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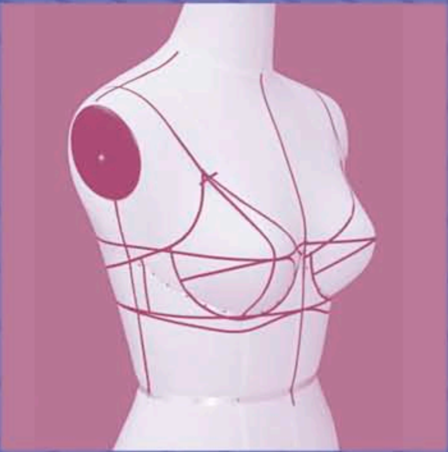

Innovation and technology of women's intimate apparel

Edited by W. Yu, J. Fan, S. C. Harlock and S. P. Ng

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Contents

Preface

The intimate apparel business has witnessed extraordinary public interest and manifold growth in the last decade. Consumers not only look for stylish lingerie but are also increasingly demanding innovative and engineered garments. The use of smart fibres and health-promoting materials as well as functional design and process engineering is transforming this traditional business into a high-tech industry, the future of which will not simply rely on craftsmanship, but be based on continuous scientific research and technological innovation as well as the education of the best talents.

Intimate apparel is an interdisciplinary subject involving body beauty, human anatomy and anthropometrics, pattern design, textile engineering as well as health science. From both the academic and industrial perspective it is important to bring together the literature, which is currently scattered in different disciplines. This monograph is the first attempt to offer a comprehensive review and critical assessment of progress in the scientific understanding and technological innovations in the field of ladies' intimate apparel.

The book comprises ten chapters related to intimate apparel research and development grouped into three main themes. Chapters 1 to 4 discuss the concepts of body beauty, breast sizing, bra innovation and bra pattern development. Chapters 5 to 7 are devoted to the innovation in girdle design and construction, particularly with regard to health issues and the effects of the pressure that they exert on the wearer. Chapters 8 to 10 introduce the special functionality and performance evaluation of intimate apparel, as well as the product and process innovation applying to seamless knitting technology.

The first chapter considers the general factors affecting the social concepts of body beauty, followed by a critical review of key research work in quantitative approaches and experimental findings on the ideal body proportions as well as the body shaping effects of bras and girdles. Chapter 2 discusses the industrial standards and techniques used by researchers for measuring women's bust anthropometry and critically evaluating bra sizing systems. An account of the historical evolution of bras and modern developments in innovative bra products is given in Chapter 3, with an emphasis on the technology behind each innovation. Although a bra is the most complex item of intimate apparel, there is a notable absence of literature regarding bra pattern and fitting technology. Chapter 4 compares the documented guidelines of bra pattern development with theories on the mathematical relationship between pattern parameters and body measurements; 2D direct drafting methods, 3D modelling and CAD systems are critically evaluated and research questions are posed for further exploration.

A girdle is an item of functional intimate apparel designed to beautify the body. Chapter 5 reviews the invention of various types of shaping and health-promoting girdles. The latest development in material technology is provided particularly with respect to the critical property of fabric extensibility. As intimate apparel is a next-to-skin garment, its potential effects on the health of the wearer are very important. Chapter 6 provides a comprehensive account of the physical and physiological effects from wearing constrictive intimate apparel supported by evidence from the literature. Since physiological effects from excessive clothing pressure are always negative, Chapter 7 is devoted to describing the research work related to measuring clothing pressure using both direct and indirect methods. It also discusses the influence of body curvature and tissue softness on pressure absorption.

Intimate apparel offers many special functions. Several common types of functional intimate apparel are introduced in Chapter 8 with a technological appreciation of their efficacy. Chapter 9 considers the industrial standards, techniques and practices used for the performance evaluation of knitted underwear. The last chapter describes the innovations used in the manufacture of intimate apparel introduced in recent years with particular emphasis on the application of seamless knitting technology that is leading a new direction in the development of intimate apparel.

Although this book is principally a research monograph, it is useful not only for academia but also provides a sound theoretical basis and practical reference for technologists, designers and engineers in the industry in their future product development and innovation.

Winnie Yu
Jintu Fan
Simon Harlock
Sun-pui Ng

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Winnie Yu and Jintu Fan

1
Assessment of women's body beauty

N-Y LIM, R ZHENG, W YU and J FAN

1.1 Introduction

The philosopher Aristotle first mentioned the concept of 'beauty' [1]. Clarke in 1887 pronounced that personal beauty was most attractive and fascinating [2]. Body beauty without doubt is the ultimate desire of most women in many parts of the world [3]. Intimate apparel is the foundation of fashion that critically affects women's beauty. Therefore, any thesis on the design of intimate apparel requires a detailed consideration of women's body beauty to understand the beauty concept and its influence on the design of intimate apparel.

Fan, Yu and Hunter [4] have recently published a monograph *Clothing Appearance and Fit* that reviewed various studies of body beauty with respect to general clothing. This chapter will firstly investigate the factors influencing women's body beauty with respect to intimate apparel. Secondly, it will review the modern definition of body beauty in terms of proportions and golden ratios, which are most important criteria in the design of intimate apparel. Lastly, it will report on current investigations into women's body beauty with regard to the female torso's proportion and contour shape.

1.2 Influential factors of body beauty

Beauty is an intangible [5] characteristic which, by definition, is very subjective. The Merriam-Webster Dictionary generally defines beauty as 'the quality or aggregate of qualities in a person or thing that gives pleasure to the senses or pleasurably exalts the mind or spirit' [6]. However, cultures at different times have developed different standards for physical attractiveness [7]. The appreciation of women's body shape has varied between different countries due to the unique cultures, customs and fashion trends that prevailed in their societies [8, 9]. The perception of body beauty has also been claimed to be influenced by the sex of the assessor and the colour of their skin.

1.2.1 Time factor

Women have used various intimate apparel or devices to shape their body according to the beauty criteria throughout history [10]. This section highlights the important milestones in the evolution of intimate apparel and body beauty.

Ancient age

The powerful 'Cretan Snake Goddess' (Fig. 1.1) was an ancient statue found in Greece around 2000 BC. She was sculpted wearing a tight-fitting garment from underbust to the waist that effectively frapped her waist and pushed up her naked breasts. This garment was considered a predecessor of today's corset [11]. In contrast, Roman women in the third and fourth centuries wore a circular band around their breasts whose purpose was to reduce the breast movement, and to hide the protrusion of natural breasts [9].

1.1 Cretan Snake Goddess, dating from around 2000 BC.
Source: Bardey C, *Lingerie: A celebration of silks satins, laces, lineus and other bare essentials,* New York, Black Dog & Leventhal Publishers, 2001.

Medieval period

During the 13th to 14th centuries, most women left their breasts unsupported. Tailors developed techniques to produce body-conscious garments through shaped pattern pieces, whereby the breasts were evident even if not emphasized [12]. At the end of the 14th century, the medieval period gave way to the Renaissance, when the appreciation of beauty was renewed. Round, small and firm, high and compact breasts were considered as the aesthetically ideal shape.

Crazy corset years

The corset was probably the most controversial garment in the entire history of fashion [13]. It was quite essential in the everyday life of women during the 16th, 17th and 18th centuries. In the early 1500s, in order to compress the breasts and to shape the torso as a smooth line, women wore corsets that were made from paste-stiffened linen and given support by thin wooden planks called busks. By the 1530s, iron corsets were being worn by the upper classes.

The iconic fashion figure of the 16th century was Catharine de Medici, the French queen. She was famous for her 13-inch waist and her edict banning 'thick waists' at court. The slim waist and small breasts that the young queen favoured were soon in vogue throughout Europe. Women compressed themselves with restrictive corsets to achieve these figures [13]. In the 16th and 17th centuries, upper-class French women also massaged their breasts with herbs and had wet nurses (a woman who suckles another woman's child) to breastfeed their children so that they could maintain small and firm breasts [7].

In contrast, by the late 18th century, corsets were styled to push the breasts up and close together rather than keeping them separated. In addition, the reigning mode was to have the exposed bosom appear more soft than plentiful with increased cleavage. The breast profile was expressed naturally rather than exaggerated to an artificially shaped dimension [7, 11]. Therefore, the breasts were exposed with a large amount of bulging bosom, and even occasionally the low necklines showed the nipples. In order to push the breasts up, ornate busks were often inserted into the front corset [14].

In the early 19th century, styles changed again in France and England when a metal device called a 'divorce corset' was invented to separate the breasts from one another [15]. The 19th century could be considered as the age of hourglass shapes (Fig. 1.2). Feminist historians have argued that the corset was deeply implicated in the construction of a 'submissive', 'masochistic' feminine ideal in the 19th century [16, 17, 18]. In order to attract the admiring attention of males, women created extreme, fashionable hourglass figures

1.2 Photograph of a tight-lacer, 1895. Source: Steele V, *The corset: a cultural history*, London, New Haven, 2001.

that demanded a waist measuring no more than 21 inches by cinching the lace in the corset tightly [10, 13]. Wearing such hourglass-shaped tight-fitting corsets brought women discomfort and health hazards (Fig. 1.3).

It is difficult to understand how the corset years started and continued for several centuries. In fact, corsets not only changed the shape of women's breasts, but also established a society's beauty criteria. Lifted and shaped breasts were considered as a normal part of the female silhouette [10].

20th century

Beauty is not a myth [19]. When the exaggeration of breasts is in fashion, women can wear foundations to push up the breasts. At other times, when fashion changed, they tended to reduce their flesh. In 1904, the Paris fashion designer Paul Poiret famously declared, 'It was in the name of Liberty that

1.3 Illustration of a woman's skeleton, uncorseted and corseted, from Witkowshy, Tetoniana, 1898, after von Soemmering, 1793.
Source: Steele V, *The corset: a cultural history*, London, New Haven, 2001.

I advocated against the corset and in favour of the brassiere'. After World War I, fashion was dominated by the straight-as-a-board silhouette. In order to achieve this boyish and careless look, a flattened chest was fashionable in some countries [12, 10].

During the 1940s and 1950s, after World War II, western clothing styles started to highlight the female shape by emphasizing the difference between the breast, waist, and hips after Dior presented his famous 'New Look' in 1947. At the same time, foundation garments lifted the breasts and often had firm and pointed breast cups for emphasis [7, 10, 11]. Following trends sets by film stars, such as Marilyn Monroe and Brigitte Bardot, cone-shaped breasts, a narrow waist, sloping hips and long leg became the ideal shape for the female body [10, 11].

In the late 1960s, the perfect body shape was influenced by a model whose nickname was Twiggy. Her 32-inch breasts, straight-pencil look became an icon of the cultural revolution [20]. By the end of the 1960s, the feminists took on the bra as a symbol of patriarchal societal constraints [12]. Going without a bra became fashionable from hippies to the 'bra burners' and to the breast-feeding movement. Some scholars considered discarding the bra was a very important step, which allowed women to emphasise their own physical comfort over society's previous beauty criteria [10]. In the 1970s, soft and natural were the features of ideal breasts. The trend for big breasts came again by the late 1980s.

Thus, throughout history, women have emphasized or de-emphasized their bodies and breasts by their foundation garments. During some eras, large breasts and slim waists were regarded as key points of female attractiveness and sexual allure. At other times, a straighter, more 'boyish' figure has been popular [7].

1.2.2 Culture factor

Kenrick [21] found that little variation of physical attractiveness and preference has been found across cultures. However, Randy *et al.* [22] reported dissimilarity among ratings of body pictures resulting from the differences in viewers' social and cultural backgrounds. Evidence can be found from a number of studies, for example,

- Kenyan Asian females perceived thin female shapes slightly more negatively than British females (Furnham and Alibhai [23]).
- Ugandans preferred more obese females than the British (Furnham and Baguma [24]).
- Ugandans preferred heavy figures in contrast to a preference for light figures by the Greeks and the British (Furnham and Greaves [25]).
- Greek and British judges clearly showed their preference for small size in both the light and the heavy figures (Adrian [26]).
- Body fat is attractive in societies in which food resources are limited and not storable. The opposite results were obtained in western societies because most women have access to plenty of calories (Anderson *et al.* [27]).
- The optimum volume height index (VHI = volume/height^2) preferred by a Chinese survey group is 14.1 1/m^2, while it was 16–17.5 1/m^2 for a Caucasian group (Fan [87]).

1.2.3 Skin-color factor

Among the many factors related to cultural backgrounds, women's skin colour is proven to be a significant factor in the assessment of beauty, as reported in the following literature.

- Lighter weight is associated with beauty for white women (Cohn and Adler [28], Cunningham *et al.* [29] and Monello and Mayer [30]).
- Thin white women and heavy black women were considered 'better' than heavy white women and thin black women (Powell and Kahn [31]).
- Men hold the strongest skin colour biases regarding notions of feminine beauty (Allen *et al.* [32]).
- A darker skin in African American women made them less attractive (Mark [33]).

- Black men were more likely than white men to find overweight women attractive (Harris Walters and Waschull [34]).
- Black Americans were less prone to the influence of a thin beauty standard (Crago, Shisslak and Estes [35]).

1.2.4 Gender of assessors

Fallon and Rozin [36, 37] reported the gender differences in the ratings of female images by men and women assessors. Shih and Kubo [38] found that female figures rated by women as more attractive are thinner than the figures preferred by males. Buss [39] also asserted that women had very precise and accurate ideas of what men find attractive. However, Martin [40] argued that there is no significant difference in the rating of attractiveness by male and female raters. The gender difference on the perception of body beauty was yet to be confirmed.

In our work, four male and five female judges were invited to rate the attractiveness of 108 body-scanned images of female figures with and without bras and girdles. The results were scattered. It was found that male judges were insensitive to the minor changes in women's body figures that were created by the intimate apparel, while female judges could discern the small improvement in body shape much more readily.

1.2.5 Mass media

The mass media is always perceived as a strong channel to promote the standard of women's beauty, and this can readily make women feel anxious about their figures which are normally not perfect [41]. Young people learn from the media that a skinny body with medium breasts is ideal [42]. Fouts and Buggraf [43] studied television situation-comedies and found that thinner female characters received more positive comments. Literature [44, 45] has reported a significant decrease in the body measurements and weights of centrefold models and pageant contestants from the 1950s to 1990s. The average bust, waist and hip measurements for *Playboy* centrefold models are 90.8 bust, 58.6 waist, 89.3 cm hip. This ideal image represents a woman with a bust-to-waist ratio of 1.55 and a hip-to-waist ratio of 1.52.

1.3 Modern definitions of body proportion

In the modern world, body mass index (BMI) and waist-to-hip ratio (WHR) are the two most common factors associated with female physical attractiveness [46].

1.3.1 Body mass index (BMI)

Body mass index (BMI) is a number which can be calculated by dividing the weight in kilograms by the square of the height in metres. It is commonly used for assessing body fat content in large-scale population surveys [47, 48]. In 1941, O'Brien and Shelton suggested that a height-weight combination would be the best basis for classifying women's body types and could be used to predict subjects' other body measurements [49].

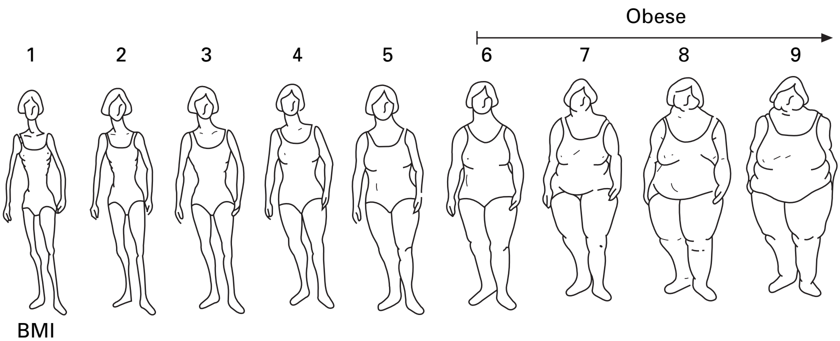
Tovée *et al*. [50] claimed that BMI was an important factor and a stronger predictor [51] to determine a female's physical attractiveness. Successful female fashion and glamour models [52] were all within a narrow BMI range. Garner *et al*. [53] found that thin women were considered to be more attractive than fat women. Thornhill and Grammer [54] used real images of women and found that BMI was more strongly correlated with attractiveness than WHR. Tovée *et al*. [55] suggested that the preferred BMI for women's physical attractiveness was between 18 and 19, which was considered as the optimal number for health and fertility. It has also been suggested that a 'nice-looking' female's figure should have a BMI value between 20 and 22 [56]. Other studies [57, 58], on the other hand, considered that the extra fat stored on women's breasts and buttocks made women attractive to males.

According to the World Health Organization (WHO) report [59] as shown in Table 1.1, a BMI of 25 kg/m^2 is widely recognized as 'overweight', and a BMI value of 30 kg/m^2 is considered as 'obese'. It is well reported that the changes in BMI have a strong influence on health [60, 61] and reproductive potential [62, 63, 64]. By using Stunkard's standard figural stimuli [65], as illustrated in Fig. 1.4, Bulik *et al*. [66] studied the silhouettes of 16,728 women and 11,366 men together with their self-reported information of height-weight, actual body size, desired body size and a discrepancy score. It was reported that the six women having a BMI value of nearly 30 or over were considered as obese. They also found that although the BMI changed with age, the body shape tended to remain the same with age.

Table 1.1 Classification of under and overweight adults according to BMI.

Classification	BMI (Kg/m^2)	Risk of comorbidities
Underweight	<18.5	Low (but risk of other clinical problems increased)
Normal range	18.5–24.9	Average
Overweight	25	
Pre-obese	25–29.9	Increased
Obese class	30.0–34.9	Moderate
Obese class	35.0–39.9	Severe
Obese class	40	Very severe

Source: World Health Organization



1.4 Figures corresponding to BMI values from 1–9. Source: Ref. 65.

1.3.2 Waist-to-hip ratio (WHR)

In addition to BMI, a great deal of research has focused on the waist-hip ratio (WHR) in the determination of body shapes and attractiveness. WHR can be measured in two ways. One way is to divide the waist girth by hip girth, which has also been regarded as a factor correlating with female fertility [67]. The other way is to divide the waist width by hip width as seen from the front view, which was relevant to the body's visual cue. A low WHR was believed to have the optimal fat distribution for women's health [68], high fertility [69, 70] and attractiveness [71]. The judges were asked to evaluate attractiveness using a set of line-drawn figures of women's bodies grouped into three series – underweight, normal and overweight. An optimal WHR of 0.7 was suggested. However, Henss [72] carried out similar research and reported that the women with a WHR of 0.8 appeared more attractive.

Singh [73, 74, 75, 76] observed the changes in WHR of Miss America and *Playboy* playmates for more than 30 years. It was found that the WHR of subjects remained within a range of 0.68 to 0.72. For a healthy pre-menopausal woman, the typical WHR was between 0.67 and 0.80 [77, 78, 79].

1.3.3 Combination of BMI and WHR

BMI and WHR are correlated and co-variant. According to the Canadian Dietetic Association [80], the silhouettes of women and men were related to their body mass index (BMI). In order to assess the attractiveness of women lots of studies asked subjects to rate for the line-drawn figures including underweight, normal and overweight ones. The figures showed different WHR by changing the torso width around the waist and holding other features constant. However, when the waist width was manipulated, both BMI and WHI have been altered. Tovée and Cornelissen commented that it was impossible to conclude whether the changes in attractiveness ratings were influenced by WHR, BMI or both [81]. The same problem was also found when the photographic images were artificially changed over various WHRs [82].

1.3.4 Volume height index (VHI)

Based on their original investigations of 3D body images, Fan *et al*. [83, 84, 85] discovered that the volume height index (VHI, volume/height^2) provides a better measure of the modern beauty of women than BMI and WHR. The finding has been internationally recognized and reported in *Nature News* [84, 85]. In Fan *et al*'s study, 3D images of 31 Caucasian females with varying BMI ranging from 16 to 35 were shown to 29 male and 25 female judges (i.e. assessors), who were asked to rate the attractiveness of the bodies. They found that the body volume divided by the square of the height, defined as the Volume height index (VHI, volume/height^2), explained about 90% of the variance of the attractiveness ratings, significantly greater than the BMI or WHR could. It was therefore believed that VHI was the most important and direct visual determinant of female physical attractiveness, and was also a key factor for health and fertility.

In addition to the importance of VHI, it was reported that there was no gender difference between men and women in rating female attractiveness, and the effect of the body's physical parameters on the perception of female physical attractiveness conformed to Stevens' power law of psychophysics. Moreover, based on 69 scanned Chinese male subjects and 25 Caucasian male subjects, Fan *et al*. [86] suggested that VHI was also the most important visual cue to male body attractiveness, and could explain *circa* 73% of the variance of the attractive ratings.

1.3.5 Breast size

Furnham *et al*. [87] investigated the effect of breast size on the assessments of female attractiveness, and found that the size of the breasts made a significant contribution to the attractiveness ratings. The effect of breast size on the assessments and age estimations were dependent upon the overall body fat and WHR.

Singh and Young [88] reported that, besides WHR, the breast size is the main factor in influencing the judgement of female attractiveness, age and desirability for a long-term relationship. Slender bodies with low WHR and large breasts were considered to be the most attractive, healthy, feminine looking, and desirable. Similarly, Low [89] suggested that slim young females with large breasts have the most attractive body figure. It is also interesting to learn that the age estimations highly depend on breast size, WHR and weight, such that the perceived age of women with large breasts, high

WHR and high weight was raised by over ten years compared to their actual age.

However, Kleinke and Staneski [90] found that medium breasts gained most favourable ratings by the assessors from both sexes. As suggested by Gitter *et al*. [91], males preferred large breasts only for small and medium female figures, whereas females preferred smaller breasts. Adrian *et al*. [92] even showed that breast size was relatively less important than WHR on the influence of the attractiveness ratings, whereby large breasts only slightly increased the rating of health and femininity. Heavy figures with a high WHR and large breast size were rated to be the least attractive and healthy.

1.3.6 Hip size

Recent research has found that the size of different body parts might influence the ratings of female body attractiveness, irrespective of WHR. Tassinary and Hansen [93] reported that hip size was a stronger determinant of female figures attractiveness than WHR. Catherine *et al*. [94] found that larger figures with smaller hips were perceived as more athletic. They were more attractive than the shapely heavy-body-weight alternatives. These results indicated that hip size could be important to predict women's attractiveness perceptions. Several studies by Singh and Luis [95] also claimed that hip size was more influential than waist size.

