{i2}, σ_{i1}, σ_{i2} = mean values of Y and Y^2, standard deviation of Y and Y^2 respectively.

C_{i1}, C_{i2} = constant parameters shown in Table A.26.

Figures A.19 and A.20 express the Z_i value as function of Y_i for winter and summer suit fabrics respectively. The optimum combination of the primary

Table A.26 Parameters of the HV-THV translation equations shown in equation (A.25). This equation is useful for understanding the influence of each primary hand on the THV (a) KN-301-Winter-THV, the equation for winter suit fabrics (C_0 = 3.1466)

i	Y_i	C_{i1}	C_{i2}	M_{i1}	M_{i2}	σ_{i1}	σ_{i2}
1	Koshi	0.6750	–0.5341	5.7093	33.9032	1.1434	12.1127
2	Numeri	–0.1887	0.8041	4.7537	25.0295	1.5594	15.5621
3	Fukurami	0.9312	–0.7703	4.9798	26.9720	1.4741	15.2341
RMS[a]		0.333					
R[b]		0.900					

[a] Root mean square of regression error

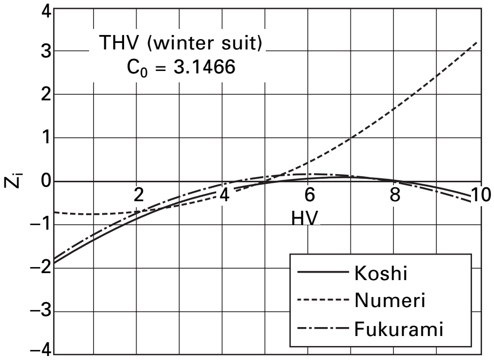
[b] Correlation coefficient between regressed and experimental values.

(b) KN-301-Summer-THV, the equation for summer suit fabrics (C_0 = 3.2146)

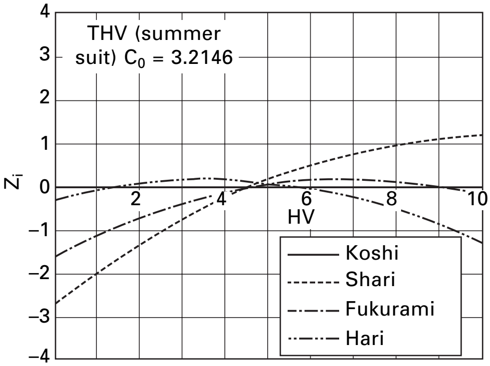
i	Y_i	C_{i1}	C_{i2}	M_{i1}	M_{i2}	σ_{i1}	σ_{i2}
1	Koshi	–0.0004	0.0066	4.6089	22.4220	1.0860	11.1468
2	Shari	1.1368	–0.5395	4.7480	24.8412	1.5156	14.9493
3	Fukurami	0.5309	–0.3741	4.9217	25.2704	1.0230	10.1442
4	Hari	0.3316	–0.4977	5.3929	30.7671	1.2975	14.1273
RMS[a]		0.354					
R[b]		0.849					

[a] Root mean square of regression error.

[b] Correlation coefficient between regressed and experimental values.



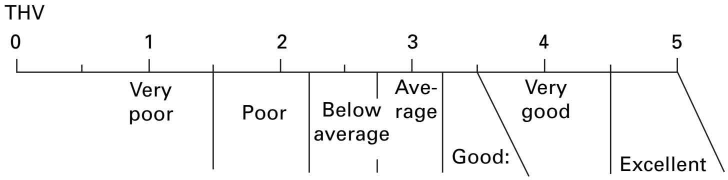
A.19 The influence of each primary hand to the total hand value is shown separately for men's winter suit fabric.



A.20 The influence of each primary hand to the total hand value is shown separately for men's summer suit fabric.

hands can be estimated from these figures. The results shown in these figures are little different from the results shown in Fig. A.11. This is probably caused by the considerable number of high quality samples added to the samples used for this analysis.

From the distribution of THV calculated from these equations, a new grading of fabrics by THV is estimated in Fig. A.21.



A.21 Grading of men's suit fabrics by THV estimated by the distribution of the calculated THV.

As mentioned before, research on total hand is now carried out with the cooperation of HESC and countries such as Australia and the USA.

A.4.5 Discriminant analysis

The total hand value which has been introduced in this chapter is one of generic hand expressions. Another example of the generic hand expression is an assortment hand such as silk-like hand, cotton-like hand, etc. Let us assume that this type of hand can be discriminated by using the primary hands such as Koshi, Hari, etc. Consider two groups of the samples:

Group A: silk fabrics
Group B: cotton fabrics

and assume that these two groups are discriminated by the value of Z given by the equation[61]

$$Z = \sum_{i=1}^{6} C_i Y_i \tag{A.26}$$

where Y_i = hand values of primary hands such that
Y_1 = HV of Koshi
Y_2 = HV of Hari
Y_3 = HV of Fukurami
Y_4 = HV of Shari
Y_5 = HV of Kishimi
Y_6 = HV of Shinayakasa
C_0, C_i = parameters determined so as to maximize the f defined by

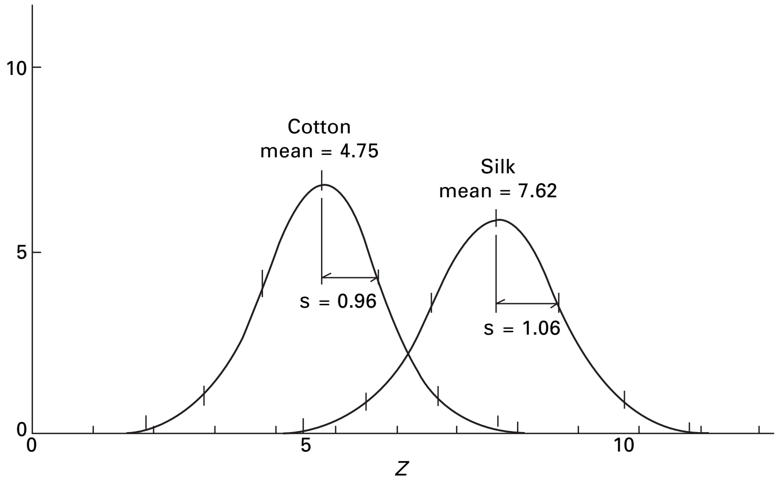
$$f = \frac{|\bar{Z}_A - \bar{Z}_B|}{\sqrt{s_A^2 + s_B^2}} \tag{A.27}$$

where $\bar{Z}_A$ and $\bar{Z}_B$ are mean values of Z_A and Z_B, respectively, which are calculated by equation (A.26) for the samples of group A and group B respectively
s_A, s_B = standard deviation of Z_A and A_B respectively.

For example, the following equation is obtained from 33 samples of cotton fabric and 31 samples of silk fabric for women's thin-dress fabrics:

$$Z = Y_1 - 0.481\ Y_2 - 0.096\ Y_3 + 0.069\ Y_4 + 0.583\ Y_5 + 0.155\ Y_6 \tag{A.28}$$

Figure A.22 shows how the two groups are discriminated by this Z value, in other words, by a combination of primary hands. In this figure, the distributions of the Z_A and the Z_B are shown and it is seen that separation of both groups is good.



A.22 Discrimination of silk and cotton fabrics by *Z* values.

When we examine a sample, regardless whether the sample is silk, cotton or another fabric, being silk-like or cotton-like, we substitute the primary hand values of this sample into equation (A.28) to obtain the Z value. If the Z value is larger than the boundary value between two groups shown in Fig. A.22, the sample may have silk-like hand.

We can expand this method to the discrimination of three groups, A, B and C. In this case, we have two discriminant equations such that[59]

$$Z_1 = \sum_{i=1}^{6} C_i Y_i$$

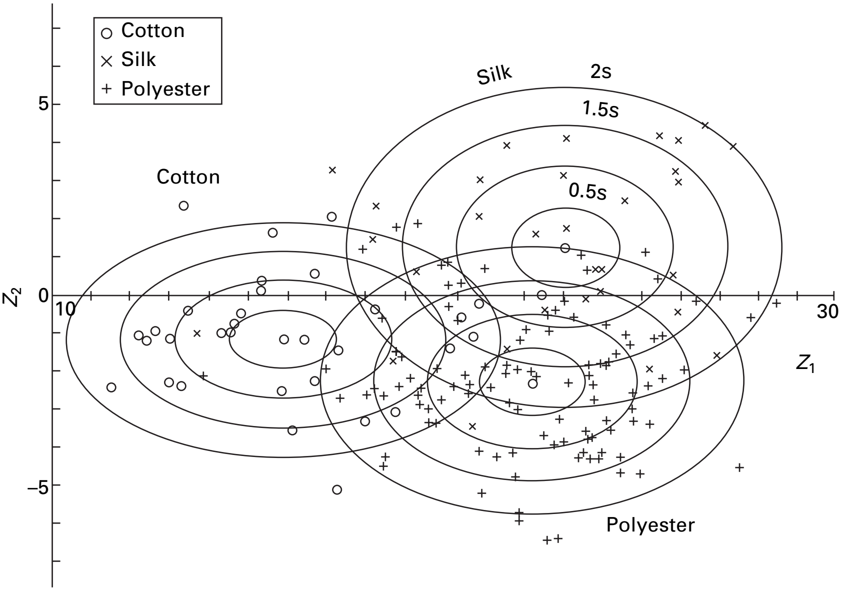
$$Z_2 = \sum_{i=1}^{6} C_i' Y_i \qquad \text{(A.29)}$$

C_i and C_i' are also determined following the same principle as shown in the case of two groups. Figure A.23 shows the discriminant area and

zone A = silk-like hand
zone B = cotton-like hand
zone C = polyester-like hand

and lines shown in the figure are contour lines of distribution density presented by the scale of standard deviation of corresponding distribution.

$$\begin{aligned} Z_1 &= 1.9473\ Y_1 - 05433\ Y_2 - 0.3183\ Y_3 + 0.6725\ Y_4 \\ &\quad + Y_5 + 1.2677\ Y_6 \\ Z_2 &= 1.4027\ Y_1 - 1.1520\ Y_2 + 0.1413\ Y_3 - 0.7693\ Y_4 \\ &\quad + Y_5 - 0.8543\ Y_6 \end{aligned} \qquad \text{(A.30)}$$



A.23 Discrimination of three groups of fabric, silk, cotton and polyester groups by Z_1 and Z_2. The Z values are calculated from the hand values of primary hands of these samples.

A.5 Hand evaluation in the future

The primary hands selected here are essentially the experts' hands. Each of these experts in the textile factories, especially in the finishing process, has studied his evaluating technique by himself but, as mentioned before, his judgement is based on information which has been gathered from many people including consumers, concerned with clothing materials for a long time.

From such a situation, Kawabata thinks that we must appreciate these hand expressions to be a precise expression of the property required for our clothing materials.

The author also considers that all these hand expressions with respect to the fabric quality will be replaced by some mechanical or physical properties of the fabric in future. Our committee has also started this research already as mentioned in section A.3 and these primary hands, which have been brought up by the experts, will become an important guiding principle for the progress of this research.

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Appendix B

SiroFAST – fabric assurance by simple testing*

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B.1 Introduction

SiroFAST (Fabric Assurance by Simple Testing) is the most recently developed integrated set of instruments and test methods available for fabric objective measurement. SiroFAST measures the mechanical and dimensional properties of fabric that can be used to predict performance in garment manufacture and the appearance of the garments in wear.