Malgorzata [96] showed that men are sensitive to WHR differences only based on waist change instead of hip change. When the waist size decreased, the attractiveness of the female figure increased, yet there was no significant difference of attractiveness in a range of WHRs from 0.65 to 0.80. According to Voracek and Fisher 2002 [97], *Playboy* centrefold models have shown a tendency towards a higher WHR over the past 50 years. Tovée *et al*. [98] discovered that over 90% participants perceived the subject with a bigger hip size as the heavier. Therefore an increased hip size of WHR from 0.65 to 0.6 may lead to the perception of increased weight as well, and cause a decrease in attractiveness rating.

1.3.7 Fluctuating asymmetry (FA)

Thornhill and Gangestad [99] showed that minimal fluctuation asymmetry on human figures is judged to be most attractive and to be preferred in sexual partners. In 1995, Singh [100] arbitrarily changed the symmetry of the bust in line-drawn figures to investigate the relationship between breast asymmetry and attractiveness. The result showed that they were inversely correlated. However, the finding was not directly obtained from the real human body.

With regard to health and fertility, the epidemiological studies of Scutt *et al*. [101] claimed that an increased FA in human females was correlated with increased health risks. Møller *et al*. [102] and Manning *et al*. [103] both believed that lower FA seemed to be correlated with higher fertility. Lars *et al*. [104] revealed that males preferred symmetrical to asymmetrical females. The judgement of attractiveness, feminine looks and desirability for a long-term relationship were still certainly influenced by asymmetry. However, Tovée [105] generated the images with perfect symmetry and compared them with the relative attractiveness of the normal asymmetric image. The comparison showed that there is no significant difference between symmetric and asymmetric images perception.

Singh [106] also showed that, regardless of their degree of breast asymmetry, the figures with low WHRs were more attractive than those with high WHRs. This showed that breast asymmetry is less determining than WHR. In many cases, the symmetric image is relatively more attractive, but the conclusion is that FA is not an important cue to identify the perception of attractiveness compared to BMI or WHR.

1.3.8 Anatomy of breast beauty

In the field of plastic surgery, aesthetically pleasing breasts [107, 108, 109] were non-drooping, full, in proportion to the body, having minimal ptosis, conical, teardrop in shape, with the nipples at the anterior-most position. In 1934, Maliniac [110] first developed a concept of the ideal nipple plane. The ideal level of the nipple for all women was a point on the midpoint from the olecranon to acromium. It was also confirmed by Melvyn [111] that the ideal nipple plane passed through the midhumeral point.

The 'Universal Aesthetic Triangle' was proposed by Penn [112] and has been used for breast reduction surgery for many years. It means an equal length from manubrium to each side of the nipple, and from nipple to nipple. However, some researchers indicated that both parameters making up the triangle would increase with breast size and vary with breast volume. They recommended a slightly squatter triangle [113] to determine the height of the nipple according to the position of the infra-mammary fold.

Based on the above research results, for breast augmentation practice, researchers [114, 115] analyzed each patient's breasts to determine the size and type of implant for the desired outcome by using important parameters including original projection, diameter, volume, nipple position, infra-mammary fold position, chest wall circumference and symmetry.

1.4 Golden ratio

1.4.1 Generic golden ratio

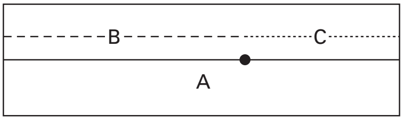
Beauty is a mystic thing. Francis Bacon [116] said 'there is no excellent beauty that has not any strangeness in the proportion'. Among many different opinions about good proportion, there is one 'golden ratio' prevalent in nature that appears to give a special sense of balance and harmony. The golden ratio showed up early in 300 BC [117], when Euclid, a Greek mathematician, showed how to divide a line in mean and extreme ratio. The golden ratio is also called the golden section, golden number or golden mean. It is a simple proportion which is denoted by phi (Ø) or 1.618033988749895…. Phi is a ratio defined by a geometric construction where a line is divided in one very special and unique way [118].

The golden ratio represents a cross-cultural, cross-disciplinary and cross-temporal mystery of divine proportions [119]. It can be described by drawing a line as one unit long and dividing it in two unequal segments, so that the ratio of the longer segment (B) to the whole line (A) is the same as the ratio of the shorter segment (C) to the longer one (B). Thus, A is Ø times B and B is Ø times C, as shown in Fig. 1.5. For centuries, the golden ratio has been applied in many ways such as architecture, painting, art and sculpture. The Egyptians used both pi (p) and phi (Ø) in the design of the great pyramids. The Greeks developed the entire design of the Parthenon in Athens based on this ratio. The golden ratio was also extensively used in the paintings of famous artists, like Da Vinci and Seurat [120]. Kepler [121] regarded it as one of the treasures of geometry.

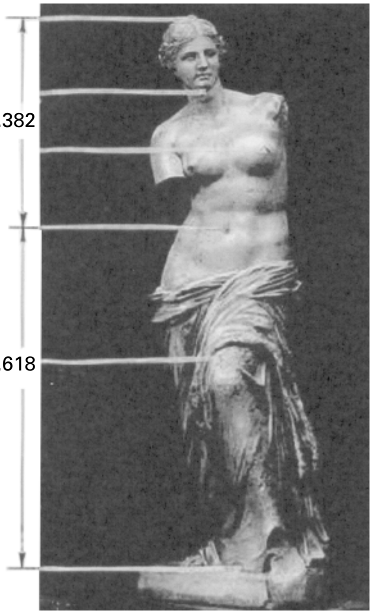
1.4.2 Golden ratio of the human body

The golden ratio is also regarded as one of the attractiveness 'standards' for the human being. The Russian philosopher Krukovsky [122] wrote, 'Contemplating the perfect, fine human face and body we come unintentionally to the thought about some latent, but obviously felt mathematical refinement of their forms, about the mathematical regularity and perfection of their curvilinear surfaces'. For example, Aphrodite's sculpture created by Agesander is considered as a masterpiece of woman's beauty (Fig. 1.6).

Marcus Vitruvius Pollio, the first-century Roman architect and writer revealed the relationship of the human body to the circle and the square [123]. His ten books on architecture were the earliest literature dealing with human proportions. Marcus stated that there was a perfect harmony between all body parts, which later was captured in Leonardo da Vinci's [124] famous



1.5 The explanation of the golden ratio.
Source: http://goldennumber.net/neophite.htm.



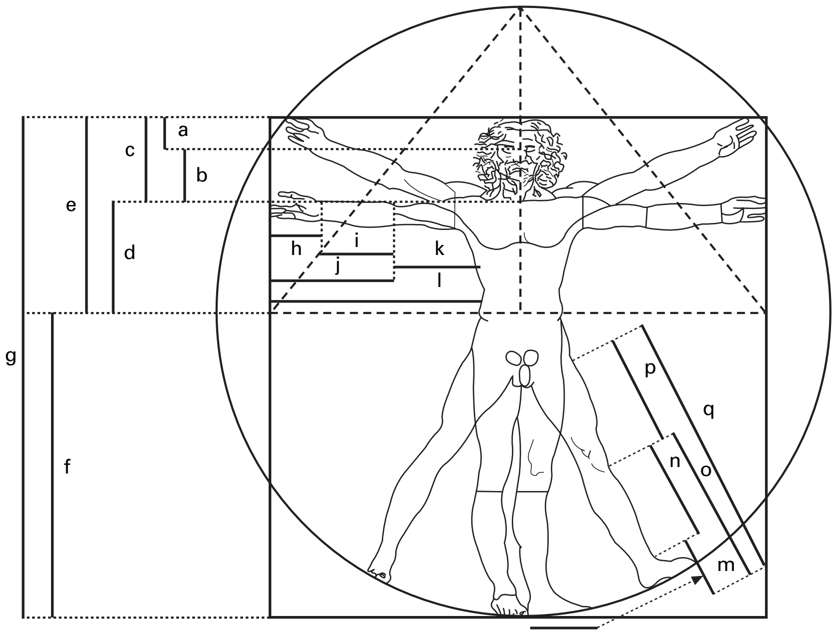
1.6 Aphrodite's sculpture (The Venus de Milo) created by Agesandr. Source: http://www.goldenmuseum.com/index_engl.html.

sketch of Vitruvian Man [125] (Fig. 1.7) in 1509 named 'Da Divina Proportion'. Several research publications [126, 127, 128, 129] also indicated the presence of the golden proportion in a correlation of the body parts of man, specifically the hand.

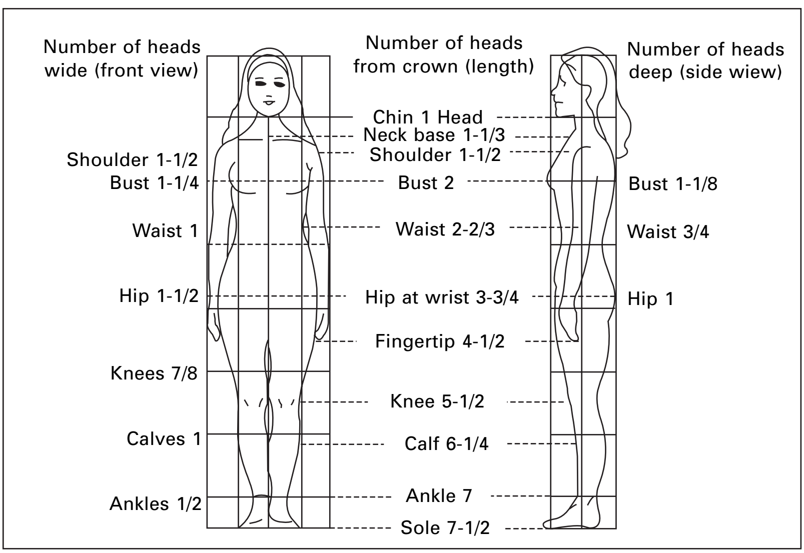
According to classical average Greek body proportions (Fig. 1.8), various body measurements were explained in a unit of head length. For the ideal female, the height is approximately seven and half head lengths. The hip and shoulder should have the same width. The fullest part of the bust is located two head lengths from the crown. The breast point width is the same as the distance from the breasts to the navel and from navel to division of legs [130].

Brinkley and Aletti believed that an ideal female figure (Fig. 1.9) should be well proportioned all over. Height proportion should be two-fifths of the total height from the top of the head to the waist, the hipline should be half the total length and knees should be in the bottom quarter. For general measurements, the figure is well proportioned when the bust and hip are almost the same measurement with the waist approximately ten inches smaller [131].

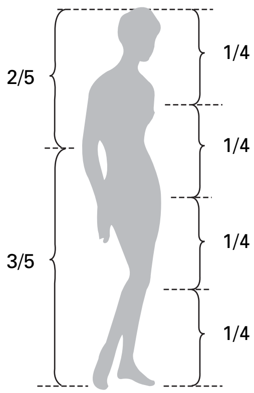
According to a book in Chinese, the normal length of a Chinese woman's head (a) is about 22 to 26 cm, which is the same as the distance between bust point and neck base (b). Breast sagging is indicated when this distance is



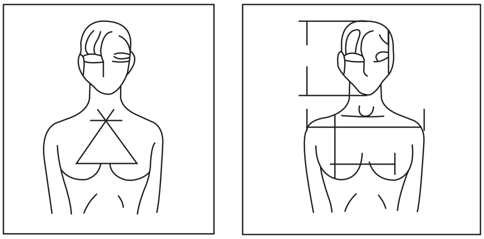
1.7 Leonardo da Vinci's interpretation of Vitruvius.
Source: Gielol-Perczak K [126].



1.8 Ideal female body proportion according to the ancient Greeks.
Source: Horn M J and Gurel L M (1981). *The Second Skin*, third edition.



1.9 Optimal proportion of female body figure.
Source: Jeanne Brinkley and Ann Aletti (1976). *Altering Ready-To-Wear Fashion, A Bennett Career Book.*



1.10 Normal body proportions of Chinese women.

longer than the head length. The normal distance between two breasts (c) is half of the shoulder width (d), which is 17 to 18 cm. An optimal breast width and height are obtained when an equilateral triangle is drawn from the clavicle to the two nipples. Figure 1.10 illustrates the definitions of the above-mentioned measurements.

1.4.3 Golden ratio of women's torso

In order to incorporate the concepts of beauty into intimate apparel design, the Human Science Research Center of Wacoal [132] has been observing individual women for over 40 years. Based on their research findings, Wacoal has developed several indices of beauty including 'Golden Proportions' in 1955, 'Beautiful Proportions' in 1979 and 'Golden Canon' in 1995. In 1955, the 'Golden Proportion' had an ideal height of 162 cm. The body height was 7.3 times the head length, and the optimal ratio indicated the ratio bust:waist:height to be 53:37:55.

In 1979, Wacoal revised the proportion and proposed a new standard called 'Beautiful Proportion'. It specified the ideal body circumference in terms of a portion of body height, for different age groups. In 1994, Wacoal investigated 1,115 women's body sizes and asked six judges to assess their body beauty [133]. Based on both the manual measurement data and 3-dimensional (3D) data, key parameters were identified that were strongly related to a female's body beauty, as shown in Fig. 1.11. It also shows the balance of the width, height and circumference of bust, waist and hip.

1.5 Effect of women's contour shape

As mentioned by Marilyn *et al.* [136], underwear can change the body appearance as reflected on the body contours, which were important visual cues to predict physical perception. Recently, a research was conducted at the Hong Kong Polytechnic University which specified the correlation between body contour parameters in quantitative terms and the subjective rating of body attractiveness. Eighteen Chinese women were selected from 68 volunteers to participate in these experiments. They were aged between 20 and 26 and were of different sizes. The average height was 158.3 ± 4.91 cm, and average weight was 53.42 ± 6.82 kg. First of all, each subject was measured manually and topless using a Tecmath 3D body scanner. Then each subject was asked to wear five sets of bras and girdles to fit her own size. Each clothed body was captured again by the body scanner.

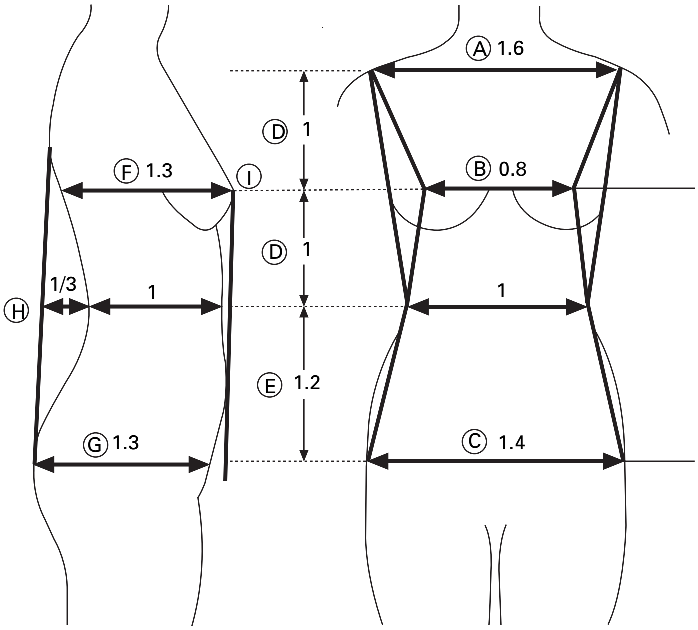
1.5.1 Computation of body parameters

Eighty-five measurements were automatically provided by the Tecmath body scanner, however, only a few were found useful for the shape analysis of women's body torsos. A software program was therefore written to analyze the relevant body parameters, based on the data cloud stored in ASCII format. The software simultaneously shows a naked and a clothed body contour. From there, the body parameters in terms of girth, depth, width, height and area can be calculated at any specified levels such as bust, waist and hip.

Table 1.2 Wacoal's 'Beautiful Proportion'

Age	20–29	30–39	40–49
Bust height	H ¥ 0.719	H ¥ 0.715	H ¥ 0.711
Bust girth	H ¥ 0.515	H ¥ 0.525	H ¥ 0.543
Underbust girth	H ¥ 0.432	H ¥ 0.453	H ¥ 0.468
Waist girth	H ¥ 0.370	H ¥ 0.386	H ¥ 0.401
Abdomen girth	H ¥ 0.457	H ¥ 0.475	H ¥ 0.501
Hip girth	H ¥ 0.542	H ¥ 0.553	H ¥ 0.565
Hip height	H ¥ 0.500	H ¥ 0.500	H ¥ 0.500

Source: Wacoal Corp.



1.11 Ratio balance of torso from Wacoal's 'Golden Canon'. Source: Wacoal Corp.

Using these body parameters, the attractiveness cues including Wacoal's Golden Ratios and WHR are readily found. In addition, the overall volume and VHI can be computed by integration.

1.5.2 Analysis of body contour

Attributes of body contours in different regions may affect body attractiveness, so each scanned image was investigated from both side and front views. Six typical contours are leftside, rightside, bust, abdomen, back and hip. To qualify the contour shape, a 'Body landmarking software interface' was also developed that allows the operator to identify the body landmarks (neck, bust point, under bust, waist, hip and crotch) manually from the computer screen. Fitting curves along the landmarks defined the apparent six body contours for further analysis of symmetry, smoothness and shape.

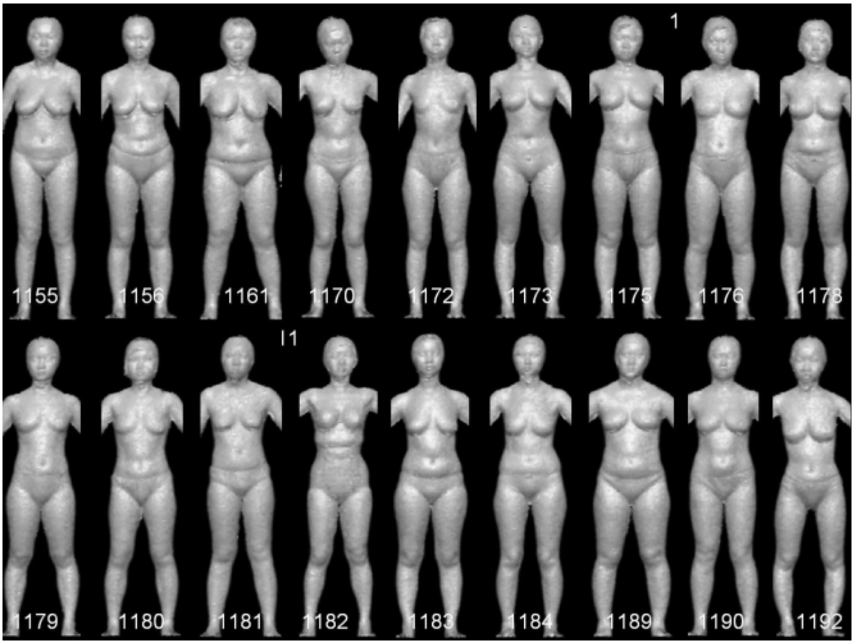
1.5.3 Relationship of body parameters and attractiveness

After the above-mentioned body parameters had been quantified, they were correlated with the subjective assessments of body attractiveness. For the subjective assessment of body beauty, 30 female experienced lingerie consultants were invited to be the judges. Each 3D nude and clothed body image was rated in a score ranging from '1' for the least attractive to '9' for the most attractive. Overall, 108 body images were visualized 3D using a VRML (virtual reality modelling language) program. Each image was viewed and rotated by moving the cursor on the computer screen. The image resolution was 436 ¥ 668 pixels and stored as grey colour. The arms and hands were trimmed, but the heads of the images remained because they were blurred enough so that the face would not affect the body attractiveness ratings.

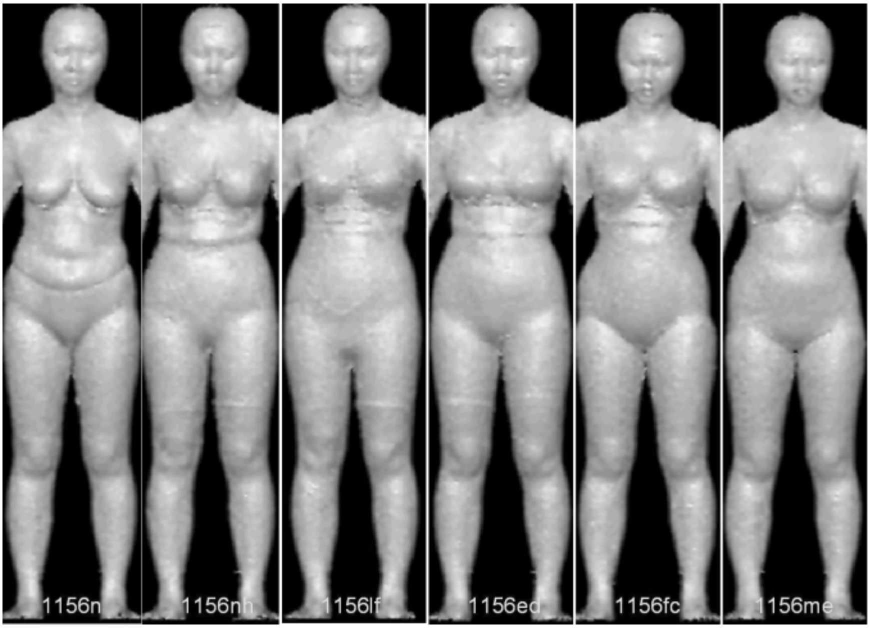
For overall rating of attractiveness, several image sheets were prepared for the judges to assess. They included:

- Eighteen naked images (Fig. 1.12)
- Six front images of each subject (Fig. 1.13)
- Six side images of each subject (Fig. 1.14)

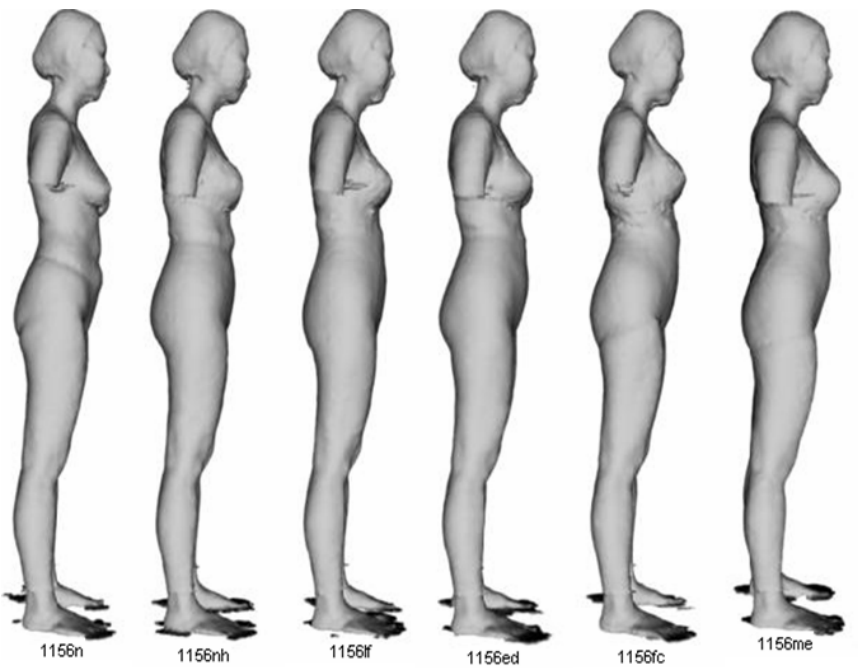
Regarding the body contour attractiveness in terms of contour symmetry, smoothness, shape and the overall contour attractiveness on specific body contours, the assessors ranked the attractiveness in a preference order from '1' for the most attractive contour to '6' for the least attractive contour. This revealed that the body wearing a bra and girdle always looked better than the nude shape. The most significant visual cues to assess the improvement in body figures, by wearing a set of bra and girdle, were the shape of the breasts and hips as well as the contour smoothness of abdomen. Judges confirmed



1.12 Eighteen subjects' images with nude upper body.



1.13 Six front images of each subject.



1.14 Six side images of each subject.

that the breast contour and hip contour were the two main important features in the assessment of women's body beauty.