SiroFAST was developed in Australia by the CSIRO Division of Wool Technology to meet industry's need for a simple, reliable method of predicting fabric performance. Despite SiroFAST's simple appearance, it is based on considerable research into the relationships between measured fabric properties and fabric performance. Fabric objective measurement, in particular SiroFAST, is currently being used by fabric and garment manufacturers in many parts of the world in a wide variety of applications.

The first part of this report is a description of the background developments in fabric objective measurement that form the basis of SiroFAST. This section includes a description of the SiroFAST system, its instruments, test methods, and the methods used to display and use SiroFAST results.

The principles of fabric objective measurement are common to all measurement systems, such that the information contained in this report could be obtained using alternative systems. The applications illustrated here show the value of fabric objective measurement in general, and SiroFAST in particular, to both fabric and garment manufacturers.

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* This appendix has been adapted for this publication by Professor H. Behery. With great thanks to CSIRO Textile and Fibre Technology for allowing the use and inclusion of this information.

B.1.1 The properties of fabrics

The properties of fabrics can be loosely described as either functional or aesthetic.

- Functional properties relate to the failure (normally mechanical) of the fibres or yarns that make up the fabric during use.
- Aesthetic properties are the most highly subjective and complex features of fabrics.

Properties include appearance and handle, and involve visual or tactile aspects of the fabric, rather than simply the nature of fabric, yarns or fibres. Most aspects of fabric performance fall into one or other of these categories; some of these are listed in Table B.1.

Table B.1 Functional and aesthetic properties of fabrics

Functional	Tear strength Tensile strength Abrasion resistance Shrink resistance Flammability
Aesthetic	Handle – firmness, smoothness, etc. Performance in garment manufacture Performance in cutting, sewing and pressing Appearance of garment after manufacture and in wear Shape distortion Panel distortion Seam pucker Wrinkle recovery Pilling resistance

Since the aesthetic properties of fabrics are subjective, their description and measurement can be quite complex. For example, the attractiveness of a given fabric's handle will depend on its end use as well as possible cultural and individual preferences of the wearer [1]. The properties of each fabric will also influence the style of the garment that can be made and the level of skill required of the garment makers [2]. Finally, there are many aspects to the appearance of garments in wear. These include seam pucker [3], panel distortion, wrinkling [4] and pilling [5]. Concern over appearance after manufacture, and in wear, will depend on the garment, the design of the fabric (e.g. check, plain) and the requirements of the individual.

Extensive research in Sweden [6], the Netherlands [7], Japan [8–10], the UK [11] and Australia [12–16] has identified many of those mechanical, dimensional and other properties of fabrics that affect handle, performance in garment manufacture and the appearance of garments in wear. Some of the most important properties are shown in Table B.2.

Table B.2 Fabric properties related to handle, performance in garment manufacture, and garment appearance after manufacture and in wear

Properties (*important)	Performance in manufacturing	Handle	Appearance in wear
Physical properties			
Thickness		*	
Weight	*	*	*
Dimensional stability			
Relaxation shrinkage	*		*
Hygral expansion	*		*
Mechanical properties			
Extensibility	*	*	*
Bending properties	*	*	*
Shear properties	*	*	*
In-plane compression		*	*
Surface properties			
Compression		*	
Friction		*	
Surface irregularity		*	
Optical properties			
Lustre			*
Performance properties			
Pilling			*
Wrinkling			*
Surface abrasion			*

B.1.2 Objective measurement and fabric aesthetics

The idea of using the objective measurement of properties to predict fabric performance is not new. Measurements have been used to predict some aspects of fabric performance for many years. However, fabric objective measurement in the context of this report involves quite different objective measurements. The tests described in this report are designed to predict the success or failure of a fabric to 'make up well', to feel 'good', or for garments to look 'good' after manufacture and 'in wear'. This requires very subtle measurements that are much more accurate than those required to cause fabric to 'fail' in the normally accepted sense. The difference between the testing referred to in this report and that previously required to predict functional performance is that testing to assess aesthetic properties involves measurement at low deformations.

Recently, techniques have been developed to measure the mechanical properties of fabrics and use these measurements to quantify handle [10] and quantitatively predict performance in both garment manufacture and the appearance of garments [8]. However, mechanical properties are not the only properties that determine fabric aesthetics. Thermal properties, such as insulation and the warm–cool touch sensation, also play an important part in determining fabric handle [17]. The so-called dimensional stability of the fabric (perhaps more correctly called dimensional instability [11]) is also critical, not only in the manufacturing process but also to the subsequent appearance of the garment in wear.

The need for tests to predict or assess subjective aspects of fabric aesthetics has increased in recent years for three main reasons:

1. The trend towards lightweight clothing has resulted in the increased use of fabrics that are difficult to make up and require new handling skills.
2. The trend towards shorter ‘seasons’ and the use of rapid systems (such as just-in-time manufacturing) have meant that the delivery of fabrics that are difficult to make up will disrupt production schedules. For this reason it is even more important that garment makers are able to predict fabric performance.
3. The increased use of automation in garment manufacture removes the opportunity for skilled operators to correct for difficult or variable fabrics.

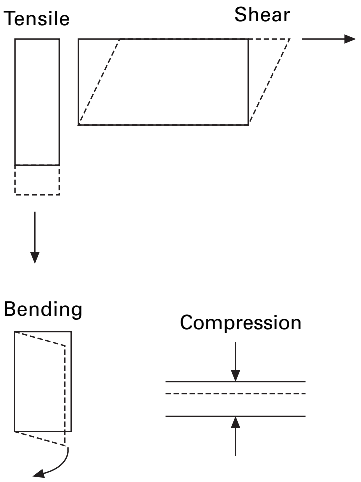
Mechanical properties

The first experimental work on the objective measurement of fabric mechanical properties dates back to the 1930s [18]. The prediction of fabric performance in garment manufacturing from mechanical properties was first extensively examined by Swedish [6] and Dutch [7] research teams in the 1960s. These teams identified many properties of fabric associated with performance in garment manufacture. These included extensibility, bending and shear properties as well as fabric weight. Several measurements are required to fully describe tensile, shear or bending behaviour of fabric. Those used to describe resistance to deformation are normally considered to be the most important and are defined in Table B.3.The deformations involved are represented in Fig. B.1.

Table B.3 Properties describing resistance to deformation

Deformation	Property	Definition
Tensile	Extensibility	Extension of a fabric under a predefined load
Bending	Bending rigidity	Couple required to bend unit width of fabric to unit curvature
Shear	Shear rigidity	Shear load required to deform unit width of fabric to unit strain

The work of the Swedish and Dutch groups has been confirmed by industrial users of objective measurement. Summarised in Table B.4 is part of a Japanese



B.1 Schematic diagram of deformations important in garment manufacture.

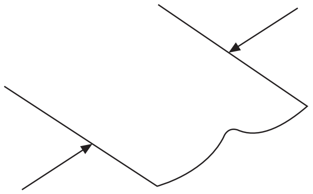
Table B.4 Some fabric properties related to problems in garment manufacture [19]

Region of manufacturing difficulties	Related fabric property	Problem zone
Cutting Sewing	Warp extension	High
Front-back	Warp extension	High
	Weft extension	Low
Arm hole	Warp extension	High
	Weft extension	High
	Shear rigidity	Low
	Shear hysteresis[a]	Low
Canvas	Warp extension	High
	Weft extension	Low
	Shear rigidity	High
Side seam	Warp extension	High or low
	Weft extension, shear hysteresis	Low
	Shear rigidity	High
Collar	Shear rigidity	High or low
	Weft extension	Low
Sleeve setting	Shear rigidity	High or low
	Shear hysteresis	Low
	Bending rigidity	Low
	Bending hysteresis[a]	High
	Weft extension	High
	Warp extension	High

[a] Shear and bending hystereses are measures of energy loss in deformation

report [19] on the relationship between problems in garment making and the mechanical properties of fabrics. This work demonstrated that there are optimum ranges for fabric mechanical properties, notably extensibility and shear rigidity.

The Swedish research team also identified two extra properties of fabrics termed ‘compressibility’ and ‘formability’ [6]. These properties are related to the tendency of a fabric to buckle when subjected to an in-plane compressive load (Fig. B.2). When a seam is sewn, the sewing thread and any overfeed applied to the components of the seam put in-plane compression on the fabric. If the formability is too low, the fabric will buckle and the seam will pucker. If the formability is high, the fabric will accept the compression without buckling and the seam will usually have a good appearance. Formability has also been shown to influence the overall appearance of men’s suit jackets [12].



B.2 Behaviour of fabric in longitudinal compression.

Formability is defined using the in-plane compressibility of fabric, but because this is difficult to measure, fabric extensibility at low loads (typically 10–50 g/cm width) is often used to obtain an approximate measure of compressibility [2]. An alternative equation is normally used to calculate formability. For most purposes, this is an adequate approximation.

Formability = bending rigidity ¥ extensibility (at low loads)

Dimensional stability

The dimensional stability of wool fabrics has two components, both of which contribute to the shrinkage or growth of fabrics in garment manufacture [11]:

1. Relaxation shrinkage, the irreversible change in dimensions that occurs when a fabric is relaxed in steam or water.
2. Hygral expansion, the reversible change in fabric dimensions that occurs when the moisture content of the fibres is altered.

The importance of these properties in garment making, and on the appearance of garments, depends on the particular garment-making operation or conditions of wearing (Table B.5). The importance of fabric shrinkage is relatively familiar to garment makers, but hygral expansion is just as important. A simple test is available that separates these two components of dimensional stability of wool fabrics [11].

Table B.5 Problems often associated with poor dimensional stability

Property	High value	Low value
Relaxation shrinkage	Size variation	Delamination of fusible interlining
	Seam pucker	Seam pucker
	Excessive shrinkage	Moulding difficulties
Hygral expansion	Excessive shrinkage Poor garment appearance Delamination of fusible interlinings Seam pucker	

There are many alternative test procedures used to measure fabric dimensional stability [20]. These procedures include the DIN test [21], the WIRA cylinder, the locked-press shrinkage test [22] and a large number of in-house procedures designed to simulate the conditions met in the garment-making process. However, some of these tests measure only one component of dimensional stability and, in other cases, give a complex mixture of both which can give a misleading impression of potential fabric performance [20].

B.1.3 Instrumentation for objective measurement

Measurement of all the properties that determine important aesthetic characteristics of fabrics is not feasible for industrial users. However, fabric or garment makers require a system that measures only the necessary properties to achieve satisfactory quality control [23].

Simple instruments have been used for many years by research workers to measure individual fabric properties, such as thickness and extensibility. Until recently, the use of these separate instruments to predict fabric performance was not sufficiently coordinated to be widely used except by a small sector of the fabric and garment manufacturing industries.

Two developments have raised the status of fabric objective measurement from a research instrument to a tool suitable for use in industry:

1. The availability of a set of instruments that are relatively inexpensive and simple to use [24].

2. The coordination of background information needed to interpret the large amount of data produced by the instruments and use it to predict fabric performance.

The first coherent set of instruments for this type of fabric objective measurement was developed by Kawabata [25] in Japan. While these instruments are accurate, comprehensive and effective, they are also relatively complex, difficult to use and too expensive for all but the largest textile companies. The most recently developed set of instruments (SiroFAST – Fabric Assurance by Simple Testing) was designed to meet the industrial need for a simple, robust system to predict fabric performance [24, 26, 27].