1.6 Clothing influence on body cathexis

Labat *et al*. [134] noted that body cathexis and satisfaction level of the perceived overall body image was highly related to the satisfaction of the clothing fit. Markee *et al*. [135] reported that women were significantly more satisfied with their clothed bodies than with their nude bodies. Clothing played an important role in enhancing the perceived body image and body attractiveness. Among all types of clothing, intimate apparel, being a next-to-skin item, should act to help the wearer to beautify her figure. Women believe that when they wear beautiful lingerie, they walk differently and feel sexier, so in fact, intimate apparel represents society's ideal of beauty and femininity.

1.7 Conclusion

Body beauty is in the eyes of the beholders, so it can change with time and culture. The earliest theory of beauty was presented by the Golden Ratio. With studies of the body attractiveness cues and their correlation with attractiveness perception, the Golden Section, Wacoal's Golden proportion and other indices such as BMI, WHR, VHI have been developed. Our recent research has shown that, in addition to body proportion, body contour also influences the attractiveness of women's body shapes.

Many researchers argued that the perception of body beauty is subjective, significantly influenced by time, social environment, cultural background, race, skin colour, sex and mass media. More objectively, recent studies showed some useful ratios of body parameters that can quantify and explain body beauty. Literature indicated that body beauty can be mainly predicted by body size and proportion such as BMI or WHR. The volume approach of using VHI is a new method to identify individual body beauty. Shape-up intimate apparel is supposed to improve the body shape and attractiveness, but the wearer's BMI, WHR and VHI would not change at all. Our current study is therefore aimed at studying how the geometric body parameters and contour shape relate to the subjective attractiveness rating of both the nude and clothed body.

1.8 Acknowledgement

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2
Breast measurement and sizing

R ZHENG, W YU and J FAN

2.1 Introduction

The technical understanding of intimate apparel requires in-depth knowledge of human anthropometry and sizing. To achieve an accurate fit of second-skin intimate apparel, in particular bras, detailed body measurements are necessary for the definitions of body shape, curve profile and dimensions of the torso, especially for the breast region. Fan, Yu and Hunter have authored a research monograph [1] published by Woodhead Publishing Limited that critically reviewed various research works on body measurements, sizing systems and body beauty in general. However, there was limited literature found that related to body sizing for intimate apparel.

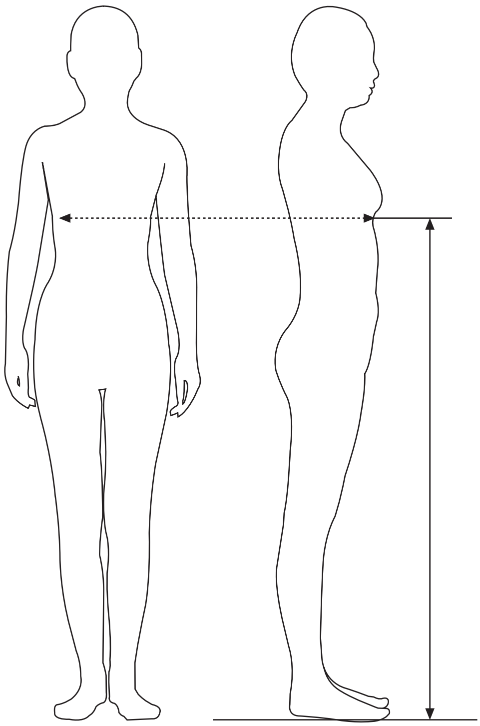
2.2 Measurement of breast dimensions

In order to obtain accurate measurements for the upper torso and the breasts, it is important to control the human subject's posture, clothing and body landmarks, as well as carefully selecting the measuring devices and relevant measurement items.

2.2.1 Control of posture and clothing

Similar to the general body measurements, accuracy is also affected by the clothing worn by the human subject, his/her breathing and posture. Bra size is even more difficult to measure because the natural breasts may tend to drop low and spread wide. Historically, bra tailors asked the model to take off her bra and lift her breasts to where she wants the bra to fit. Then at that level, the measurement was taken by tape measure. However, the determination of desirable breast position varied from one person to another and from time to time.

The international standards of breast dimensions, ISO 8559 [2] suggests measuring over a well-fitted, unpadded and thin brassiere with minimum



2.1 Recommended standing measurement postures from AIMER HEC-BUCT. Source: AIMER HEC-BUCT [5].

accessories and support. ISO 7250 [3] specifies the body measuring procedures based on a nude subject who is wearing minimal clothing and no shoes, standing fully erect with feet together, head in the Frankfurt plane[1] and shoulders relaxed with arms hanging freely during the standing position measurements. ISO/DIS 20685 [4] recommends three standing positions for various 3D body scanners to obtain reliable data. It was suggested that during the 3D body scanning, measurements should be taken during the subject's quiet respiration; the shoulders should be straight, being natural with relaxed muscles. The first author, Zheng previously chaired the Aimer Human Engineering Research Centre of the Beijing university of Clothing Technology (AIMER HEC-BUCT). The centre adopted the following procedures to ensure that subjects stood erect during the manual measuring (see Fig. 2.1). The

1. Standard horizontal plane at the level of the upper edge of the opening of the external auditory meatus (external ear opening) and the lower border of the orbital margin (lower edge of the eye socket), when the median plane of the head is held vertically (ISO 7250, 2.2.8).

subject was asked to wear only a close-fitting panty and no bra, to stand erect with bared heels together and feet open at an angle of about 30 degrees, then look straight ahead with arms hanging naturally. In order to obtain more reliable data for 3D scanning, the posture was changed with the heels splayed to about 100–150 mm and the upper arms held apart from the sides of the torso at an angle of 15–20 degrees.

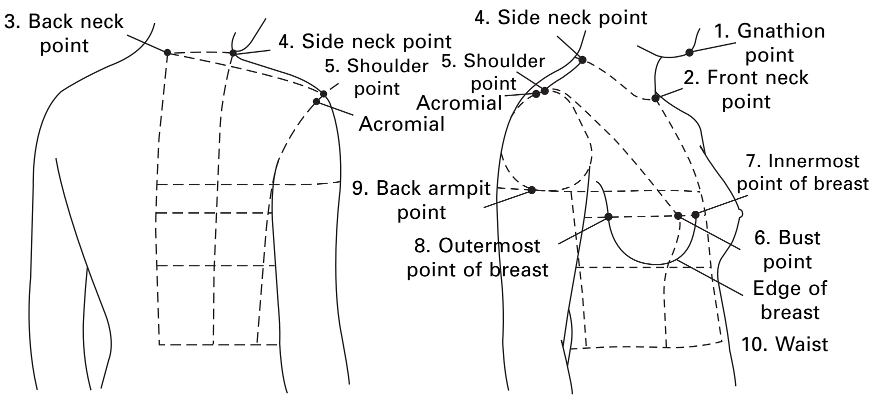
2.2.2 Body landmarks

In the collection of anthropometric data, the identification of body landmarks is the first key step to prevent operational errors in handling the measuring device and determination of the body position. By definition, a body landmark is an anatomical feature used as a point of reference to locate body features for measurements [6]. International Standards identify only the common anthropometric measurement points and lines for the sizing of general clothing, but more detailed points and lines are needed for meaningful measurements of the breast size and shape.

Anthropometric measuring points for landmarking

In addition to the traditional methods of making body landmarks [7], Zheng [8] has developed additional measuring points, based on the subcutaneous bone framework of the human body related to the breast measurements. The specific points are shown in Fig. 2.2 and defined in Table 2.1.

All the anthropometric measurement points should be marked on the skin with a non-smearing pencil [12] or skin-safe washable ink [16] before the actual breast manual measurements. Furthermore, for 3D scanning purposes it is recommended that special raised stickers [17] be used to mark the key



2.2 Breast anthropometric measuring points [7, 8].

Table 2.1 The definitions of breast anthropometric measuring points

Measuring points	Definition
Gnathion point	The lowest point of the mandible in the midline.
Front neck point	The midpoint between two collarbones, at the centre of the front neck base girth.
Back neck point (Cervicale)	The base of the neck portion of the spine, located at the tip of the spinous process of the seventh cervical vertebra, determined by palpation, often found by bending the neck or head forward [9, 10, 11, 12, 13].
Side neck point	The intersection point of the neck base line and the anterior border of the trapezius muscle.
Shoulder point (Acromion[1])	As viewed from the side, is the intersection point of the arm scye girth passing the acromial and a line running down the middle of the shoulder from the side neck point to the tip of the shoulder. It is the most prominent point on the upper edge of the acromial process of the shoulder blade (scapula) as determined by palpation [10, 9].
Bust point	The centre of the most prominent point on the naked bust, or the most prominent protrusion of the bra cup [11, 9, 12].
Innermost point of the breast	The inner intersection point of a horizontal line across the bust point and the under edge of the breast.
Outermost point of the breast	The outer intersection point of a horizontal line across the bust point and the under edge of the breast.
Back armpit point	The lowest point of the back axillaries[2] posterior, or the point at the lower (inferior) edge, determined by placing a straight edge horizontally and as high as possible into the armpit without compressing the skin and marking the front and rear points or the hollow part under the arm at the shoulder [9, 13].
Waist (natural indentation)	The point of greatest indentation on the shape line of the right side of the torso as viewed from the front of the subject, or the profile of the torso or half the distance between the 10th rib and iliocristale landmarks [11]. Some defined it as the location between the lowest rib and the hip identified by bending the body to the side [13].
Crown	Top of the head [13, 12].
Abdominal extrusion	As viewed from the side, is the greatest protuberance point of the abdomen, usually taken at the high hip level [13], taken approximately three inches below the waist, parallel to the floor [14, 15].
Hip extrusion	As viewed from the side, is the greatest protuberance point of the hip.

[1] Acromion: the outer end of the scapula to which the collarbone is attached.
[2] Axillary: relating to or located near the axilla.

landmark locations on the subject to ensure the measuring points can be found. In the applications of 3D body scanners, it is also important to establish landmarks so that the data automatically obtained and calculated can be widely understood and used by various industries. Simmons and Istook [18] compared the common body-scanners [TC][2], Cyberware, and SYMCAD with traditional manual anthropometric methods. They found that measuring techniques varied among different scanners. It was impossible to use the current standards to determine the measuring process in 3D scanning. Using such non-contact methods, absolute identification of landmarks could not be satisfactorily achieved automatically.

From the CAESAR anthropometric survey, Robinette and Daanen [17] found that the automatic landmarking methods for 3D body scanners did not work consistently enough on all body types. Even using neural networks or other automated recognition packages to identify the landmark location of the stickers, it seemed to be successful for only 70% of the measurements. They considered that manual intervention for validation and verification of the landmark locations on all subjects was still required.

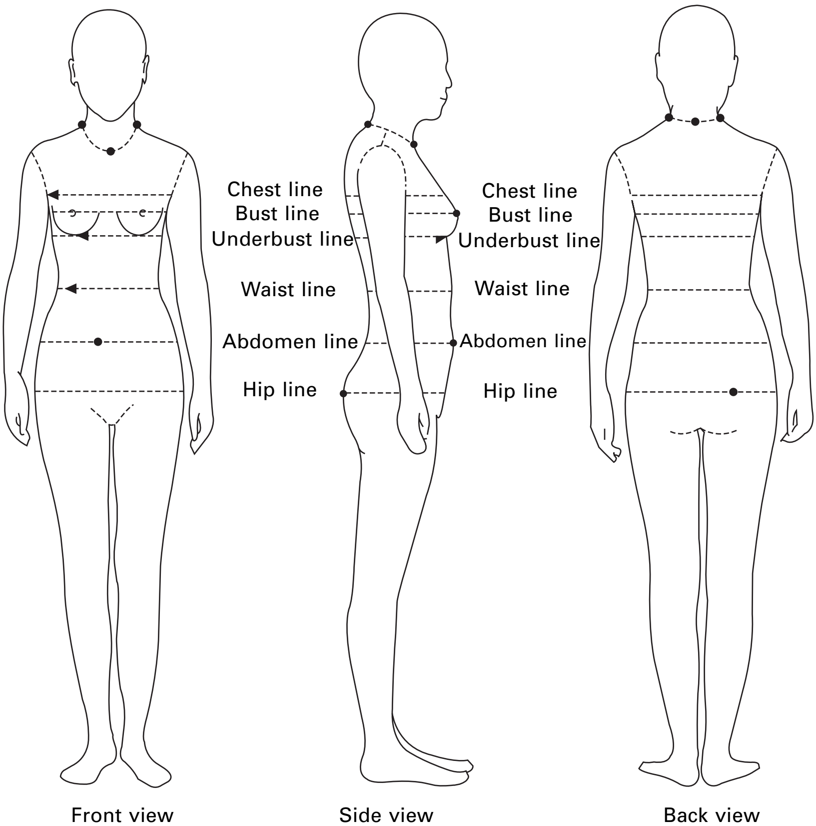
Anthropometric measuring lines for landmarking

The common body measuring lines are well known by anthropometrists and their definitions are shown in Fig. 2.3 and Table 2.2. Tailors and researchers normally use tape measures to record the body circumference at a specific body height. However, it can be difficult to ensure data accuracy because the measuring tape might not be exactly horizontal and in a plane parallel to the ground.

Miyoshi [19] applied a sliding gauge (Fig. 2.4) to draw women's cross-sections. Using a similar concept but much simpler mechanical design, the authors have developed a laser device (Fig. 2.5) to determine four body points simultaneously at the four body planes on the skin, exactly at the same height level. Before developing the new device, the authors used a height caliper to locate the required landmarks at the same level on the left, front, and back of the model, for measuring reliable circumference across the three or four points. This method is easy to perform, but time-consuming.

2.2.3 Manual measurements

Measuring a breast using manual methods can be very embarrassing [20] and difficult to ensure accuracy although there is a good set of Martin measurement tools [21]. Therefore, some non-contact methods based on 2D photo silhouette imaging and 3D body scanning [7] have been developed which are more readily accepted by the models. In the medical field, mammograms, magnetic resonance imaging, and Archimedes measurement



2.3 Anthropometric measurements lines.

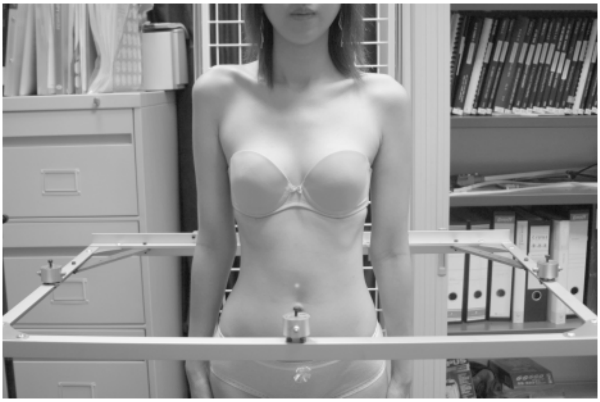
Table 2.2 The definitions of breast anthropometric measuring points

Measuring lines	Definition
Chest line	Line across the back armpit points.
Bust line	Line across the bust points.
Underbust line	Line across the lowest edge of the breasts. If two breasts vary, the right side breast is used.
Waist line	Line across the innermost point on the right side of the torso.
Abdomen line	Line across the abdominal extrusive point.
Hip line	Line across the hip extrusive points.

principles are often used to assess the breast volume [22]. They are sophisticated and accurate methods, but very expensive and to some extent invasive.

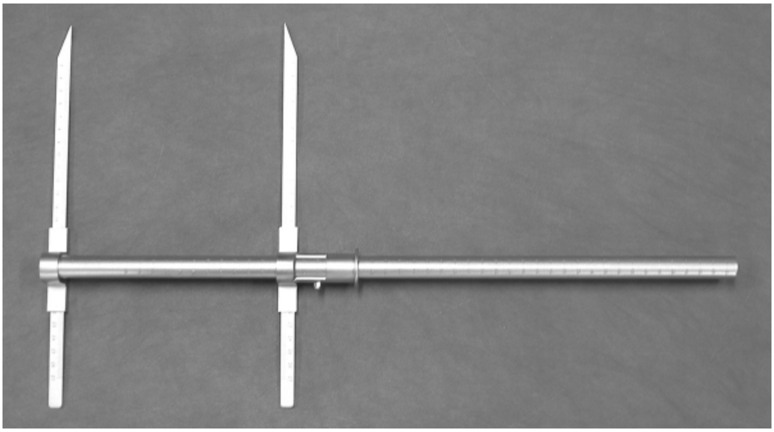
Figure 2.6 shows the typical Martin style measuring tools and the breast depth caliper. The use of these instruments is demonstrated in Fig. 2.7. Even

2.4 The horizontal sliding gauge. Source: Miyoshi M, Clothing construction, Bunka Publishing Bureau, 2001 [7].

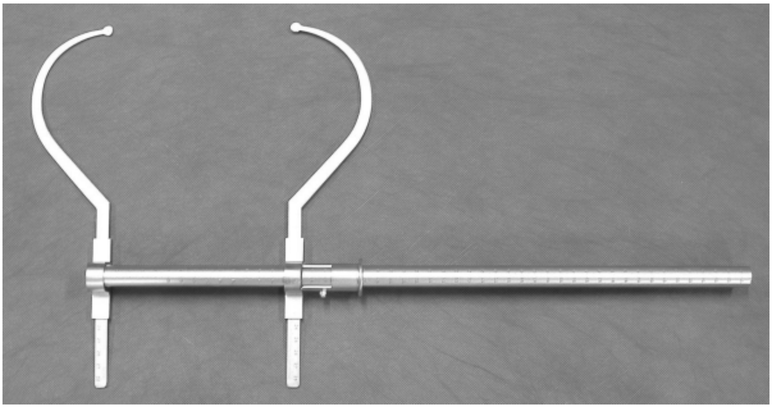


2.5 A laser device developed by the authors.

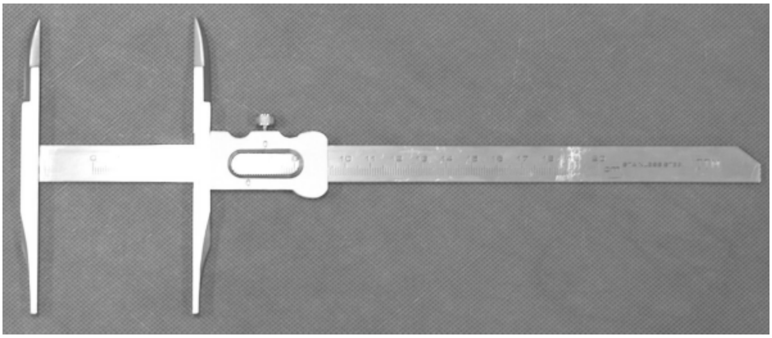
though measurers are usually trained to measure subjects for a study, the manual measurement process is still very difficult to perform and time consuming [23]. For example, in a 1988 anthropometric survey of US Army personnel, four hours were required to physically landmark, measure, and record the data for one subject [24]. Using Martin's techniques, Zheng's research team described [25] the breast proportion and shape based on 46 body dimensions including height, width, thickness, girth, surface distances and detailed breast measurement items (Table 2.3).