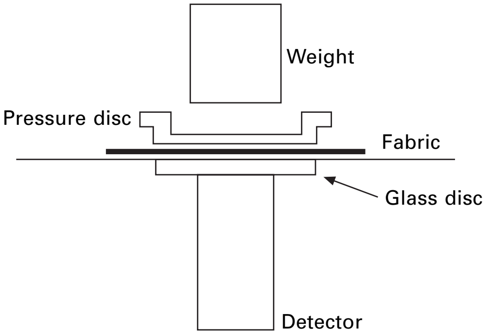
B.2 SiroFAST – fabric assurance by simple testing

SiroFAST is a set of instruments and test methods for measuring mechanical and dimensional properties of wool fabrics. These measurements allow the prediction of fabric performance in garment manufacture and the appearance of the garment during wear [24]. The instruments were developed by the Australian CSIRO Textile Fibre and Technology. The system was designed to be relatively inexpensive, reliable, accurate, robust and simple to operate. A simple method of interpreting the data to predict fabric performance is an integral part of the system.

SiroFAST consists of three instruments and a test method:

- SiroFAST-1 is a compression meter that measures fabric thickness.
- SiroFAST-2 is a bending meter that measures the fabric bending length.
- SiroFAST-3 is an extension meter that measures fabric extensibility.
- SiroFAST-4 is a test procedure for measuring dimensional properties of fabric.

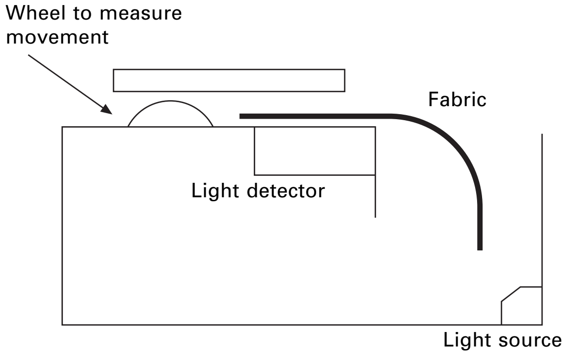
Schematic diagrams of the instruments are shown in Figs B.3, B.4 and B.5.



B.3 Schematic diagram of SiroFAST-1 compression meter.

B.2.1 SiroFAST-1 Compression meter

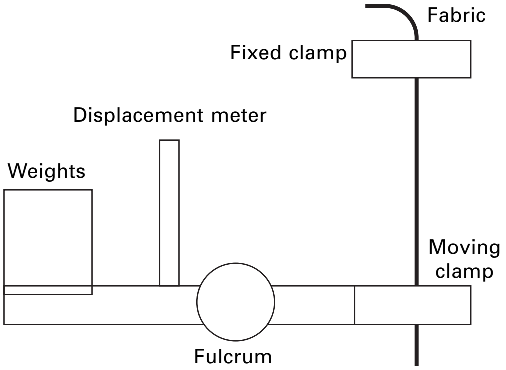
The SiroFAST-1 Compression meter accurately measures fabric thickness at loads of 2 g/cm^2 and 100 g/cm^2. The surface layer thickness [28] is defined as the difference in thickness measured at the two loads, and is calculated from these measurements. The measurements are normally made on the (conditioned) fabric and then repeated after the fabric has been relaxed in steam. From these measurements the released thickness and released surface layer thickness are obtained. Comparison of the original surface thickness and the released surface thickness can be used to assess the stability of the finish on the fabric under the conditions of garment manufacture, such as pressing and steaming [29].



B.4 Schematic diagram of SiroFAST-2 bending meter.

B.2.2 SiroFAST-2 Bending meter

This instrument measures fabric bending length using the cantilever bending principle, as described in British Standard Method BS:3356(1961). From the



B.5 Schematic diagram of SiroFAST-3 extension meter.

values of bending length obtained, the bending rigidity of the fabric is calculated. Bending rigidity is a measure of the stiffness of a fabric and is related to handling in garment making. SiroFAST-2 uses a photocell to detect the leading edge of the sample, which is done by eye in some other test methods. The elimination of this source of operator error makes the SiroFAST bending meter more reliable and simpler to use than alternative instruments [26].

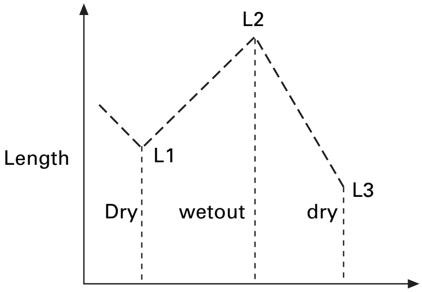
B.2.3 SiroFAST-3 Extensibility meter

The SiroFAST-3 extensibility meter measures the extensibility of a fabric under three different loads (5, 20 and 100 g/cm of width). The loads are chosen to simulate the level of deformation the fabric is likely to undergo during garment manufacture. SiroFAST-3 is also used to measure the bias extensibility of the fabric (at 45° to the warp direction) under a low load (5 g/cm width). Bias extensibility is not used directly but instead is used to calculate shear rigidity [30]. Shear rigidity is one of the principal determinants of the ease, which is a measure of the ease with which a fabric can be deformed into a three-dimensional shape. Formability is derived from measurements made using SiroFAST-3 in combination with data from SiroFAST-2 (see Table B.7 on page 454).

$$\text{Formability} = \text{bending rigidity} \times \left(\frac{\text{extension (20 g/cm)} - \text{extension (5 g/cm)}}{14.7}\right)$$