(a)

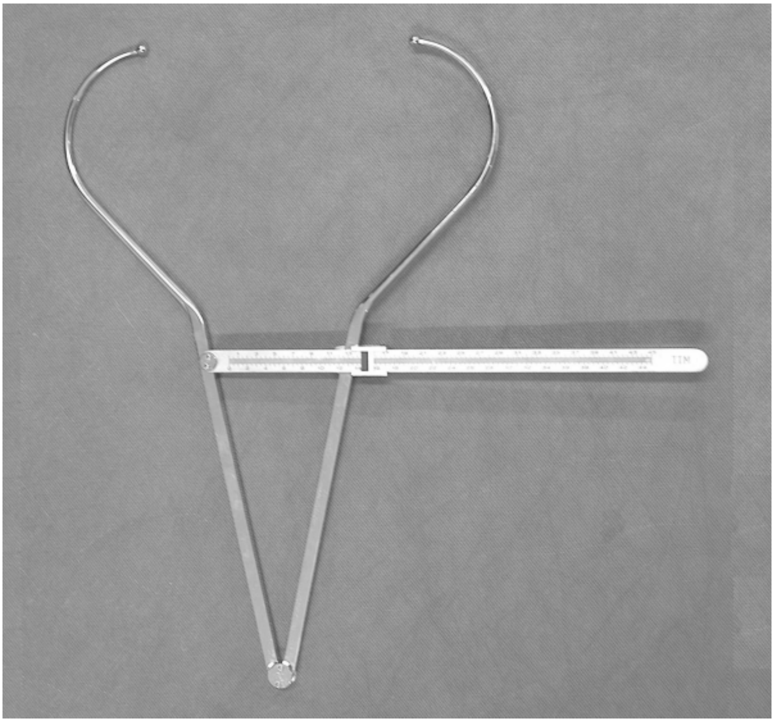


(b)

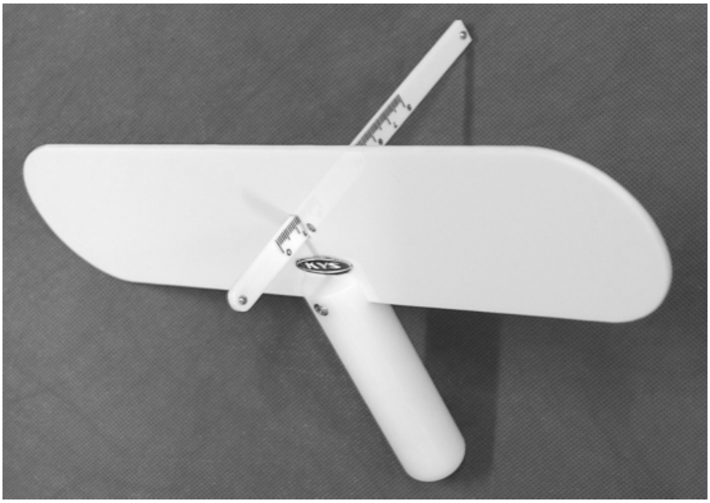


(c)

2.6 Manual measurement tools for body measurement. (a) Large sliding caliper of Martin; (b) spreading caliper of Martin; (c) sliding caliper of Martin; (d) compasses spreading caliper of Martin; (e) breast depth caliper. Source: AIMER HEC-BUCT, 2001 Annual report of Anthropometric survey data analysis [25].

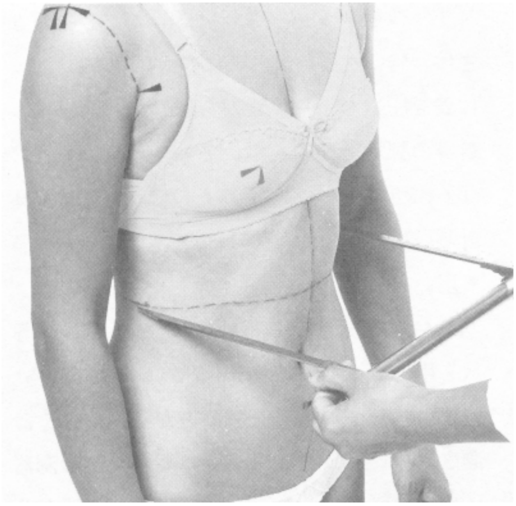


(d)

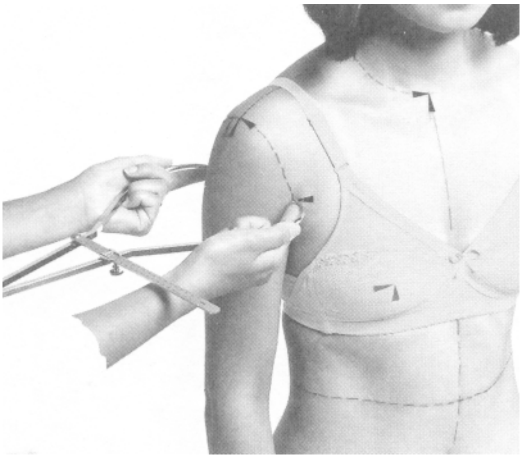


(e)

2.6 Continued



(a)



(b)

2.7 Method for using manual measurement tools. (a) Large sliding caliper being used, (b) Compasses spreading caliper being used. Source: Miyoshi M, *Clothing construction*, Bunka Publishing Bureau, 2001 [7].

2.2.4 2D measurements

To compensate for the complicated and time-consuming body measurements especially in the breast region. Miyoshi *et al*. have reported the use of a horizontal sliding gauge (Fig. 2.4) and a vertical sliding gauge (Fig. 2.8) to obtain 2D profiles of cross-sections and longitudinal-sections of a woman's body [26]. Using optical methods, Makabe [27] and Nakai [28] *et al*. employed 2D photo silhouette imaging using a camera or silhouette analyzer (Fig. 2.9)

Table 2.3 Manual measurements related to breast sizing

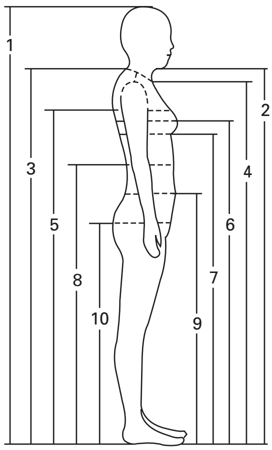
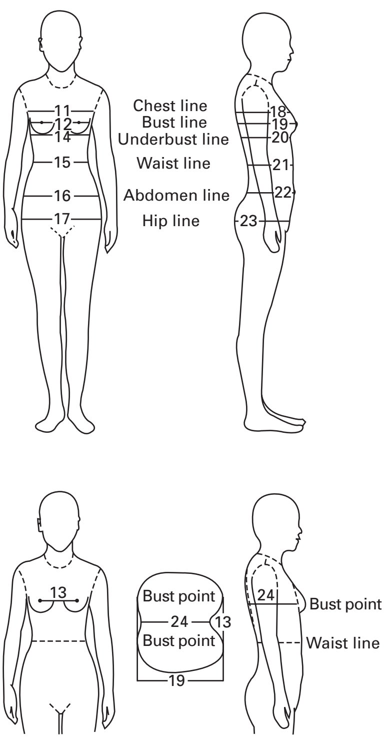
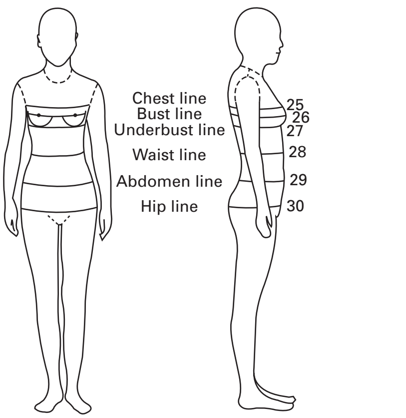
Vertical measurements	
	1 Whole body height 2 Gnathion height 3 Back neck point height 4 Front neck point height 5 Chest height 6 Bust height 7 Underbust height 8 Waist height 9 Abdomen height 10 Hip height
Width and depth measurements	
	11 Chest width 12 Bust width 13 Bust point width 14 Underbust width 15 Waist width 16 Abdomen width 17 Hip width 18 Chest depth 19 Bust depth 20 Underbust depth 21 Waist depth 22 Abdomen depth 23 Hip depth 24 Median chest depth

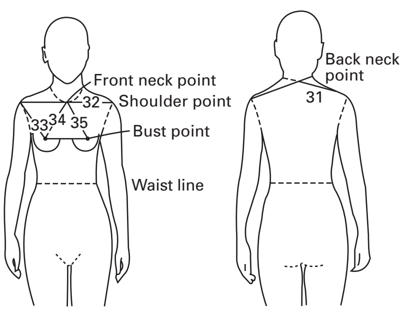
Table 2.3 Continued

Girth measurements



25 Chest girth
26 Bust girth
27 Underbust girth
28 Waist girth
29 Abdomen girth
30 Hip girth

Surface distances measurements



31 Cross shoulder length over back neck point
32 Cross shoulder length over front neck point
33 Length from right shoulder point to right bust point
34 Length from front neck point to right bust point
35 Length from front neck point to left bust point

Detailed breast measurements

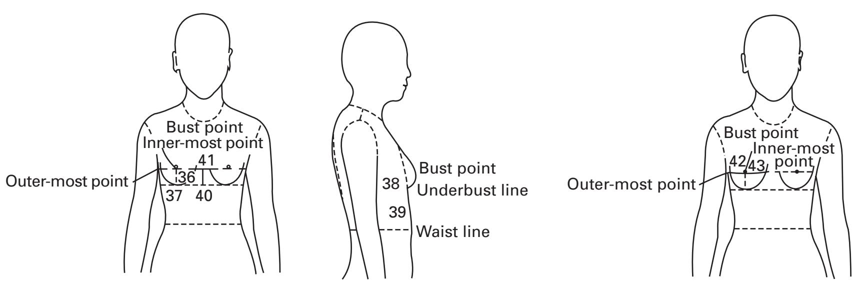
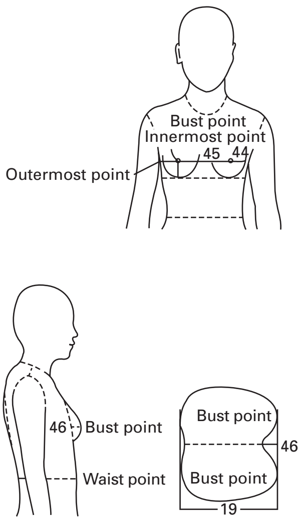


Table 2.3 Continued



36	Inner arc length of right breast root
37	Total arc length of right breast root
38	Vertical arc length from right bust point to underbust
39	Vertical distance from right bust point to waist
40	Centre bridge height
41	Horizontal distance between innermost point of bust
42	Outer arc length of right breast
43	Total arc length of right breast
44	Outer arc length of left breast
45	Total arc length of breast from right to left
46	Breast depth

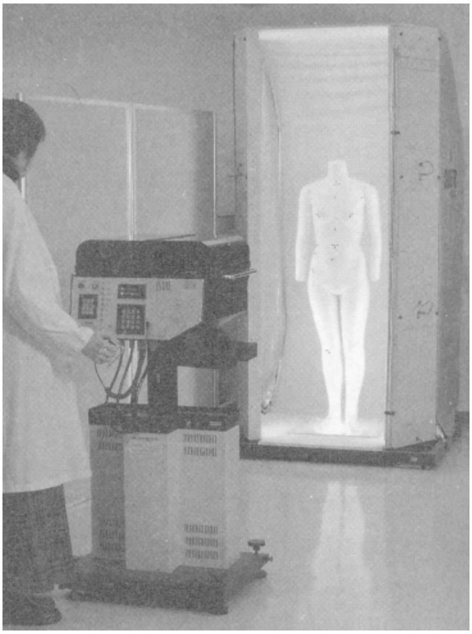
Source: AIMER HEC-BUCT, [25].

to classify the posture and the figure of adult women in Japan. Gazzuolo *et al.* [29] further proposed a photographic method of measurements using video capture and automated measurement of frontal and lateral view photographs which they claimed was useful in determining pattern dimensions for the upper torso of the female body form.

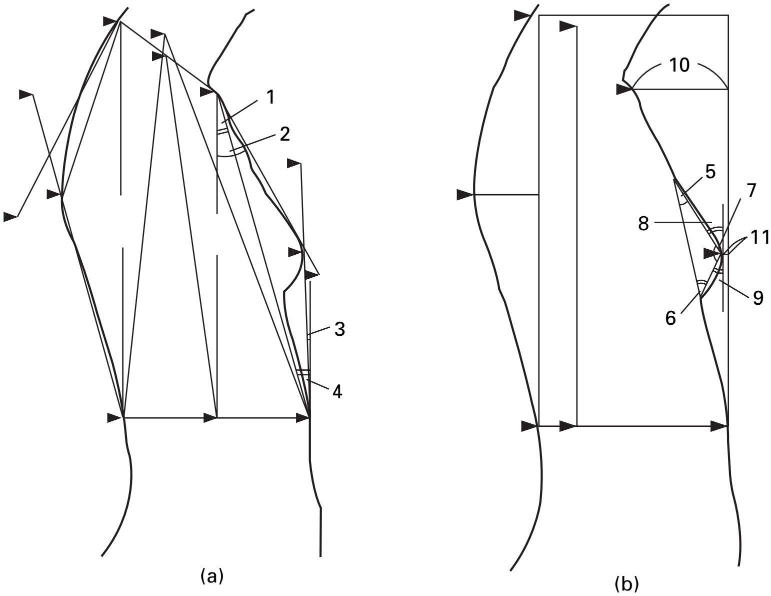
For commercial purposes, Wacoal designed a 2D profile analyzer based on the use of a television camera in association with Osaka University in 1984 [30, 31]. This system was used in Wacoal's monopolistic shop so that the customer could see her front and side profile on the screen and understand how different underwear would correct her anatomical profile. The authors' research team has developed a system for individual users to assess their body beauty and compare the nude body and the clothed body. This system captures two body images of a female from the front and side views, retrieves the silhouettes, and determines body beauty with reference to the beauty parameters.

Based on a CCD camera, Zheng's team has also developed an automatic 2D shape anthropometric system [32]. It measured the body shape angles, height, width and thickness from 2D photo imaging, and compared the whole body shape from different silhouettes, especially the breasts and upper torso. According to the 2D photogrammetry system of AIMER HEC-BUCT (Figure 2.10a and b), there are at least 11 data items of breast measurements (see Table 2.4) that can be obtained from the side view silhouette of the body.

2.8 The vertical sliding gauge. Source: Miyoshi M, *Clothing construction*, Bunka Publishing Bureau, 2001 [7].



2.9 The silhouette analyzer. Source: Miyoshi M, *Clothing construction*, Bunka Publishing Bureau, 2001 [7].



2.10 (a) and (b) 2D shape information from AIMER HEC-BUCT Shape Anthropometric System. Source: Zheng *et al*. [32].

Table 2.4 2D measuring items related to breast sizing

No.	Measuring items
1	Vertical angle of upper torso from front neck point to waist centre
2	Vertical angle of upper breast from front neck point
3	Angle of lower breast from waist centre
4	Acclivitous angle of lower breast from waist centre to front neck point
5	Inner angle of upper breast
6	Inner angle of lower breast
7	Inner angle of whole breast
8	Vertical angle of upper breast
9	Vertical angle of lower breast
10	Horizontal distance from front neck point to waist centre
11	Horizontal distance from bust point to waist centre

Source: Zheng *et al*. [32].

2.3 Latest technologies for breast measurements

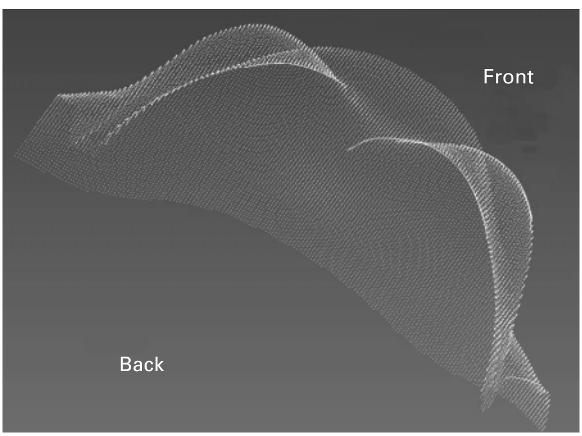
2.3.1 3D body scanning

3D body scanning is not new to the apparel industry [33], but it can have significant potential for use in the lingerie industry. Wacoal pioneered the use of 3D scanning technology to obtain a large number of measurement data [34] for the breast in order to assess the breast shape characteristics. AGMS-3D [35] created patterns to fit the three-dimensional shapes of breasts. Moreover, the digital format obtained from the 3D body scanning system could be integrated into intimate apparel. CAD systems such as Gerber Technology's V-stitcher, which can virtually stitch up a bra automatically and visualize the tension involved along the bra materials.

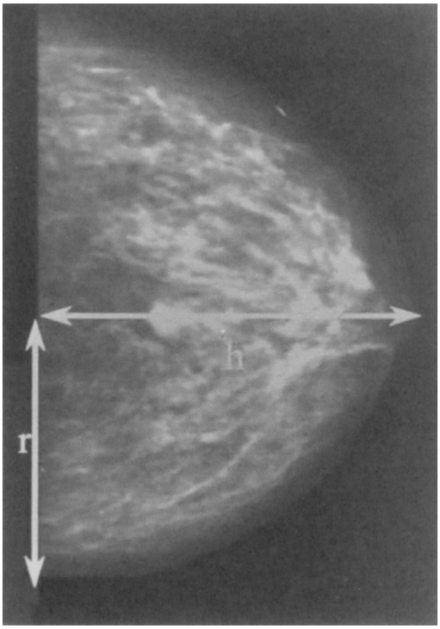
Using 3D measuring technologies, more information can be obtained from 3D surface point clouds accurately (Fig. 2.11). Zheng's Ph.D. project uses special Voxelan 3D body scanning devices (VOXELAN LPW-2000FW) and software to determine breast volume data in addition to the normal set of measurements. Although the volume of a breast can be derived using the 3D scan data, defining the area of the breast is very difficult since the base of a breast is always unclear especially for heavy and dropped breasts. Lee *et al*. demonstrated a folding line method [36] to find a continuous and natural boundary for the breasts so that the base and volume could be measured more accurately.

2.3.2 Medical research

In addition to the apparel industry, some medical research has been carried out into breast volume measurements for asymmetry assessment or breast surgery [37, 38, 39, 40]. Katariya [41] demonstrated a method to calculate the breast volume by taking measurements from the mammogram (Fig. 2.12). He assumed the breast shape to be a regular cone, so the formula for the volume is $1/3pr^2h$, where r is the half-length of the base of the breast and h



2.11 3D point cloud information by VOXELAN LPW-2000FW Scanner. Source: AIMER HEC-BUCT [5].

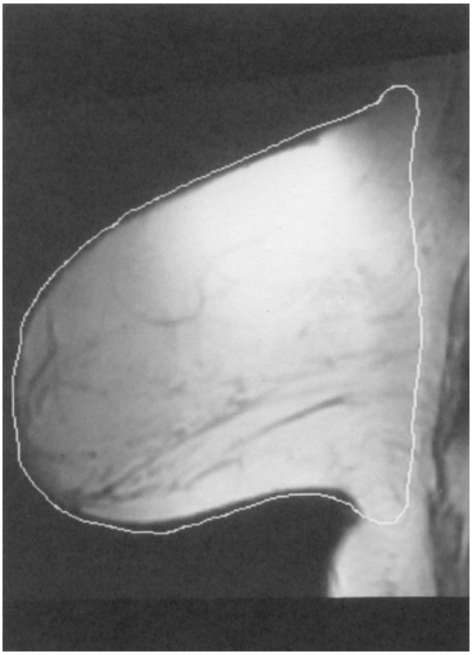


2.12 Mammogram with dimensions measured to calculate breast volume. Source: Bulstrode *et al.* [22].

is the distance from the nipple to base. Malini *et al.* [42] used ultrasound to scan the breast by 1 cm longitudinal and transverse slices and calculated the volume by an integrated sum. Smith *et al.* [43] performed an analysis of breast volume by making a gypsum cast of the subject's chest and then measured the amount of sand that the mould contained.

Loughry *et al.* [44, 45] used biostereometric analysis to study the right and left breast volumes of 248 subjects in 1987 and 598 subjects in 1989. This measurement technology used close-range stereophotogrammetry to analyze the breasts' shape. Fowler *et al.* [46] utilized magnetic resonance imaging (Fig. 2.13) to assess changes in breast volume and composition during the menstrual cycle. Edsander-Nord *et al.* [47] produced a negative replica of the breast by using a perforated 2 mm thermoplastic sheet (Fig. 2.14). The volume is then measured by laying cling film into the mould to obliterate the perforations and filling it with water.

In addition, another method named the Archimedes principle, involving the use of a calibrated container, has been generally used [22]. The patient is asked to put her breast into the container filled with water at body temperature. Then the volume of the water displaced is measured. After repeating this procedure three times, an average volume for each breast is obtained.



2.13 Magnetic resonance imaging with outlined sagittal breast slice. Source: Bulstrode *et al.* [22].

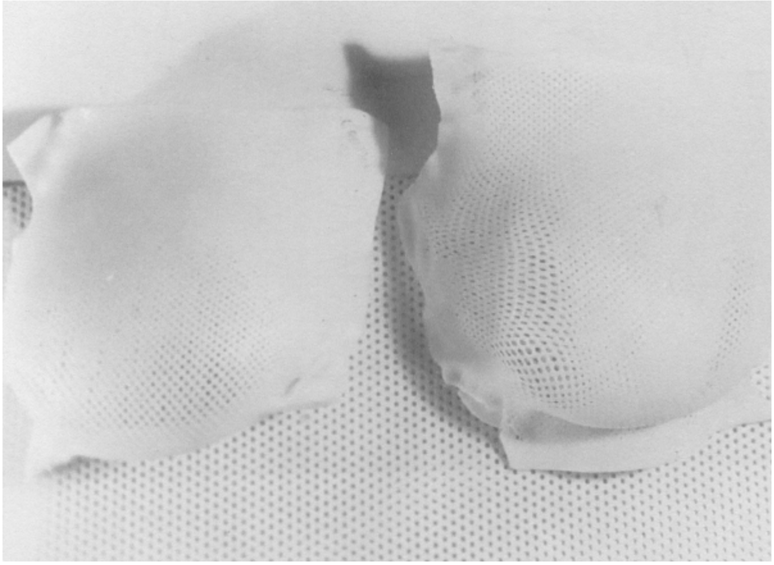
2.4 Breast sizing systems

2.4.1 History of bra sizing

According to the history on record [48], the fundamentals of current bra-sizing systems were founded as early as 1926. Its original intent was to classify breast shapes into analogous types. Berlei in Australia first carried out a size survey to study women's figures. It primarily used the circumference of the women's chest, bust and underbust (known as ribcage) to identify the bra size.

Ida Rosenthal, [49, 50] a founder of Maidenform, introduced cup sizes for bras in 1928. Later in 1935, Warner in America realized that, in addition to the full bust measurement, it was necessary to incorporate the volume of breasts into the bra size specification. It first advertised the alphabet bras as A cup = youthful, B cup = average, C cup = large and D cup = heavy [51] and this system became the basic modern bra sizing standard (Fig. 2.15).

Throughout the past 70 years, bra sizes have generally been described in terms of the underbust girth (e.g. size 75, 80, 85) together with the difference between the bust girth and underbust girth (e.g. cup A, B, C). Limited progress has been made on developing a more accurate and scientific breast sizing



2.14 Thermoplastic sheet before and after moulding.
Source: Bulstrode *et al.* [22].

2.15 Warner's alphabetic bra.
Source: http://www.corsetiere.net/Spirella/Brassieres/Bras.htm [52].

system. For commercial and marketing considerations, intimate apparel designers and manufacturers of different brands usually have their own bra size charts [53]. This happens because the only ground rule in developing such size charts is based on the body figures of their brand's live models, and the patterns are modified until the bra fits nicely on the models. Hence, one woman may find herself having a better fit with one brand rather than another, even though the size of the two bras is the same.

2.4.2 Imperial versus metric bra-sizing formula

The 3D shape and dimensions of women's breasts are complex and variable. Conventional linear measurements are probably not sufficient to present the breast size that describes the fit of a bra. However, a simple standard is necessary for communication between customers and retailers, designers and manufacturers. Since Warner's introduction of the alphabetic bra size in 1935, there are two major breast-sizing systems that have been universally used for more than 70 years. They are the Imperial system (Table 2.5) and the metric system (Table 2.7).

Imperial system

The imperial system makes a calculation from the underbust girth in a unit of inches to specify the band size. The basis adopted in this system is that a woman of conventional dress size 12 has a 29″ or 30″ underbust girth. By adding five inch (for an odd number measurement) or four inch (for an even number), it gives a band size (or back size) 34 for the bra. If the full bust girth is one inch more than the band size, the woman should fit a bra cup B. If the difference is two inch, it becomes a cup C. Other sizes use the same logic and are presented in Table 2.5.

Table 2.5 Imperial bra sizing system

Bra size	30B	32B	34B	36B	38B	40B	42B	44B
Underbust girth (inches)	25–26	27–28	29–30	31–32	33–34	35–36	37–38	39–40
Bust girth (inches)	31	33	35	37	39	41	43	45
Bra size	34AA	34A	34B	34C	34D	34DD	34E	34F
Underbust girth (inches)	29–30	29–30	29–30	29–30	29–30	29–30	29–30	29–30
Bust girth (inches)	33	34	35	36	37	38	39	40

The normal procedure for calculating bra size is outlined below:

1. Measurement around the ribcage just under the bust, e.g., 29″.
2. For even number measurement add four inches, otherwise add five to get the band size, i.e., 34″.
3. Measure around the bust at its fullest point, i.e., 36″.
4. Subtract the result of 2. from the result of 3, i.e., two inch.
5. Convert this number to a letter (see Table 2.6) to determine the cup size as indicated in Table 2.6, i.e., C for a two inch difference between bust girth and band size.

This system is widely used in Britain which historically used the imperial system of measurement.

Metric system

Most other European, American and Asian countries use the metric system that determines the cup size in a simpler approach. The bra size number directly indicates the underbust girth. For example, a bra size 75 corresponds to an underbust measurement of 75 cm. The cup volume is presented by the centimetre difference between the full bust measurement and the underbust. A 12.5 cm difference means a cup volume B, while a cup C full bust girth is 15 cm larger than the underbust. The sizing table is shown in Table 2.7.

Comparison between Imperial and metric systems

To compare the two popular systems, the authors have plotted the equivalent centimetre values of the bust girth indicated in the imperial system with the corresponding bust girth as in the metric system for each bra size as shown

Table 2.6 Determination of bra cup size letters

Bust girth – band size	–1″	0″	1″	2″	3″	4″	5″	6″	7″
Cup size	AA	A	B	C	D	DD	E	F	G

Table 2.7 Metric bra-sizing system

Bra size	65A	70A	75B	80B	85B	90B	95B	100B
Underbust girth (cm)	65	70	75	80	85	90	95	100
Bust girth (cm)	75	80	87.5	92.5	97.5	102.5	107.5	112.5
Bra size	75AA	75A	75B	75C	75D	75DD	75E	75F
Underbust girth (cm)	75	75	75	75	75	75	75	75
Bust girth (cm)	82.5	85	87.5	90	92.5	95	97.5	100

Table 2.8 Comparison table of imperial and metric systems

B cups with different band sizes								
Imperial size	30B	32B	34B	36B	38B	40B	42B	44B
Corresponding full bust (cm)	78.7	83.8	88.9	94.0	99.1	104.1	109.2	114.3
Metric size	65B	70B	75B	80B	85B	90B	95B	100B
Corresponding full bust (cm)	77.5	82.5	87.5	92.5	97.5	102.5	107.5	112.5
Band size 34 with different cup sizes								
Imperial size	34AA	34A	34B	34C	34D	34DD	34E	34F
Corresponding full bust (cm)	83.8	86.4	88.9	91.4	94.0	96.5	99.1	101.6
Metric size	75AA	75A	75B	75C	75D	75DD	75E	75F
Corresponding full bust (cm)	82.5	85	87.5	90	92.5	95	97.5	100

in Table 2.6 and Table 2.7. From Table 2.8 and Fig. 2.16, the following conclusions may be reached:

- the size interval of both systems is almost the same (5 cm or 2″) per one band-size difference
- the cup grading of both systems is almost the same (2.5 cm or 1″) per one cup-size difference
- for the sizes smaller and larger 75B, the bust girth under the metric system is always smaller than that of the imperial system.
- the relationship between the imperial and metric system, along different band sizes or different cup sizes, is represented by the same linear regression equations $y = 0.9843\,x$ (see Fig. 2.16), where y denotes the metric bust girth, x is the imperial bust girth.

2.4.3 Other bra-sizing systems

ISO Standard

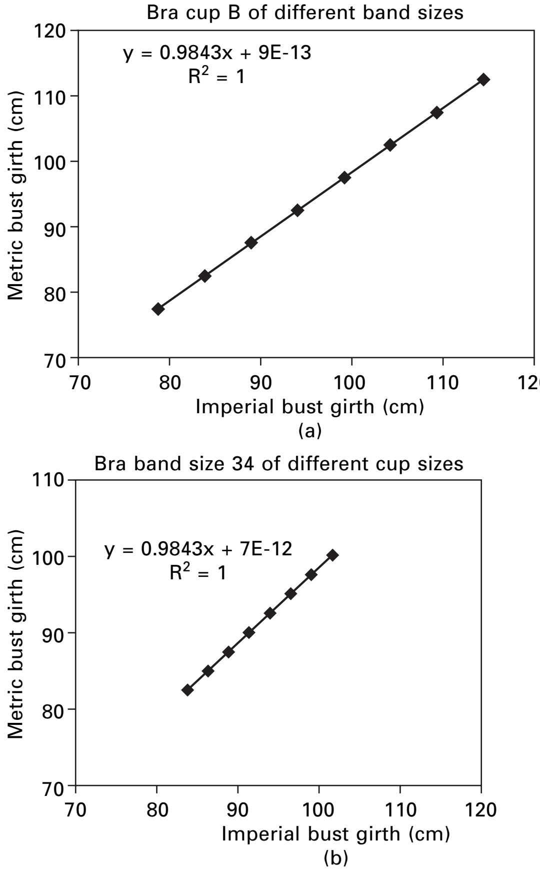
ISO DIS 4416 [54, 55] suggests preferred size scales for women's foundation garments based on bust girth and cup size as shown in Table 2.9.

European standards

For French and Italian sizing systems, there is a noteworthy difference on bra band sizes from the above imperial system (see Table 2.10). However their cup sizing systems are the same.

Japanese and chinese bra-sizing systems

The bra-sizing systems of the Japanese and Chinese are very similar to the European and American (see Table 2.11). However, there are some differences



2.16 Comparison between imperial and metric systems.

Table 2.9 Preferred sizes scales from ISO 4416

	Underbust girth (cm)												
	64	68	72	76	80	84	88	92	96	100	104	108	112
Bust girth (cm)													
Cup A	76	80	84	88	92	96	100	104	108	112	116	120	124
Cup B	80	84	88	92	96	100	104	108	112	116	120	124	128
Cup C	84	88	92	96	100	104	108	112	116	120	124	128	132

Source: Winks J M [55].

Table 2.10 Bra band sizing conversion between imperial, French and Italian systems

Imperial band size	32	34	36	38	40	42	44	46
French band size	75	80	85	90	95	100	105	110
Italian band size	1	2	3	4	5	6	7	8

Table 2.11 Japanese and Chinese bra-sizing systems based on the metric system

	Bra band size (cm)							
	65	70	75	80	85	90	95	100
	Underbust girth (cm)							
	62.5–67.5	67.5–72.5	72.5–77.5	77.5–82.5	82.5–87.5	87.5–92.5	92.5–97.5	97.5–102.5
Bust girth (cm)								
Cup AA	70–75	75–80	80–85	85–90	90–95	95–100	100–105	105–110
Cup A	72.5–77.5	77.5–82.5	82.5–87.5	87.5–92.5	92.5–97.5	97.5–102.5	102.5–107.5	107.5–112.5
Cup B	75–80	80–85	85–90	90–95	95–100	100–105	105–110	110–115
Cup C	77.5–82.5	82.5–87.5	87.5–92.5	92.5–97.5	97.5–102.5	102.5–107.5	107.5–112.5	112.5–117.5
Cup D	80–85	85–90	90–95	95–100	100–105	105–110	110–115	115–120
Cup E	82.5–87.5	87.5–92.5	92.5–97.5	97.5–102.5	102.5–107.5	107.5–112.5	112.5–117.5	117.5–122.5

such as the related range of underbust girth and the cup size designators are not the same.

Medical standard

In the medical field, Pechter [56] complained that the traditional breast-sizing system is so often inaccurate and useless. He stressed the importance of direct measurement of mammary hemi-circumference in the determination of cup size particularly for the practice of plastic surgery. He measured the boundary of the unclothed breast from the lateral breast crease to the medical breast crease, and proposed that a mammary hemi-circumference of seven inch corresponded to an A cup, eight inch to a B cup, nine inch to a C cup, with each one inch increment or decrease determining a cup size up or down. Kanhai, [57] however, added that this formula is valid only for a 34 band size. The size and volume of a B cup on a small ribcage is different from that on a large chest. The same eight inch mammary hemi-circumference corresponds not only to a 34B, but sometimes also to a 32C or 36A.

2.4.4 Criticism of imperial bra sizing system

Based on the conventional definition of imperial bra sizes, Wright [58] presented the procedures for defining the band size mathematically as shown in eqns 2.1 and 2.2.

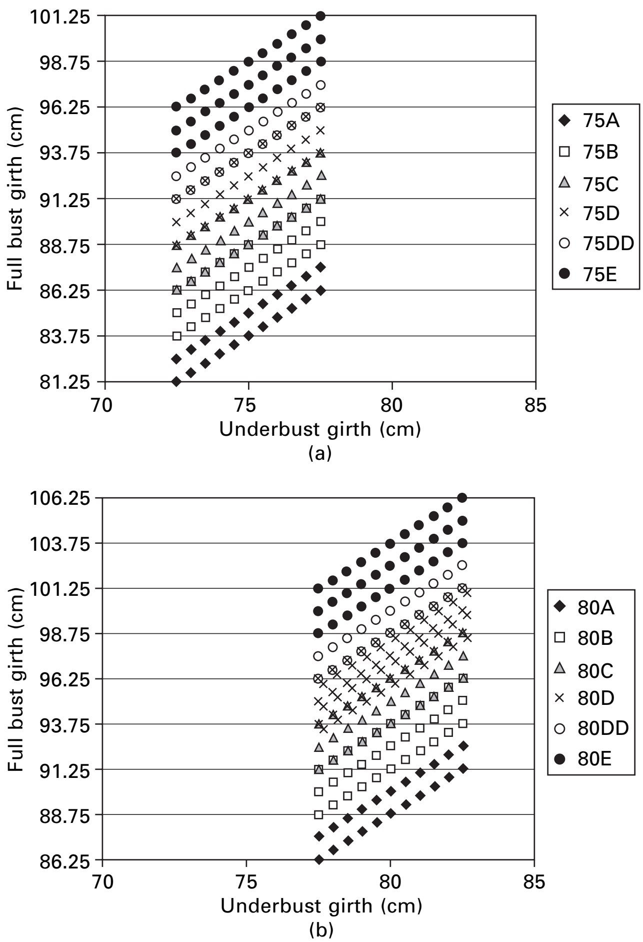
$$X = 2[([x + 1/2] + 5)/2], \quad 2.1$$

$$Y = [y + 1/2] - 2[([x + 1/2] + 5)/2], \quad 2.2$$

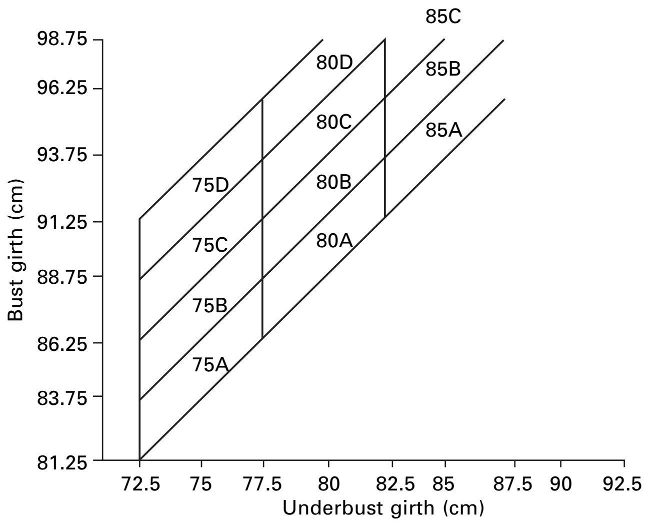
Where x is underbust girth and y is bust girth, integer X is the resulting band size and integer Y is converted into the corresponding cup size letter as in Table 2.6. However, this imperial system creates anomalies. For example, a small error in x, y could cause the resulting size to cross the diagonal boundary between domains, and change a predicted size from an A cup to a D cup.

Coincidentally, many articles [59, 60, 61] have reported that 70% of the UK female population, especially large-breasted women, wear the wrong-size bra. Pechter [56] surveyed 100 women and found that they were wearing the wrong-sized bra 77% of the time. Greenbaum *et al.* [62] studied 102 women; all of their claimed bra sizes did not match the manufacturers' recommendation for their measurements. All of them wore an undersized band (the mean of the shortfall was four inch and ranged from two inch to ten inch) and oversized cups (the mean of the over-estimation was three sizes ranging from one size to seven sizes larger). The more obese they were, the more marked the disparity between the recommended and actual band size became. It is worthy of note that the women who most need supportive bras were the least likely to get accurately fitted bras. This may significantly affect their physical health and quality of life. The health issues of ill-fitting bras will be discussed in Chapter 6.

The approximation involved in the sizing formula is probably the root cause. As seen in eqn 2.2, the band size X is rounded twice – firstly when x is rounded $\pm\, ^1/_2''$ and secondly when it is made even by $\pm 1''$. The cup size Y is the difference between two rounded values which allows the rounding errors to accumulate and leads to an accumulated error of $\pm 1^1/_2''$ corresponding to a three inch size range. In order to remove the error, Wright has revised eqn 2.2 to a new formula as shown in eqn 2.3.



2.17 Bust measurements of various bra size groups using the metric system.



2.18 Mapping of metric system.

$$Y = [y - x + 1] - 5, \qquad 2.3$$

Equation 2.3 proposed to make a simple deduction of the full bust girth (y) by the underbust girth (x) for the determination of cup size letter Y. This new formula coincidentally matches the concept used in the metric bra-sizing system, where the cup size is derived from the calculated difference between the full bust girth and the underbust girth.

Figure 2.17 presents a scatter diagram plotting the underbust girth against the bust girth for bra sizes ranging from 75A to 75E and from 80A to 80E. It shows the data cloud of bust measurements within each bra size group of the common 75 and 80 band sizes. Based on the data cloud, a map can be drawn to include the bra size groups of 75 and 80, and extends to the size group 85. From Fig. 2.18, it can be found that the diagonal-shaped domain of the metric system has the same grading direction (slope = 1) and same dimensions (width = 5 cm and height = 5 cm) as Wright's modified imperial system described in his paper. Therefore, it is clear that the original metric system is more reliable than the conventional imperial system. Wright's modification actually adopted the concept and formula of the metric system.

2.5 Conclusions

This chapter reviews the literature relevant to breast measurement and sizing, but presents more recent research work into breast anthropometric studies and mathematical interpretation of the bra-sizing systems conducted by the authors. It is evident that the current imperial bra-sizing system is unreliable and incomplete, which can lead to confusion and ill-fitting bras. Although research has been carried out to propose new methods of breast measurement and sizing, the sizing processes are still based on linear correlations and do not consider 3D breast shape, angle and profile.

With the use of 2D and 3D optical measuring technologies, more information can be captured from the surface of breasts. This hopefully will enable a new standard sizing system to be formulated and stimulate further developments in intimate apparel design, manufacture and retailing.

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3
Innovations of bras

W YU and S-P NG

3.1 Definition of innovation

Innovation refers to a new method, custom or device [1]. It can also be a new idea, practice or object [2]. Innovation occurs after a considerable time following an invention. An invention is the solution to a problem, whereas an innovation is the commercially successful application of the solution [3]. Innovation covers all the activities of bringing a new product or process to market, so it is a time-consuming transformation process involving intensive management and, often, significant resources. The innovation process comprises five stages – recognition, invention, development, implementation and diffusion [4]. Successful innovation is about creating value. Incremental innovation is improving existing goods, processes or services. Radical innovation is the development of new goods, processes or services of value that have not existed previously.

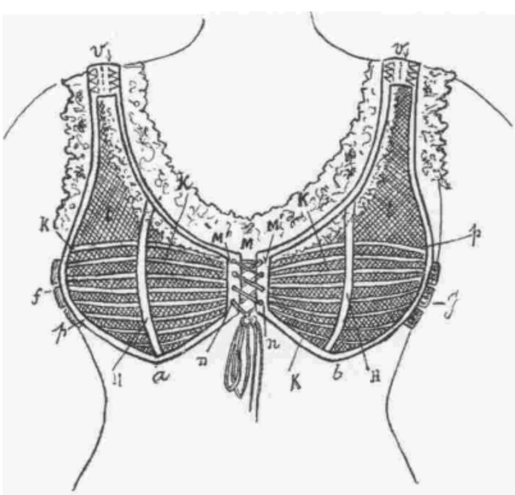
In the field of intimate apparel, product innovation is mainly carried out in an individual company's laboratory or workshop. Since the market is always looking for new products, new inventions are quite easily accepted when they are launched with an advertising campaign. Universities continuously develop new inventions and strive hard to commercialise their new technologies by licensing, joint ventures or spin-off to make them successful innovations. Success still depends on the business model, marketing and finance which must involve industrial partners in management. Throughout the history of bras, many inventions have gone through a successful innovation process and were widely marketable with good functionality and the ability to create value. Innovation is obviously important for the bra industry to develop future business.

3.2 A brief history of bra invention and innovation

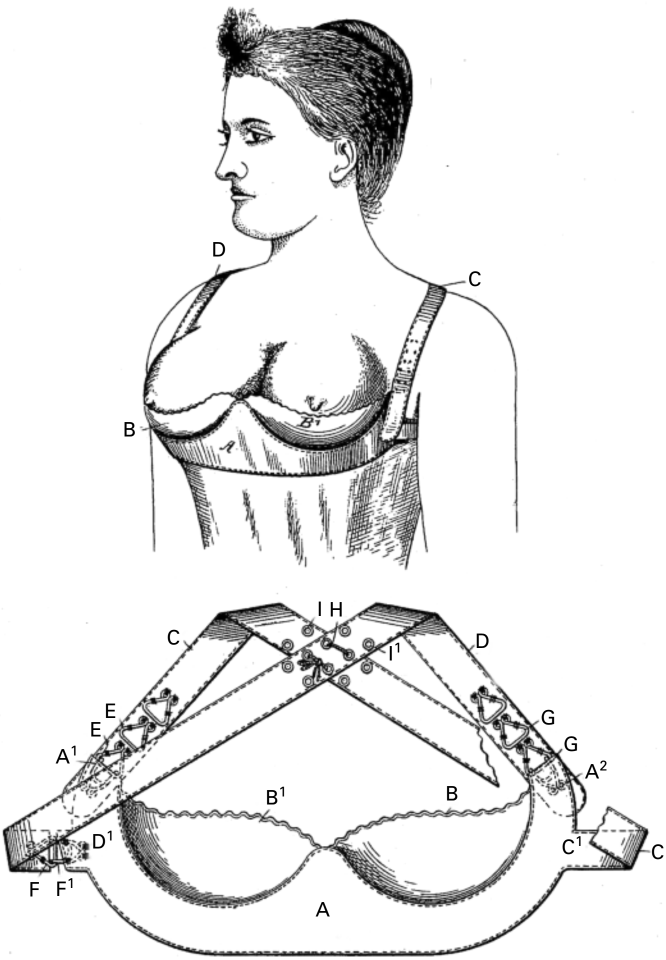
The brassiere or bra was born at the dawn of the 20th century just after the decline in the popularity of corsets in the late 19th century. The early bra invention was based on an idea to use shoulder straps and cups to support the weight of the breasts in order to make a garment that was more comfortable to wear and healthier than the corset [5]. This basic concept and design is still being used today. For the enhancement of body shape, artificial aids were used to increase the apparent size of the breast. Cotton wadding and bust pads had been for a long time sewn inside the dress to help enhance the appearance of the figure.

Literature relating the history of the bra is mostly available from fashion books and websites, rather than research articles. There are some inconsistencies in the accounts, therefore, cross-checking of information and further examination of the original patents is necessary to confirm them and to understand the technology behind each invention. The following summarises, chronologically, the inventions pertaining to bras that it has been possible to validate. According to the Wikipedia encyclopedia [6], Herminie Cadolle of France was the inventor of the first modern bra in 1889. She cut a corset in half and invented a two-piece undergarment. The lower part was a corset for the waist while the upper supported the breasts by means of shoulder straps (Fig. 3.1).