B.2.4 SiroFAST-4 Dimensional stability test

SiroFAST-4 is a test method for measuring the hygral expansion and relaxation shrinkage of fabric. SiroFAST-4 is a modification of the conventional 'wet–dry' test [11] and can be completed in under two hours [31]. Another advantage of SiroFAST-4 is that the fabric does not require conditioning. With SiroFAST-4 the fabric is dried in a convection oven at 105°C and its dry dimensions measured. The fabric is then relaxed by wetting in water and its wet dimensions measured. Lastly, the fabric is dried again at 105°C and its final dry dimensions are measured. The method for calculating relaxation shrinkage, hygral expansion and a schematic diagram of the SiroFAST-4 procedure is shown in Fig. B.6. The properties measured directly are shown in Table B.6. Those measurements derived or calculated from these measurements are shown in Table B.7.



$$\text{RS} = \frac{\text{L1} - \text{L3}}{\text{L1}} \text{ ¥ } 100\%$$

$$\text{HE} = \frac{\text{L2} - \text{L3}}{\text{L3}} \text{ ¥ } 100\%$$

B.6 Schematic diagram of SiroFAST-4 dimensional stability test.

Table B.6 List of fabric properties measured using SiroFAST

Properties measured	SiroFAST instrument
Fabric weight	
Compression	
Fabric thickness at 2 g/cm^2	SiroFAST-1
Fabric thickness at 100 g/cm^2	
Released thickness at 2 g/cm^2	
Released thickness at 100 g/cm^2	
Bending	
Bending length	SiroFAST-2
Tensile	
Warp extensibility	SiroFAST-3
Weft extensibility	
Bias extensibility	
Dimensional stability	
Relaxation shrinkage	SiroFAST-4
Hygral expansion	

B.2.5 Sampling for SiroFAST tests

SiroFAST-1, 2, 3 test samples are 150 mm ¥ 50 mm. The tests are performed in the order SiroFAST-1, SiroFAST-2, SiroFAST-3. This avoids deformations that would affect later results. The SiroFAST manual recommends:

- SiroFAST-1 Compression – 5 replicates
- SiroFAST-2 Bending – 3 warp and 3 weft replicates
- SiroFAST-3 Extension – 3 warp, 3 weft, and 6 bias replicates (3 left-bias and 3 right-bias).

The samples are then steam released and the SiroFAST-1 tests repeated. The

Table B.7 List of fabric properties which can be derived from measurements made using SiroFAST

Derived properties	Calculated from
Surface thickness	Thicknesses at 2 g/cm^2 and 100 g/cm^2
Released surface thickness	Released thicknesses at 2 g/cm^2 and 100 g/cm^2
Finish stability	Fabric surface thickness Released surface thickness
Bending rigidity	Bending length Weight
Shear rigidity	Bias extensibility
Formability	Bending rigidity Extensibility at low loads

dimensional stability test (SiroFAST-4) requires a separate sample (300 ¥ 300 mm).

In practice, about half a metre of fabric at full width is required to carry out the whole range of tests and allow reasonable sampling across the piece. Results for about 6–10 fabrics can be obtained within one working day. The SiroFAST instruments are interfaced with a computer which does the data handling automatically.

B.2.6 Interpretation of SiroFAST data

Measurement of fabric properties using SiroFAST is a relatively simple process, but interpretation of the data to assess the potential performance of the fabric in garment manufacture is much more difficult. The SiroFAST system uses a control chart as an aid to interpreting the data. This approach is not new and has been recommended for other objective measurement systems [32, 33]. The fingerprint is formed by plotting properties of the fabric on the appropriate scales and then joining the points. Computer software is available that performs this task automatically. A wide range of information can be obtained from direct observation of the fingerprint's position in relation to the 'grey zones' on the SiroFAST chart. These grey zones indicate where potential problems can be anticipated in the manufacture of suits or structured jackets. Slightly different zones would be used for other applications, such as women's dress goods or pleated skirts.

Higher skill levels in a factory manufacturing a particular type of garment would allow an increase in the range of fabrics and fabric properties that could be successfully handled. Software is available for use with SiroFAST that allows users to adjust limits to meet changing garment designs and skill levels in their factory. The limits shown on the SiroFAST chart are derived from published information, research at CSIRO during the development of SiroFAST, the experience of users of SiroFAST and other forms of fabric objective measurement.

The warnings listed indicate the potential problems associated with fabrics with properties outside the recommended limits. The first section of this report detailed some of the problems associated with inappropriate dimensional and mechanical properties; the chart lists just a few. The 'grey zones' on the SiroFAST chart are not intended for use only as 'accept or reject' zones; they should be used as indicators that forewarn the garment maker that problems can be anticipated and these problems should be considered in garment manufacture.

The use of a fabric fingerprint is preferred over alternative techniques for interpreting objective measurement data [8,13]. This is because the fingerprint makes it easier for the garment maker to categorise different garment-making problems and to identify, and possibly correct (by re-finishing for example), the property or properties associated with poor fabric performance.

B.2.7 Repeatability and reproducibility of the SiroFAST system

It is essential for the effective commercial use of fabric objective measurement that all instruments provide the same answer for a given property on the same fabric. This enables the measurements to be used as a common language between supplier and customer, regardless of location. There are two aspects ensuring good repeatability and reproducibility of fabric objective measurements:

1. The conditions of measurement.
2. The instrumentation and measurement procedure.

The conditions for the measurement of textile properties have been set by various testing organisations such as ISO and IWTO at 20°C and 65% RH. This is necessary when testing wool fabrics because the properties change with variations in the moisture content of the constituent fibres. If the measurements are to form a basis of communication or specification, then standard testing conditions must be used. The SiroFAST instruments and the measurement procedures have been tested in a series of round trials carried out using the same format as earlier trials on the KES-F instruments.

B.3 Application in fabric manufacture and finishing

The requirements of fabric manufacturers for an objective measurement system are broader than those of garment makers. First, fabric manufacturers require a quality control system that can be used to ensure fabrics are 'to specification'. This means that they meet the requirements of customers. Secondly, fabric designers need a system that will predict the performance of new fabrics in garment manufacture and the appearance of the garment after manufacture and in wear. Finally, fabric manufacturers require a tool that will optimise fabric design and finishing so that required properties can be engineered into each fabric, with a minimum number of operations and at minimum cost.

Although it has only been available for a relatively short time, SiroFAST has been used in a wide variety of applications in fabric manufacture and finishing [34]. Many of the applications described here apply equally to SiroFAST as to other systems for fabric objective measurement. The principles are the same in each case.

B.3.1 Producing fabric 'to specification'

The most obvious application of SiroFAST for fabric manufacturers and finishers is the avoidance of problem fabrics or the choice of the correct balance of fabric properties so that garment maker's problems are minimised. Customers use SiroFAST to select fabrics. This effectively means that fabric producers will be required to ensure that the fabric supplied meets the 'specifications' of the customer, in both absolute values and consistency. Production of fabrics of known properties need good design and appropriate finishing practice.

Fabric design

The construction of a fabric on the loom (weave, cover factor, etc.) affects its final properties [35, 36] and ultimately its suitability for a particular use. There are aspects of fabric design which can have little or no effect on later processes in finishing. These include fibre diameter and distribution, yarn count and twist as well as fabric weave and, to a large extent, cover factor.

At present there is relatively little quantitative information available which fabric designers can use to predict the properties of loom state fabric both from the properties of the yarn and the fabric design. Some research [37] has been undertaken to relate construction parameters to the final properties of the fabric, but the relationship is inevitably complicated by the effect of finishing.

Nevertheless, some Japanese companies have published information on the design criteria used to produce fabrics consistent with the requirements of apparel company engineers [38]. Although these criteria were based on objective measurements made using the KCES-F system, the principles used are the same for SiroFAST. Table B.8 demonstrates the way in which fabric design may be altered to prevent excessive warp extensibility in formal wear fabrics.

Table B.8 Design changes used to avoid excessive warp extensibility in formal wear fabrics

Method	Effect
Change balance of ends and picks	Large
Change fibre type	Medium
Change spinning method	Small
Blend synthetic fibres with wool	Large
Use shrink resist yarn	Medium
Change weave	n.a.
Use colour woven route	Large

Source: Derived from Mori [38].

Finishing

Although garment makers were the first to adopt objective measurement technology, the responsibility for avoiding, or correcting, problem fabrics at this stage remains primarily with the finisher. This is appropriate in many instances, since the effect of changes in finishing on certain important fabric properties is greater than can be achieved by modifying the fabric on the loom [36, 39].

Finishing is an extremely complex subject because of the large number of changes that occur in fabric properties during a finishing sequence. The effects of many finishing operations are interactive; the total effect of a sequence of operations is not the sum of the individual operations [40]. There is an interaction between fabric construction and finishing such that the effect of finishing on fabric properties will depend on both the finishing route and the construction of the loom-state fabric [39]. Many studies [40–43] are now available which document the effect of individual, and sequenced [44, 45], finishing operations on the properties of fabrics.

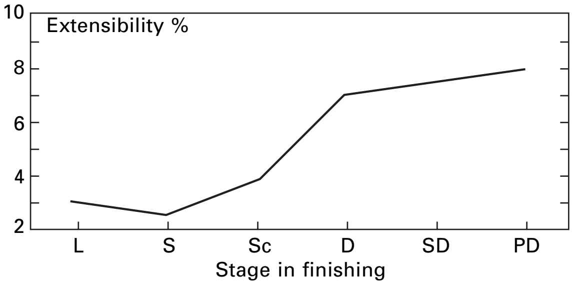
A summary of the most important changes in wool fabrics is shown in Table B.9, and an example of the change in one such property during finishing is shown in Fig. B.7. The properties of wool fabrics are significantly modified by those operations that permanently set the fibres [41] such as wet setting (crabbing), piece dyeing and pressure decatising. Milling and stenter drying are also critical operations for determining the properties of wool fabric. Milling increases yarn and fibre interaction whilst modifying the surface [44]. Stenter drying is the only operation in dry finishing where the dimensions of the fabric are directly controlled.

Information is available to assist finishers in modifying fabric properties, correcting faults in fabrics, avoiding the production of problem fabrics and producing fabrics to the specifications of their customers [46]. However, at this stage little of this information is quantitative. SiroFAST gives the finisher the tool by which the properties of the fabric can be monitored to ensure that

Table B.9 Effect of finishing operations on the properties of wool fabric

Operation	Fabric property					
	Relaxation shrinkage	Hygral expansion	Extension	Bending	Shear	Compression
Wet setting	X	X	X	X	X	X
Scouring	M	M	M	M	M	M
Milling	X	X	M–X	X	X	X
Dyeing	X	X	X	X	X	M–X
Drying	X		X			
Cropping	M		M			M
Singeing						M
Damping						M
Relaxing	X		X			X
Pressing	M–X		M–X	M	M	X
Decatising	X	X	X	X	X	X
Sponging	X		X			M

X indicates a large effect. M indicates a small but significant effect. M–X indicates that while the effects are normally small, under the appropriate conditions the effect can be large.



B.7 Change in fabric extensibility during finishing.

they are ‘on track’ to meet the final specifications. As finishers gain experience of these measurements they can considerably reduce the time needed for new fabric development.