In 1893, Marie Tucek patented her 'breast supporter' [7] (Fig. 3.2) which looked very similar to the modern demi-cup bras. However, it can be barely called a bra as it did not cover women's nipples. There were only two partial fabric pockets which were made concave to conform and support the underside of the breasts. These pockets were attached to a metallic or cardboard cradle that was bent to conform to the shape of the body at the front directly under the breasts. The entire breast supporter was held in the correct position by



3.1 Cadolle's Le Corset. (Source: Steele 2005, p. 148).



3.2 Breast supporter in 1893. (Source: US patent no. 494,397).

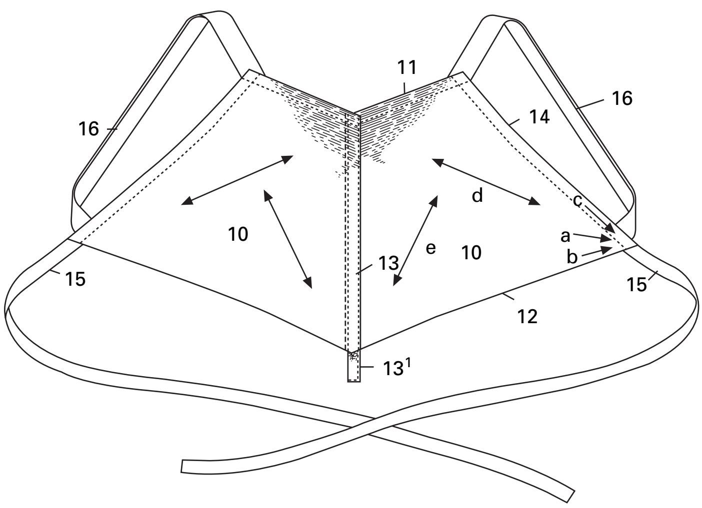
means of straps that went over the shoulder and were fastened by hook-and-eye closures at the back.

In 1904, Charles de Bevoise invented over 20 different styles of lightweight undergarment fashioned in silk and embroidered with lace to meet the women's demand for comfortable undergarments. Among these styles, he created a form-fitting corset cover with built-in shoulders. This was the first time that the breasts were supported from above instead of being pushed up from below. He called them the 'brassières' [8] from the old French *braciere*: *bras*, arm (from the Latin *brăcchium*;) + *-iere, -ier*, one associated with [9].

In 1913, Mary Phelps Jacob took two silk handkerchiefs, some ribbon and cord to make a comfortable device to support the breasts. It was made invisible under her sheer evening gown. In 1914, she was granted the first patent under a name 'brassière' [10] (Fig. 3.3) and later sold her patent rights to Warner Brothers Corset Company for $1500. Today the patent is worth at least $15,000,000. Later famous inventions include Howard Hughes's cantilevered bra in 1943 using aeronautical engineering to uplift the contour of the bosom [11] and Frederick Mellinger's first push-up bra in 1948 named the 'Rising Sun' [12].

In the 1950s, Maidenform created 'Chansonette' – the famous bullet bra with its signature circular stitching (Fig. 3.4) having the pointed cone look [13]. Similarly, Berlei introduced the original whirlpool bra which was finished with continuous stitching, giving rounded contours for separation and 'the newest forward look' [14]. In the 1960s, the first 'Wonderbra – a push up plunge bra' was created by a Canadian designer called Louise Poirier [15]. But almost at the same time, the feminists demanded women burn their bras. Rudi Gernriech designed the 'no bra' bra [16] (Fig. 3.5) which was made of see-through stretch netting with a natural transparent look. In the 1970s, technical developments in garment moulding from one piece of elastane fabric were made which the lingerie industry was quick to adopt [17]. In the 1980s, French couturier Jean-Paul Gaultier was even inspired to turn underwear into outerwear with his cutting-edge designs [18]. This design was later featured in Madonna's famous Gaultier's twin peaks conical bra (Fig. 3.6) to be visible through the outerwear.

Since the bra first appeared in the late 19th century, the basic design has not changed dramatically. Throughout the 1990s, manufacturers all over the



3.3 The first patented 'Brassiere' in 1914. (Source: US patent no. 1,115,674).

3.4 Stitched bra. (Source: Pedersen 2004, p. 57).

3.5 'No bra' bra. (Source: Pedersen 2004, p. 87).

3.6 Madonna's conical bra. (Source: Pedersen 2004, p. 57).

world have focused their efforts on introducing new versions of wonderbras. Examples include Gossard's 'Ultrabra' and 'Super Uplift bra', Victoria's Secret's 'Miracle Bra', Maidenform's 'Rendezvous', Triumph's 'Maximizer', Wacoal's 'Good-up Bra' and Olga's 'Sensuous Solution'. The names may differ but the technologies were, more or less, the same.

In the second half of the 1990s, various types of liquid-filled bras were developed such as the 'Magic Bra' by Vanity Fair, the 'Ultimo bra' with a silicon gel filled pad, the inflatable 'Air-filled bra' by Fashion Forms, the 'Aquabra' from Altesse [19]. 'BodySculpting' from Vanity Fair and 'Airotec Bra' from Gossard were innovations using different fillings for the similar purpose of pushing the breasts upwards and creating cleavage.

3.3 Bra innovations in the 21st century

Innovation in bra technology has been more exciting since 2000. The largest patent holder is Wacoal, the major bra manufacturer from Japan. For example, the company has successfully launched and sold its newly invented functional bras such as ‘3D Nami Nami bra’, ‘Shakitto bra’ and ‘Sleeping bra’. As stated, recognition is the first step in innovation. Two industrial designers recognised the needs of large-breasted women and developed the ‘Bioform bra’. They used 3D body scanning and mechanical stress analysis to create a pair of moulded soft plastic strips to replace traditional wire. This has been a well-known story of modern bra science.

Based on academic research, more creative inventions were announced, for example the ‘Smart bra’ by the University of Wollongong, the ‘Techno bra’ by the Royal College of Arts, and ‘Electronic bra’ by De Montfort University. In recent years, the United States has awarded patents covering all sorts of new-fangled undergarments, including a new underwire bra, inflatable bra, a bra with a flick-of-the-wrist release, a multi-layered bra to provide better ventilation, a bra that can be removed without taking off your blouse, and even an electromagnetic bra designed to give life to sagging breasts. Patents are pending for dozens of other bras, including one with detachable straps made to match different articles of clothing [20]. All these inventions form an important base for the future research and development of bras.

3.4 Technology behind bra innovations

Little scientific work was applied to bra design [21] in the last century, but more technological breakthroughs have been made in the recent years. The most well-known products have been selected for detailed review and to highlight the technologies involved.

3.4.1 The push-up bra

It was believed that the invention of the push-up bra [22] was attributed to the aeronautical engineer Howard Hughes in 1943. He fabricated a material with rods of curved structural steel that were sewn into the garment below each breast and connected to the shoulder straps. The rigid steel allowed the breasts to be pulled upward, and for the shoulder straps to be moved away from the neck, showing an exposed bosom curve [23].

The push-up bra has as its unique feature the incorporation of underwire that lifts the breasts upward to present a deep cleavage between the breasts that contributes to making it a distinctive fashion silhouette. By the 1960s, the wider availability of steel enabled the underwire bra to migrate towards mainstream. The 1960s push-up bra is a complicated construction, often with two separate, darted cups, each with a curved steel wire built into its base. Widely spaced shoulder straps provide uplift without compromising the view. A strong back piece contains a hook and eye fasteners. The assembly remains firm so that even when the wearer leans forward, she stays contained [24].

3.4.2 The liquid-filled bra

The magic bra is a version of the push-up bra that contains liquid-filled pads inserted in the cups that support the breasts to lift them up. It makes the bra more comfortable than the traditional cleavage-creating contraptions. It is like an implant that increases a woman's bust size. This technology actually was invented in 1993 by Taiwanese inventor Aaron Ho who made the bra to help women recover after breast surgery. He lined the bra cups with pads filled with oil and water. The differing breast weights created a constant displacement that massaged the breasts [25]. This new invention was later brought into the lingerie industry and marketed as the 'Magic Bra' [26].

Due to its popularity, many major lingerie brands have adopted the concept and launched different types of liquid-filled bras [27]. Research to find the most appropriate filling materials has proven to be difficult and time consuming, for example, the Scottish MJM company invented a silicon-based gel for its 'Ultimo Bra' [28] after three years of experiments. In contrast, many other brands have their 'Water bras' filled with a mixture of body oil and water. Later, Fashion Forms in the U.S. developed an 'Air bra' that can be inflated with an air pump like a bicycle tyre.

3.4.3 The cosmetic bra

Triumph International's cosmetic bras are produced in a range of styles and materials for the Asia-Pacific market. 'Sea Cell' is made from fabrics derived from natural seaweed which is rich in minerals, vitamins and amino acids. Alternatively the, 'Silk protein bra' exudes the smooth silk protein sericin and is charged with negative ions. 'Bio Energy' is made from infra-red-emitting Masonic N Fibre from Kanebo that will warm a woman's breasts by one degree Celsius. The Masonic material contains microscopic ceramic particles that imitate blood circulation in the breasts. Another type is the 'Aloe Vera Bra' also used for cosmetic purposes.

3.4.4 The adhesive bra

The adhesive bra or invisible bra is a pair of silicon-like, self-adhesive cups connected at the front by a hook but without the shoulder straps and band found on a conventional bra. It 'sticks' to the skin on the wearer's breast by virtue of its 'adhesive' concave surface creating a suction force that is supposed to make it stay in place, even during motion. It has become a fashion item worn with low neckline, backless and bare-shoulder clothing where the bra straps and components would otherwise be seen. It may cover the whole of the bottom of the breast or just the nipples.

The quality and performance of adhesive bras depend much on the materials used. The commercial examples are polyfoam, hypoallergenic fabric, silicon pads, 100% rayon fabrics with air holes or acrylic-based double-sided adhesive fabrics. However, consumers may develop itching, blisters or rashes on hypersensitive skin. Desirable properties are lightness, air permeability, softness, comfort and reusability. The 'Nubra' adhesive backless, strapless stick-on bras patented by Bragel are claimed to be wearable hundreds of times with proper care. Other styles include the patented snap and swivel action that adjusts to create lift and cleavage, as well as the clear wing combination and combo bra.

3.4.5 The shape-memory bra

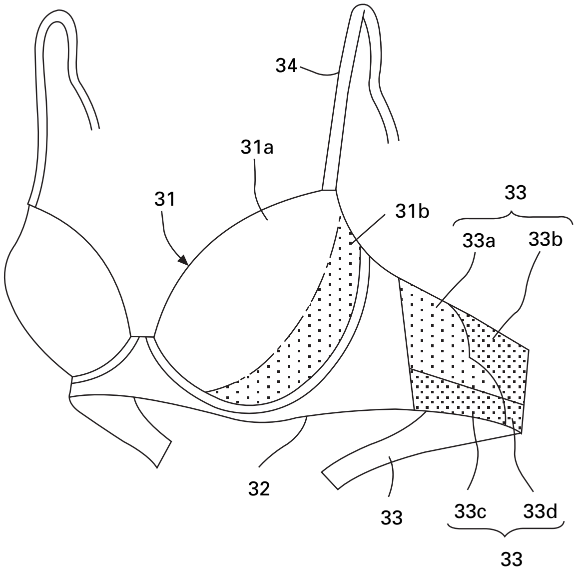
TiNi [29] – a mixture of titanium and nickel – is the most popular shape memory alloy (SMA) that has been used for bra wires as it is soft and light in weight. It exhibits shape-memory and super-elastic characteristics [30] after being subjected to heat treatment. Reheating it to the set temperature automatically restores its original shape even if it has been deformed severely [31]. Shape memory wires made of resin or plastic are preferred because they are softer, have a lower electrical conductance and high reinforcement with very little likelihood of breaking. For example, Wacoal uses resin wire for junior bras that give more stretch and a snug fit for teenage girls.

3.4.6 The Nami Nami bra

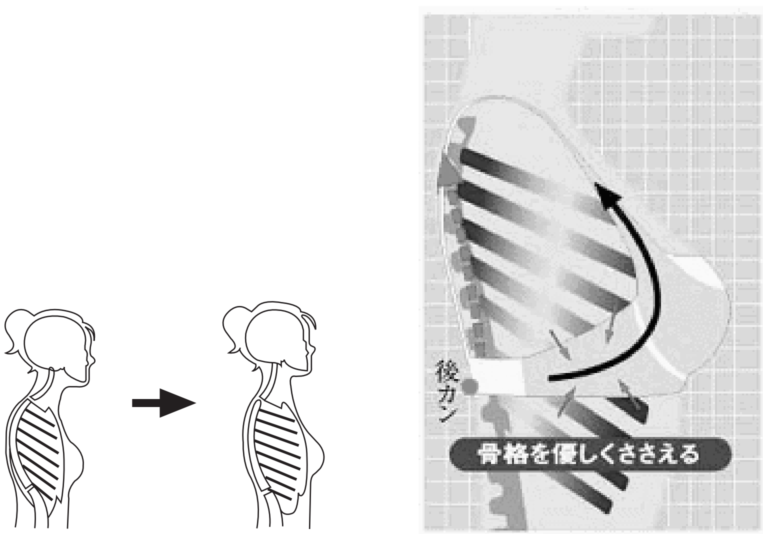
Adopting the new technology of film adhesive, Wacoal developed the famous T-Shirt Bra 'Nami Nami' (Fig. 3.7) in 2002. This seamless bra is completely glued together with a soft and highly elastic adhesive 'Bemis' film [32]. Consequently the side and back of the bra as well as the cups are less visible when worn with close-fitting summer clothes. This bonded bra is relatively light when compared with the existing cut-and-sewn designs and it is particularly good in applications where stretch as well as recovery are required to allow freedom of movement while remaining in place during exercise. This innovation was successful as it generated a new market and business.

3.4.7 The Shakitto bra

In autumn 2002, Wacoal introduced the 'Shakitto' bra with added skeletal support to correct the wearers' posture [33] to a more upright attitude (Fig. 3.8). The Wacoal Human Science Research Centre studied the breathing of



3.7 Nami Nami – bonded bra bands Oya, Kei; Saito, Masami; Wacoal Corp. (Kyoto, JP), Brassiere, United States Patent D503510, 2005-04-05



(a) (b)

3.8 (a) Posture corrected by Shakitto bra. Source: http://www.wacoal.co.jp/company/newsrelease/020510/01.html; (b) Product sketch of Shakitto bra. Source: Nishiyama N, Oya K, Takagi E and Ishimoto Y, Wacoal Corp., 'Garment with figure control or muscle support function', United States Patent no. 6,401,497, 2002-06-11.

women and revealed that the upright attitude occurs when the chest expands to take in a deep breath. Using the concept, the ‘Shakitto’ bra is designed to tilt the spine by exerting pressure to the wearer’s side muscle. To achieve this, the wing was reinforced by two bindings – one with a boned channel and the other at an angle of 45 degrees to support the bone structure at the wing seam. This triangular architecture created a strong base to hold the bra firmly around the ribcage and assist the body to stand straight using the skeletal support concept.

3.4.8 The sleeping bra

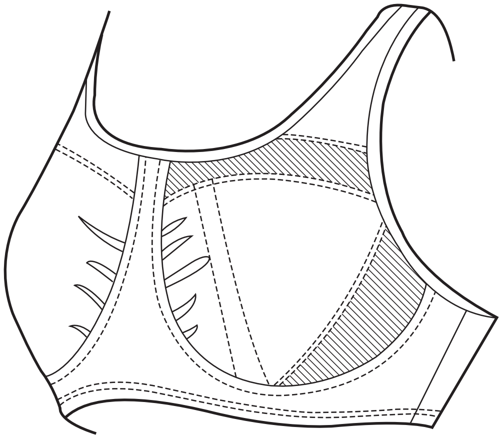
In 2003, Wacoal, in collaboration with scientific researchers, conducted a survey in Japan into woman’s attitudes towards wearing a bra whilst sleeping. The report [34] showed that 31% of the respondents wore bras in bed because they were worried about the deterioration of their breast shape (46.4%) and because they had no support for their breasts when they changed positions whilst asleep (39.3%). However, they felt the underband was too tight (39.3%) and the wire was uncomfortable to the body (32.1%). These might cause detrimental effects on sleep physiology. Those respondents who did not wear bras whilst sleeping, preferred their breasts to be totally released from the tight constraints imposed by wearing bras. However, they did express concerns about the deterioration in breast shape (42.9%) and the visibility of nipples under the sleepwear (39.7%). The findings were interesting though the sample size was not reported.

When standing, women’s breasts drop downward due to the force of gravity. When lying flat on a bed, the breasts spread out towards the arm. While lying on the left side of the body, the right breast drops towards the sternum and slightly towards the neck direction, due to the weight of the breasts. Based on the understanding of breast movement during sleeping, Wacoal has invented a ‘sleeping bra’ (Fig. 3.9) that can lightly control the breast position in all directions, by adding double layers to the surrounding of the bra cup. The sleeping bra is made of anti-bacterial cotton lycra material free from any metal or resin. Moreover, the material regulates the transfer of heat and moisture so as to ensure good sleeping quality.

3.5 Bio-electromechanical approaches to bra inventions

3.5.1 The Bioform bra

In 1998, industrial designers Powell and Seymour [35] attempted a radical redesign of bras for full-figure females. They used a Model Maker 3D laser scanner [36] to scan women of typical large sizes. The structural performance



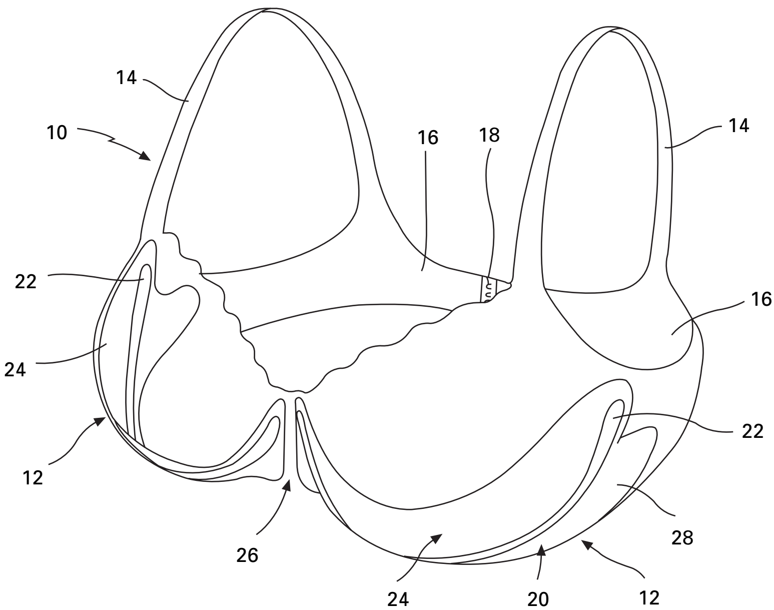
3.9 Sleeping bra. Source: www.wacoal.co.jp/news/pdf/7826_1.pdf.

of the existing bra design was assessed by Arup Technology using the dynamic non-linear finite element technique [37]. The 3D bra was visualised on a virtual body based on the scanned data. The non-linearity of the bra material and contact interaction with the body and large displacements were presented. The bra was then analysed by applying vertical accelerations to simulate a person jogging lightly or walking briskly. The analysis displayed fluctuating stresses in the bra cups and straps. The results showed that there was a high constant stress around the base band.

The 2D underwire experienced great tension when it was pulled open to fit the breast root. Therefore, the axial forces along the wire made it pop out easily from its casing after repeated wearing. Particularly for full and heavy breasts, the resulting force caused a considerable amount of rubbing and irritation to the skin. The designers therefore redesigned the bra by replacing the wire with a 3D, soft, moulded support that extended to the underarm area. The material was polypropylene TPE which was specially formulated by Krailburg, supported by a high isotactic polypropylene homopolymer from Solvay. The twin-shot moulding was used for the insert, so that the two materials would create a single and inseparable component. Extensive wear and washing trials were conducted to test durability. The idea was received well by Charnos who decided to put this into production and launched it as the 'Bioform bra' in 2001 (Fig. 3.10).

3.5.2 The 'smart bra'

In 2000, the Intelligent Polymer Research Institute at the University of Wollongong in Australia developed a 'smart bra' [38] which could tighten its own straps if an energetic wearer needed extra support. The 'smart bra' was



3.10 Bioform bra. Source: United States Patent 6,447,365.

made of a fabric with a coating of conducting polymer that made it contract when the strain on it passed a pre-set level, so as to offer instant customised support to match the movement. The conducting polymers were ‘doped’ with chemicals that changed their atomic structure so that they conducted electricity [39]. The technology has resulted in a commercial agreement with Marks and Spencer to develop a commercial prototype for active women who suffer from breast pain due to the displacement of breasts during motion.

To track the motion of women’s breasts and find better ways to support them, sensors were placed under the straps to measure how much pressure they exerted on the shoulders, and electrodes were placed on the upper torso and the neck to monitor the bra’s effects on muscle activity. Small, light-emitting diodes were placed in front of the sternum, nipples, and bra cups to measure the subject’s breast and torso movements [40].

3.5.3 The Techno bra

The Techno Bra [41], developed by Kirsty Groves, a design student at the Royal College of Arts in London, featured a heart monitor, GPS (global positioning system) locator and wireless phone. All of which were discreetly concealed within removable gel pads. The bra is made of a special fabric that transmits the wearer’s pulse to the monitor, which is sensitive enough to distinguish between changes in heart rate induced by exercise and those resulting from fear. If the bra detected a rapid jump in heart rate, the GPS system established the location and informed the police via the wireless phone. Once the monitor detected a sudden change in the wearer's heartbeat, she had 30 seconds to deactivate the bra if it was a false alarm. Otherwise, a GPS satellite received a signal, determined the location of the wearer and dispatched a text message to local police or to a close relative or friend's phone.

The research was supported by ProActiv who provided the heart-monitoring sensors for the prototypes. The bra's electronics are embedded in a thin, gel-like substance only three millimetres thick. The fabric developed for use in filtration systems was machine washable. The battery and fail-safe button were built into the front clasp and the electronics could be removed before laundering [42]. The Techno Bra will initially be aimed at women as a security device, but it could easily be adapted for patients with heart trouble or built into a T-shirt for use by anyone as an exercise monitor. Since its announcement, several companies have expressed an interest in bringing the Techno Bra to market.