Lack of adequate formability in the warp direction (caused by lack of adequate extensibility) is the single biggest problem in the manufacture of lightweight men’s suiting in Europe. Control of warp formability and extensibility is critical for the production of lightweight fabrics that make up well. Some of the techniques used to prevent inadequate fabric extensibility are shown in Table B.10. All lightweight fabrics have low bending rigidity which cannot be altered without affecting fabric handle. To ensure that a fabric has adequate formability, finishers must engineer appropriate extensibility

Table B.10 Methods used in finishing to ensure adequate warp extensibility in wool fabrics

Wet set the fabric (crabbing)
Increase severity of wet setting
Use batch- rather than conti-crab
Use chemical assistant in conti-crab
Use a piece-dye route
Increase overfeed in drying
Reduce warp tension in dry finishing
Avoid rotary pressing
Pressure decatise rather than 'blow'

Source: Derived from 'SiroFAST Users' Manual'.

into the fabric, without significantly altering its other properties. This is achieved by controlling fabric dimensions, especially in the warp direction.

B.3.2 Optimisation of finishing

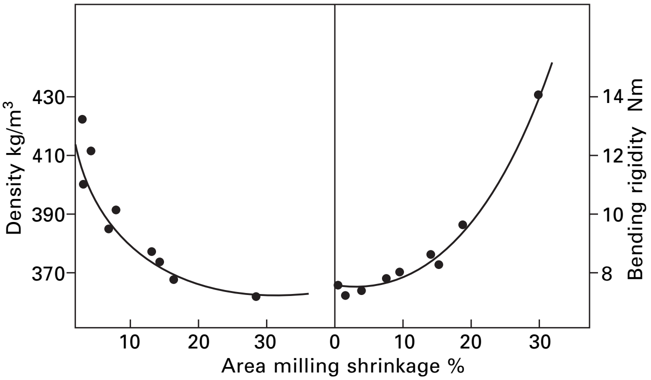
Because of the critical position of finishers in fabric production, they are able to derive maximum benefit from SiroFAST. Finishers have used SiroFAST to:

- Optimise individual and sequences of processes
- Ascertain the relevance of current practice
- Evaluate new alternative finishing machinery
- Evaluate new auxiliaries or chemical processes.

The use of SiroFAST to ascertain the value of a change in finishing sequence is described in ref. 51. The effect of two extra setting processes on the potential performance of the fabric was evaluated. These extra processes made the finishing more expensive but were expected to improve the quality of the fabric.

When a comparison of fabric properties was made before dyeing, there were significant differences that indicated that the quality was improved by the extra processes. However, in the finished fabric the differences were small, suggesting that the longer finishing route had no significant effect on the properties of the finished fabric and was simply a waste of money. Without an objective measurement system such as SiroFAST, quantitative proof of this would have been impossible. The effect of a milling on the properties of a wool fabric is shown in Fig. B.8.

The objectively derived data show the effect of milling on the properties of wool fabric is inconsistent. This means that an optimum level of milling is required to maximise changes in some properties (e.g. fabric density), while minimising changes in others (e.g. bending rigidity). Without an objective



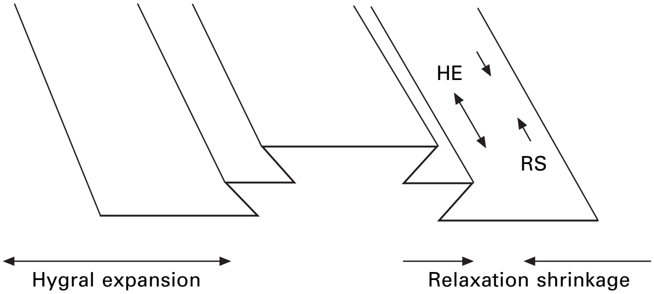
B.8 The effect of milling on the properties of wool fabric.

measurement system (such as SiroFAST), quantitative determination of the effectiveness and optimum level of milling is difficult.

B.3.3 Engineering special finishes

There are special finishes applied to wool fabrics which require engineering of fabric properties. This may be necessary to produce a certain 'look' [47], performance in the garment or to avoid problems in later processes. The best known example of these finishes is that required for wool fabrics that are to be autoclave pleated. A wool fabric that has no shrinkage can rarely be successfully autoclave pleated [11]. Autoclave pleating of wool fabrics requires an engineered balance of both relaxation shrinkage and hygral expansion. The reason for this is found in the changes that occur in fabric dimensions in the autoclave.

When steam is introduced the fabric panel relaxes, and as a result shrinkage can occur. At the same time, the moisture content of the fibres increases so there is a tendency for the fabric to (hygrally) expand as shown in Fig. B.9. To form good pleats, the shrinkage in the fabric, both across and along the



B.9 Dimensional changes in pleated panels in the autoclave.

pleats, must exceed the expansion, otherwise the fabric will buckle, creating puckered pleats. Like the pleats, the buckling will then be permanently set into the fabric.

The amount of relaxation shrinkage that must be present in the fabric depends on the hygral expansion. Equations have been derived [48, 49] to indicate the amount of relaxation shrinkage required to prevent puckering of pleated panels.

Relaxation shrinkage (required) = 1.0 + 0.33 ¥ hygral expansion

The amount of relaxation shrinkage required will also depend on fabric weight, style of pleat, regain of the fabric and conditions in the auloclave [50]. Lightweight fabrics (for example) buckle more readily than heavier fabrics and consequently require more relaxation shrinkage [50]. Without a reliable technique for measuring both components of dimensional stability (relaxation shrinkage and hygral expansion), such as SiroFAST-4, engineering a pleated finish is impossible.

Once the requirements for a fabric are established in quantitative form, there are several finishing routes available to achieve the required result. The simplest and most reliable is to wet out the fabric and re-dry it in the stenter to dimensions that will give the required relaxation shrinkage. Naturally this procedure will remove any temporary surface finish on the fabric but this can be reimposed with a light decatising. However, as such a temporary finish would be removed during autoclave pleating, decatising does not affect the properties of the pleated panel.

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