A similar concept was also developed by Philips Electronics who mixed electronics, fashion and textile technology. Applying fusing technology to smart devices in the garments, a personal area network (PAN) [43] with new fabrics and garment constructions would permit greater functionality as a key part of wearable electronics technology. For example, a running-top bra has been designed for monitoring health status.

3.5.4 The electronic bra

Researchers at De Montfort University in England have invented an 'electronic bra' to detect cancer using electrical pulses [44]. They hoped the technology could provide earlier warning of cancerous growths within the breast without the use of radiation. The bra contains electrodes that send tiny electrical currents to the breasts. This allows doctors to build up a computer image that identifies the tissue type and highlights any abnormalities on a screen. The device uses tiny electrical currents passing through the breast tissue. The denser tissue in tumours makes it harder for the electricity to pass through, so the computer-generated map could identify these as 'hot spots' without harmful radiation.

The F-cup bra system created by the biomedical engineers could spot smaller growths. It was expected to be cheaper and quicker than conventional scanning methods to provide an earlier warning system by checking whether tumours are malignant. Pathologists from Leicester's Glenfield hospital have been involved in developing the bra. It was planned to test the bra in the Chinese Health Service [45]. The concept was brilliant, but the implementation was more difficult than expected. During our visit to the research team in

2005, we were told that the project had been discontinued. This emphasises that the complete process of innovation is not easy.

3.5.5 Protective Cool Guard for sports bra

Doctor Stephen Legg, an Ergonomist at Massey University, developed the protective 'Cool Guard' as a sports bra. He created a removable plastic cup [46], so the breast is 'encapsulated' rather than 'strapped down'. These cups are made from a lightweight and flexible polyethylene which is inserted inside the pocket over each bra cup lining. The Cool Guard offers protection against painful knocks in contact sports such as Soccer, Hockey, Rugby, Football, and Martial Arts, whilst also supplying support for joggers. It was proved to reduce breast movement to below 20 mm after a test by participants who carried out a number of treadmill and field jogging exercises. This has been certified for the European market.

3.6 Conclusion

As discussed in this chapter, the bra has been developed over 110 years and has evolved in many ways to provide more than just breast support. New materials, sophisticated styles, inventive designs and innovative manufacturing techniques have added value to the products which offer a plethora of interesting functions for the wearer. However, the developments have also illustrated that successful innovation involves a lengthy process.

The recognition of customers' need may require detailed analysis of their body anatomy (e.g. Bioform designed for large-breasted ladies), in-depth surveys of their life styles and scientific research into their daily movements (e.g. sleeping bra to relieve ladies' worries about the deformation of breast shape). Invention takes inspiration from wide perspectives and new concepts. Development of new bra products that can offer 'smart' functionality may need multi-disciplinary research into material, style and processes (e.g. Smart bra applied polymeric materials to sense bra tension). Even when a brilliant idea and prototype is developed, implementation can be very difficult because it has to pass many performance tests and usability trials (e.g. the electronic bra failed in the clinical tests for detecting breast cancer). For product development in a company (e.g. Wacoal), commercialisation of the new invention comes naturally with mass production, sales and marketing. Nevertheless, academic inventions (e.g. Techno bra) can fail easily at the last stage, without support from a risk-taking company who is committed to drive the new product to the market. A practical business model and careful financial control is essential for commercialisation for both industrial and academic innovations.

3.7 Acknowledgement

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4
Bra pattern technology

W YU, J-P WANG and K SHIN

4.1 Introduction

Dobson [1] in 1885 described garment patterns as emblems of the highest skill in the art of forming models. Those patterns were supposed to guide the simplest and most accurate way of fitting the human figure. They required considerable skills, practical knowledge of cutting, and a correct representation of the art of modelling a covering for the human body [2]. Bra pattern construction requires even higher levels of expertise and understanding of the body anthropometry, movements, and fabric properties – principally extensibility. A 3D bra is created from elastic 2D fabric to be worn on a resilient body. The wearer has to feel physically comfortable in her bra, psychologically confident, socially accepted, and the garment has to be aesthetically pleasing.

Patterns for bras may be constructed by either 2D flat cutting on paper or by 3D modelling with fabric directly onto the mannequin. Bra patterns normally consist of the cup, gore, cradle and wing components. The lengths and shapes of the curves and edges must be precise so that the component pieces match together smoothly and accurately. However, throughout the bra manufacturing industry, pattern construction is usually based on empirical knowledge and this can lead to a time-consuming and cost-intensive process of 'trial and error' [3] in the development of new products.

Pattern designers are normally trained through experience. Consequently they possess a variety of different approaches to pattern drafting. Some pattern designers perceive fitting for lingerie as a simple issue because of the built-in stretch and recovery of the fabric components [4], whereas it is often a more complicated art which requires stringent fitting close to the skin. Therefore pattern construction, particularly for bras, has often been regarded as an art that was difficult to explain [5].

As a result of the high demands in relation to bra patterns and fit, the product development cycle for the bra is amongst the longest in the clothing sector. However, there is a notable absence of related literature and guidelines in both academia and the industrial world. This chapter therefore is the first attempt to provide a thorough review of various pattern-making methods, a rationalisation of the pattern parameters involved, and an evaluation of their potential accuracy.

4.2 Basic block of bra pattern

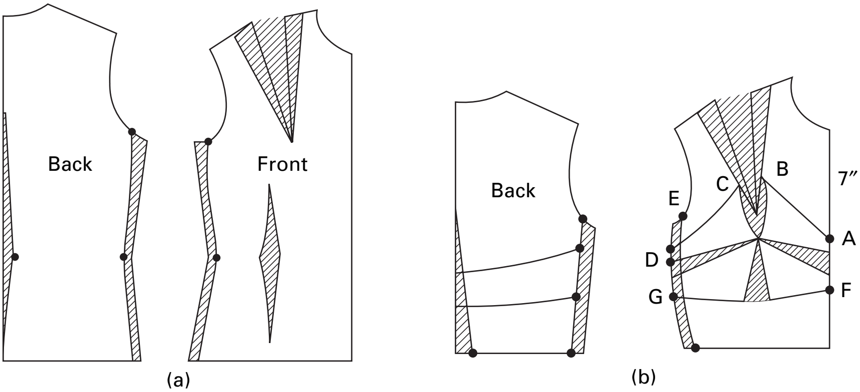
For efficient mass production in the fashion industry, patterns for various styles are normally developed from a basic block that is expected to give a promising fit to the key dimensions of the average-sized customer. Therefore, the accuracy of this block pattern is crucial to successful design.

With regard to bra patternmaking, literature is traditionally found only in small sections of books about flat-pattern drafting. A review of this literature reveals that, since 1968, only six books, containing fairly meagre sections about bra pattern making, have been written. All of these used bodice blocks as the starting point for the development of a bra block. Generally, the steps are illustrated in the format of a ‘recipe’. No detailed description is available to explain the reason behind the measurements being promulgated. Therefore, theorisation of the pattern characteristics and the mathematical relationships between pattern dimensions and body measurements is overdue. This chapter will provide an in-depth study of bra pattern technology, both to highlight the developments that have been made and the scope for further work to try to achieve the optimum design for accurate fit and support, efficiently and cost-effectively.

4.2.1 Melliar’s method

Early in 1968, Melliar [6] first introduced a method of making a bra pattern from the bodice block. She developed a lingerie block from a bodice block by taking one half inch from each front and back side seam, one inch from the back centre, and doubling the mid-shoulder dart amount (Fig. 4.1(a)). Then she developed three different styles of bra blocks from the lingerie block. As illustrated in Fig. 4.1(b), the bra block was simply a connection of those key positions that were defined arbitrarily on the lingerie block (bust size 34 inches). As shown in Fig. 4.1, A was seven inches down from the centre front neck and D was two inches from the new armhole point (E) in order to make the upper cup design line for the bra; F and G were both located four inches up from the waist, while B and C were defined as six inches down from the shoulder.

To tighten up the chest area, she suggested enlarging the shoulder dart and trimming 1/2 inch on the side seam. The new bust point was marked one inch below the shoulder dart point, and the waist dart was moved up and widened to 1.5 inches to immediately join the bust point. Furthermore, two inches



4.1 (a) Melliar's lingerie block; (b) Melliar's bra block. (Source: Melliar M. 1968 p. 92).

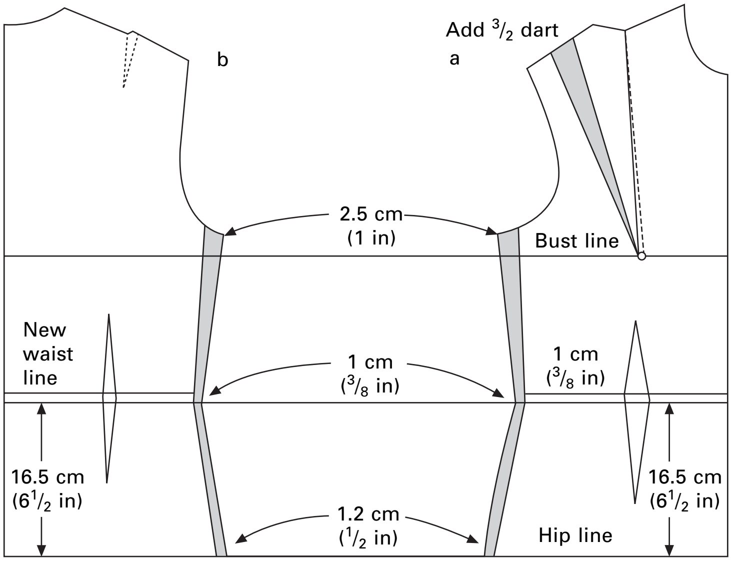
wide horizontal darts were added at both the centre front and side seam also meeting the bust point. The whole idea was to remove the ease from the bodice by an estimated amount.

4.2.2 Stanley's method

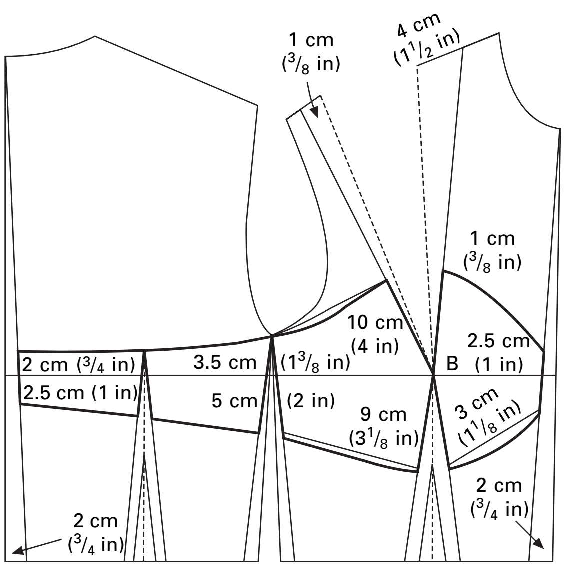
Later (1972), Stanley [7] also developed a basic slip block from the bodice block (bust size 38 inches). Then she developed a bra block from the basic slip block (Fig. 4.2(a)). For the basic slip block, the bodice block was trimmed one inch from each side seam and widened mid-shoulder by adding half of the shoulder dart amount. The waist line was altered upward by 3/8 inch. She enlarged the darts and trimmed the seams from the basic slip block in order to make the bra block. As in Fig. 4.2(b), the drawing clearly shows the measurements of each edge involved in the bra block. This method seems more logical because all the lines are measured from the bust line, which is critical for fitting the region of bust and ribcage. She closed the back dart and side seam after alteration and moved the side seam 1.5 inches forward.

4.2.3 Bray's method

Bray [8] published the first edition of her pattern design book in 1974 by using bust size 88 cm to 92 cm dress form. She added lingerie pattern designs including bra patterns when she published the second edition in 1986. Bray also developed a petticoat block which was originally designed for tight-fitting garments with no sleeves. From the petticoat block, she trimmed the side seams by 1 cm, changed the bust point position to the actual bust point by dropping 4 cm, and added half of the shoulder dart to the mid-shoulder dart. This bra block was modified by reducing the front centre

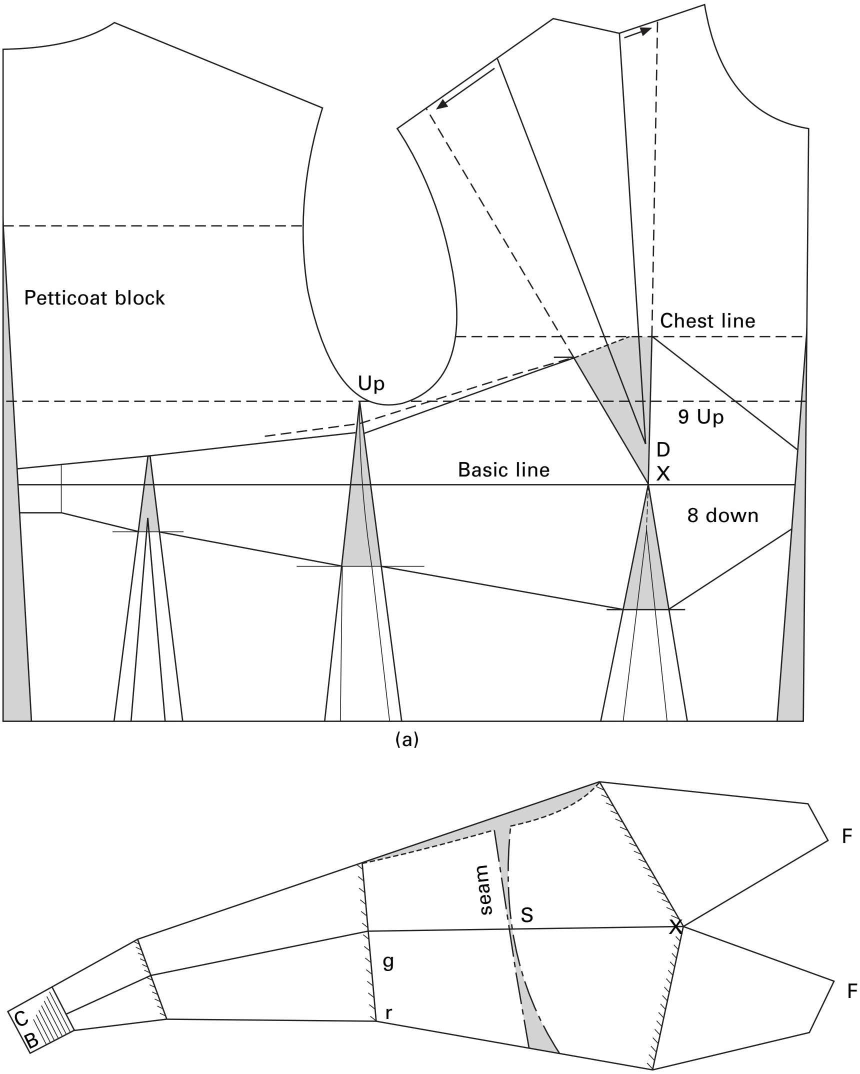


(a)



(b)

4.2 (a) Stanley's basic slip block. Reproduced with the permission of Nelson Thornes Ltd from *Flat Pattern Cutting and Modelling For Fashion*, 3rd edn – Helen Stanley – ISBN 0 7487 0427 2 first published in 1972 p. 192. (b) Stanley's bra block. Reproduced with the permission of Nelson Thornes Ltd from *Flat Pattern Cutting and Modelling For Fashion*, 3rd edn – Helen Stanley – ISBN 0 7487 0427 2 first published in 1972 p. 196.



(a)

(b)

4.3 (a) Bray's bra block development; (b) Bray's finished bra block. (Source: Bray N., 1986 p. 87).

and back centre from the petticoat block and basic block darts were used for enlargement (Fig. 4.3(a)). In addition, a shaped and forward side seam was recommended to be moved closer to the bust. The new side seam's distance from the bust point X was the same as that from centre point F to bust point X (Fig. 4.3(b)). However, she gave the key dimensions in a range of measurements that might vary from case to case. Total side seam length could be from 7.5 cm to 9 cm depending on the style while the vertical cup centre line could be from 17 cm to 19 cm. This sounds surprising as cup seam length had normally been expected to be fixed to ensure accurate fitting.

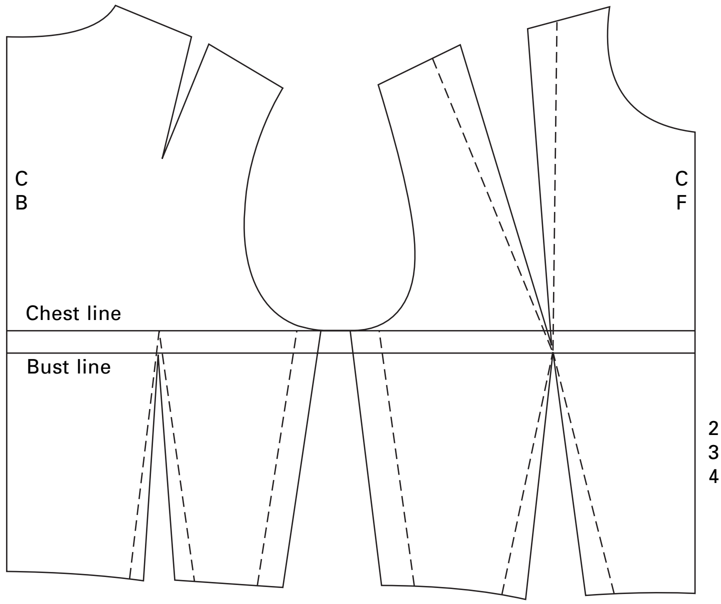
4.2.4 Campbell's method

Unlike the methods identified to date, Campbell [9] removed 2 cm ease of regular width from each side seam and doubled the amount of all the darts (Fig. 4.4(a)). The enlargements of the shoulder darts at both the left and right sides are the same and in symmetrical proportion. This meant that the bra seam length at CF, CB, side, top cup, and bottom cup were all clearly defined. After connecting these points together, the outline of the bra block was almost completed. From this position, the side cup section was traced off along the curve line L–K at a specified distance from the side seam (Fig. 4.4(b)). This method was different from Bray's which marked on the side seam the equal distance from centre front to bust point.

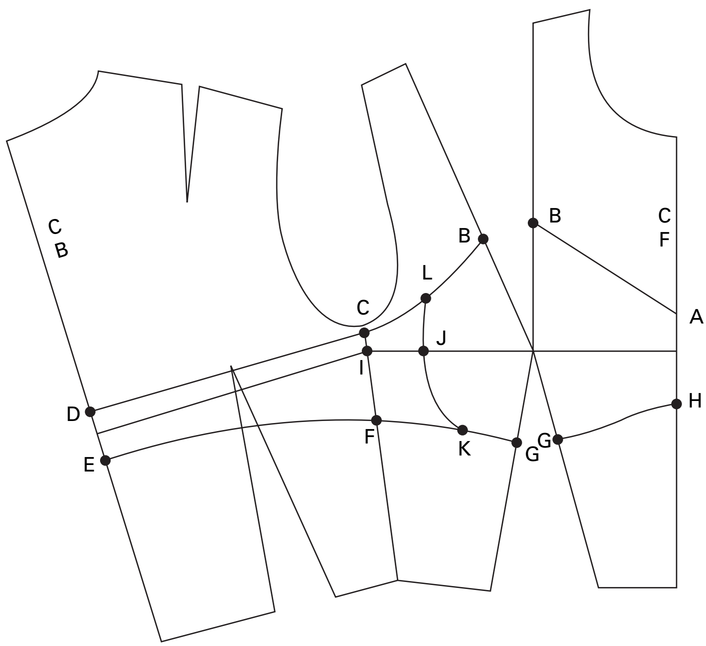
4.2.5 Armstrong's method

Armstrong [10] introduced a quite different approach using a 'contour guide pattern' as the base to start the development of the bra block. As illustrated in Fig. 4.5(a), a three inch bust radius was used to draw a circle from the bust point. She took off the ease along the circle. Unlike the other textbook authors, Armstrong used a waist dart basic block which contains two darts in one. To remove the ease, Armstrong added 7/8 inch to the upper-bust dart width AB, 3/8 inch to both the under-bust darts CD and EF, and 3/4 inch to the front bust dart HG. The ease from side seams was trimmed by 1/2 inch toward the cup and one inch down the underarm. It is necessary to check the length of the front bust line against the back bust line. Normally, the front section is larger than the back and their summation should be equal to the full bust girth if inextensible fabric is used.

To be consistent with the front, the ease at the back side seam (Fig. 4.5(c)) was also trimmed by 1/2 inch towards the cup and one inch down the underarm. Therefore, both side seams should match accurately with the same angle and length. At the centre back, 3/4 inch ease was removed and the back waist dart was eliminated. The bra pattern was cut into three pieces of cup panels (Fig. 4.5(b)) and one piece of wing (Fig. 4.5(d)). To eliminate the horizontal cup seam, the top and bottom front panels were combined, and the final vertical cup seam was smoothed out by adding 1/4 inch horizontally beyond the bust point in order to provide room for the breast volume. The strap was placed on the shoulder dart position vertically down to the wing at the back and connected to the cup apex at the front.

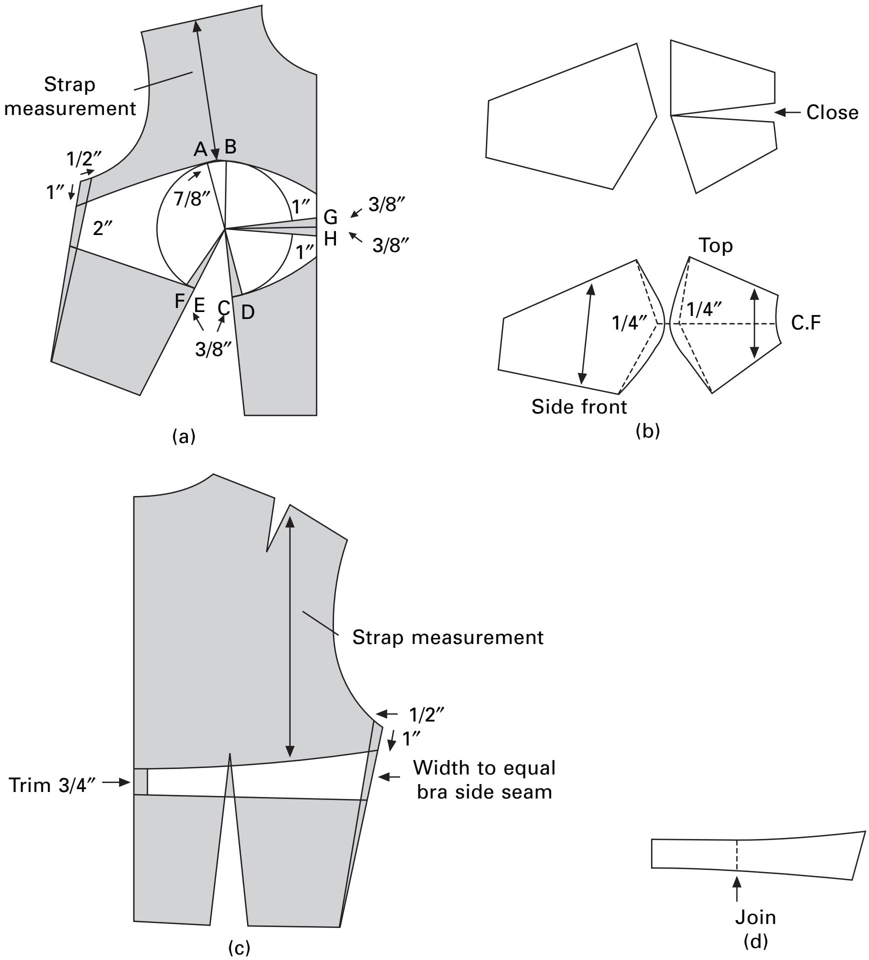


(a)



(b)

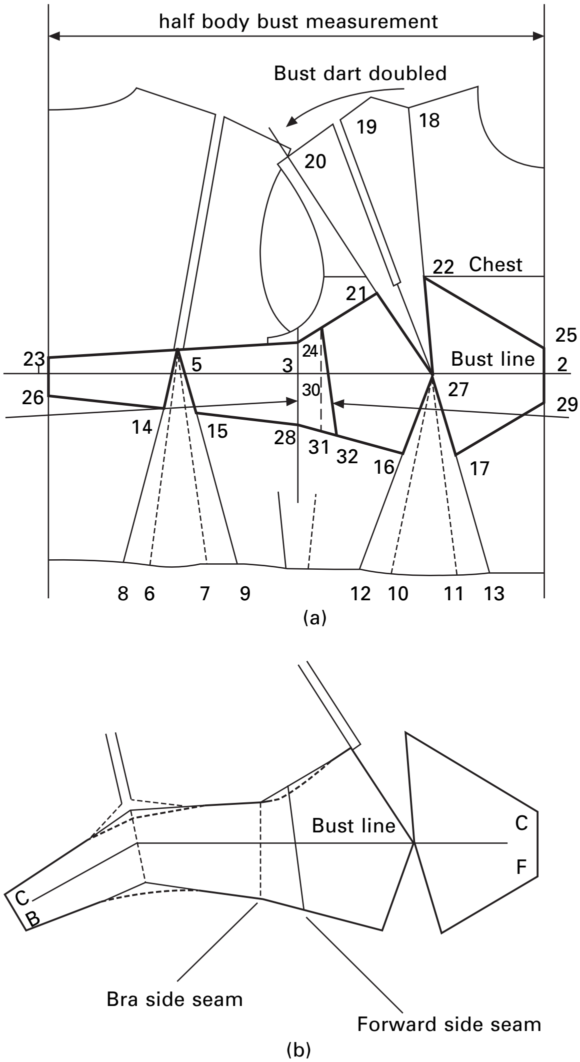
4.4 (a) Campbell's bra block development; (b) Campbell's finished bra block. (Source: Campbell H., 1989).



4.5 (a) Armstrong's bra front block development; (b) Armstrong's finished bra front; (c) Armstrong's bra back block development; (d) Armstrong's finished bra back. (Source: Armstrong H.J., 1987, p. 651).

4.2.6 Haggar's method

In 1990, the first book to emphasise pattern cutting for lingerie was written by Haggar [11]. She suggested overlapping the side regions until the bust line length is half the length of the bust girth, which is more reasonable than the other methods that simply trimmed an arbitrary amount at the side/front/back seams. Figures 4.6(a) and (b) show the development of Haggar's bra block drafting from the basic block. Table 4.1 systematically shows the logic behind Haggar's method. The formulae show the geometric relationship between the corresponding pattern parameters. The purpose of each step is



4.6 (a) Development of bra block from bodice block; (b) finished basic bra block. (Source: Haggar 2004 p. 63).

explained based on our academic understanding of the pattern logic. We also anticipate the possible assumptions on which the pattern was built. However, questions are sometimes raised about uncertainties related to the matching of pattern size and body measurement.

These methods of bra block development served as a useful guideline to outline an initial bra pattern, but experimental work had not yet taken place to test these methods and evaluate the resultant fit. The logic behind both the methods and the mathematical relationships between a bra pattern and body

Table 4.1 Haggar's development of bra block

Step	Haggar's method	Expected formula	Purpose	Assumptions/questions
1	Overlap the side regions until the bust line length is half of the bust girth	[1–2] = $^1/_2$ bust girth	To get rid of the ease in basic block	Rigid inextensible fabric is used
2	Draw the bra side seam halfway between the overlap	[1–3] = [2–3]	To define the position of side seam quartering the bust girth	Midway position of side seam is suitable for soft bra
3	Lengthen back waist dart 2.5 cm above bust line	[4–5] = 2.5 cm	To propose the level of upper band	The upper band is 2.5 cm over the bust line
4	Double back and front waist darts	[8–9] = 2 [6–7], [12–13] = 2 [10–11]	To remove all the ease under bust	2 (14–15 + 16–17) = bust girth – underbust girth?
5	Double the mid-shoulder dart towards the armhole side	[18–20] = 2 [18–19] where [18–19] = bust 88 cm ÷16–0.3 = 5.2 cm	To eliminate all the ease on chest	2 (21–22) = bust girth – chest girth?
6	To shape the top edge, a. raise 1.5 cm at CB b. raise 3 cm at side seam c. raise 9 cm from bust point to both sides of dart d. raise 2.5 cm at CF	[1–23] = 1.5 cm, [3–24] =3 cm, [21–27] = [22–27] = 9 cm, [2–25] = 2.5 cm	To design the style of upper band	It covers the nipple and holds the bra securely in position
7	To shape the lower edge, a. lower 2 cm at CB b. lower 4.5 cm at side seam c. lower 7.5 cm from bust point to both sides of dart d. lower 2.5 cm at CF	[1–26] = 2 cm, [3–28] = 4.5 cm, [16–27] = [17–27] = 7.5 cm, [2–29] = 2.5 cm	To design the style of lower band	Width of hooks and eyes = end width of band = 3.5 cm? [16–27] = [17–27] = lower breast curve?

Table 4.1 Continued

Step	Haggar's method	Expected formula	Purpose	Assumptions/questions
8	Sketch a forward side seam by marking the perpendicular position equidistant from the bust point to CF	[30–27] = [2–27]	To exercise more control over the cup region	Each breast is assumed bilaterally symmetrical
9	Add 1 cm on the lower edge towards the CF	[31–32] = 1 cm	To tilt a bit toward the cup	Slanting side seam provides more control of cup position
10	Draw the strap midway of the enlarged bust dart, up to the cup apex	Front strap touches shoulder at pt. 19	To put the strap at the shoulder end	
11	Mark the back strap position at the tip of back waist dart	Back strap ends at pt. 5 on the upper band	To put the strap at the mid-shoulder	
12	Close the back dart and trace the basic bra block outline (Fig. 4.7)	By pivoting during tracing	To connect all the matching points	
13	To refine the connected edges, a. fill in the 'dent' b. hollow the underarm	 By smoothing by 0.5 cm	To smooth out style line and provide more comfort	Final edges are too curved?
14	Measure the length of newly curved top and lower edges, and add required length at CB	Length loss = [23–24] – new [23–24]	To add back the length loss from the previous version	Cup seams not a smooth curve?

Note: Numbers in square brackets denote the straight line distance between the numbered points shown on Fig. 4.6a.

measurements require further exploration. The accuracy of the fitting resulting from the recommended distribution of darts remains in question.

4.2.7 Comparison of the various bra blocks

All the methods considered so far derived the basic bra block from a close-fitting bodice block with removal of all the ease at the bust region, side seam, and back areas. The bra is made to fit the body surface without ease for movement. A vertical cup seam, although the least likely style, was considered the most convenient position for initial cup shaping on the bra block. However, the methods vary in terms of trimming of seams, adding of dart amounts, seam length, and cup depth. A more detailed comparison is provided in Table 4.2.

Despite some variations of the block size and seam lengths, there are many common features within the different methods. The most commonly agreed measurements were found to be more or less consistent with Haggar's recommendations. After critical analysis of all the documented methods of bra block development, the following questions remain to be answered:

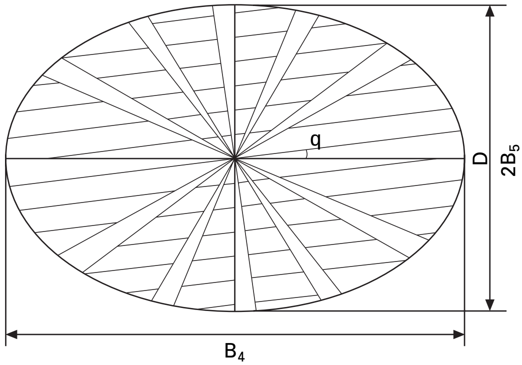
- Could doubling the front waist dart remove all the ease on the under bust?
- Could doubling the bust darts remove all the ease on the chest?
- Was it appropriate to double the back waist dart?
- Where is the correct position for the shoulder strap on the shoulder and back?
- Did the volume of the cup fit the wearer's breast?
- Did the length and width of the upper and lower band fit the wearer's back?

4.2.8 Dart distribution for optimum fit

Yu and Wang [12] performed a study to establish the relationship between the dart distribution in a bra cup and the resultant fitting on both a soft mannequin and a live model of bra size 80C. They initially assumed that the quantity and positions of the darts were evenly distributed in the bra cup pattern. An inextensible woven cotton fabric was used to make the patterns for the cup and cradle. Based on Luk's method [13], 12 evenly distributed darts were designed like a 'bra pattern clock', each with an angle of 7°, making the total dart angle 84° as shown in Fig. 4.7. In the first prototype, the fitting was bad because breast shape is not so round as a regular quasi-cone. The fitting results showed that the bra neckline and underarm line cut into the body because they were too short. After upper cup darts were transferred to the lower cup, the overall cup appearance was smoother. However, small transverse creases were still evident on the lower cup which indicated insufficient darts.

Table 4.2 Comparison of different bra block constructions

Author	Melliar	Stanley	Bray	Campbell	Armstrong	Haggar
1st edn	1968	1972	1974	1985	1987	1990
Latest edn	1968	1995	1986	1989	2000	2004
Bodice block	Size 34	size 12	N/A	Size 40	Size 10	size 12
Bust size	86 cm	97 cm	88–92 cm	88 cm	91 cm	88 cm
Trimming side seam	2.5 cm	2.5 cm (arm) 1 cm (waist)	2.2 cm (arm) 5.8 cm (waist)	4 cm	1.25 cm	5 cm (bust)
Trimming CF seam	5 cm	0 (CF) to 2 cm (waist)	0.8 cm (CF) 1.6 cm (waist)	–	–	–
Trimming CB seam	5 cm	0 (CB) to 2 cm (waist)	0.8 cm (bust) 1.6 cm (waist)	–	2 cm	–
Add shoulder dart	2x	4 cm (right) 4.5 cm (left)	2x + (0.25 cm right & 0.75 cm left)	2x	2 cm	2x
Adding F waist dart	3.8 cm	2x	2x	2x	2 cm	2x
Adding B waist dart	–	2x	2x	2x	–	2x
Adding CF dart	5 cm	–	–	–	2 cm	–
Adding side dart	5 cm	–	–	–	–	–
Raising B waist dart	–	2 cm	1 cm	2.5 cm	–	2.5 cm
CF seam	6.4 cm	5.5 cm	5 cm	6.5 cm	5 cm	5 cm
CB seam	N/A	4.5 cm	3.5 cm	3.5 cm	3.5 cm	3.5 cm
Side seam	7.6 cm	8.5 cm	7.5~9 cm	6.5 cm	5 cm	7.5 cm
Top cup length	N/A	10 cm	9~10 cm	9 cm	7.6 cm	9 cm
Bottom cup length	N/A	9 cm	8~9 cm	7 cm	7.6 cm	7.5 cm



4.7 Twelve evenly distributed darts in a 'bra pattern clock'.

With systematic pattern modification, nine prototypes were made until the perfect-fit bra sample was developed. Yu and Wang revealed that the optimum total dart angle was 91° in total, and the darts of a bra cup should be distributed below the bust line for the best fitting performance. This novel finding provides an important guideline for designers to develop various styles of bra.

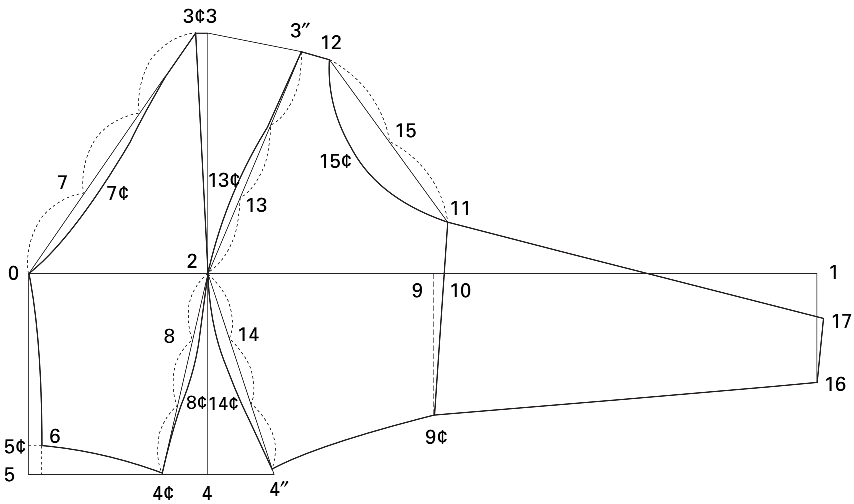
4.3 Direct drafting of flat pattern

Based on the theories and experience learned from bra block development, direct drafting becomes possible if the critical measurements can be determined. In fact, direct drafting is a common method being used in the bra industry. Experienced pattern designers have their formulae and lengths in mind when they draw the lines and curves with rulers. However, almost none of the literature has discussed and evaluated these methods of direct bra pattern drafting.

Direct drafting develops a 2D pattern by freehand drawing based on body measurements and garment specifications. To develop the pattern drafting concept and formulae, the designer must understand the relationship between each pattern parameter and its corresponding body measurements in order to determine the fractions and scales of measurements involved. This also requires some knowledge of the human skeleton and bone structure, muscles, and joint movement. The accuracy of the pattern is assessed by examining how the bra fits on the dummy or the live model.

4.3.1 Direct drafting of soft bra

In comparison with the methods of developing the bra block, So's [14] method, as delivered in his bra course, can be regarded as a basic guide for



4.8 So's soft bra drafting method.

direct pattern drafting. The soft bra (size 75B) with vertical cup seam is used for easy reference to the aforementioned bra block methods. As in Fig. 4.8, So starts his pattern drafting from a horizontal bust line. The critical points on this bust line determine the proportion of a bra that fits the bust point and its left and right regions.

The key measurements are specified in Table 4.3 where the purposes and possible assumptions are given. Each step of the pattern drafting procedure is analysed by formulae which are presented in terms of 'point to point' distances. Each critical point on the bra pattern is identified by numbers and the purpose of each step is anticipated with the assumptions involved in the formulae, based on logical and geometrical understanding.

4.3.2 Direct drafting of wired bra

Nowadays wire plays a major role in bra manufacturing as it gives better support and/or shaping to the wearer's breast volume. Therefore drafting a correct curve on the cradle is crucial. Direct drafting of a wire bra consists of two parts. One is cup drafting based on breast measurement. Another is band drafting based on wire. In order to achieve a good fit that gives support to heavy breasts, using a wire shape that matches with the breast root shape is important. Mass production makes it impossible to customise bra pattern making to an individual but it should be taken into account when the customer selects a good fitting bra. Morris's [15] wired bra drafting method shows how wire shape determines bra band cradle shape. Morris used 63 cm as a bra band length excluding hook and eye tape length. Finding a wire centre

Table 4.3 Direct drafting of soft cup bra

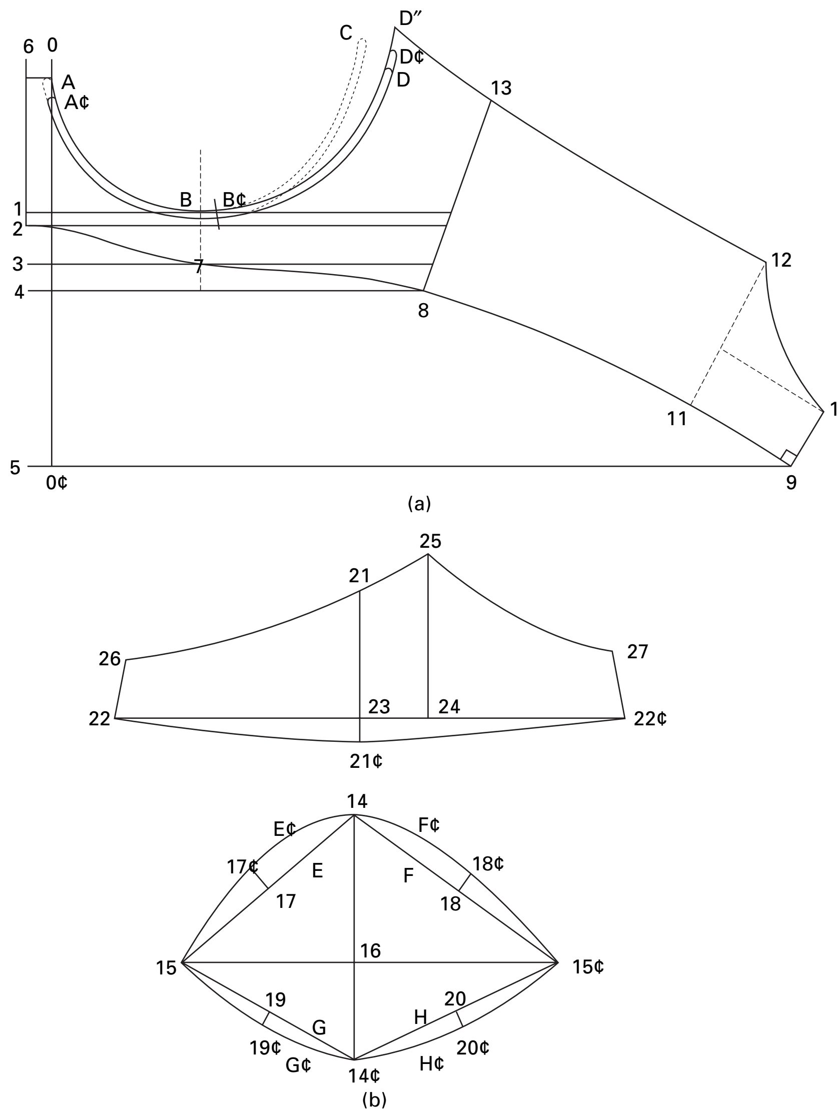
Step	Description	Formula	Purpose	Assumptions/questions
1	Draw a horizontal line [0–1]	[0–1] = 36 cm	To mark the bust line	
2	Mark point 2 and point 9	[0–2] = 8 cm [2–9] = 10 cm	To determine bust point placement	
3	Draw a vertical line [3-4] which passes point 2	[2–3] = 10.5 cm [2–4] = 9 cm	To determine the cup height	
4	Mark point 3¢and 3″ from point 3 and draw a slight curve line connecting point 2 and point 3¢	[3–3¢] = 0.6 cm [3–3″] = 4.4 cm [2–3″] = 10.5 cm	To make the shoulder dart	How to decide the right shoulder dart amount?
5	Draw a straight line connecting point 0 and point 3' and divide line [0–3¢] by 3.		To guide the cup shape	–
6	Mark the point 7¢from the point 7 on line [0–3¢]	[7–7¢] = 0.5 cm	To fit neck line edge	
7	Draw a curve line connecting point 0, 7¢and 3¢according to the figure			
8	Mark point 4¢and point 4″ from the point 4	[4–4¢] = 2.0 cm [4–4″] = 3.0 cm	To make the under-bust dart	How to decide the right under-bust dart amount?
9	Draw straight lines connecting point 2 to point 4¢and point 4″	[2–4¢] = 9 cm [2–4″] = 9 cm	To cover the bust depth (8.5 cm for 75B)	Can this measurement be bigger than 9 cm?
10	Divide the line [2–4¢] and [2–4″] by 3 and mark the point 8 and 14		To guide the cup shape	
11	Mark the point 8¢and 14″	[8–8¢] = 0.3 cm [14–14″] = 0.5 cm	To add volume around the bust point	
12	Draw a curve line connecting point 2, 8¢ 4¢and draw another curve line connecting point 2, 14¢ 4″			Need to match the length of curves after finishing curve lines
13	Mark the point 6	[0–5] = 9 cm [5–5'] = 1.2 cm [5¢-6] = 0.5 cm	To make the tight centre front fit	

Table 4.3 Continued

Step	Description	Formula	Purpose	Assumption/questions
14	Connect point 0 to point 6 and point 6 to 4¢with a smooth curve			How to determine the length of CF seam
15	Divide [2–3″] by 3 and mark the point 13 and mark point 13¢	[13–13¢] = 0.4 cm	To add volume around the bust point	
16	Draw a curve line connecting point 2, 13¢ 3″		Make sure length of curve line [2–3″] is same as [2–3¢	
17	Square out from the point 3″ and label point 12	[3″–12] = 1.2 cm		Shoulder strap width is 1.2 cm
18	Square out point 9¢from point 9 and mark the point 10	[9–9¢] = 6.3 cm [9–10] = 0.5 cm	In order to tilt side seam line	What is the correct amount for tilting side seam?
19	Connect the point 9', 10 and extend line to make point 11	[10–11] = 2.3 cm		How to determine this measurement
20	Connect the point 11 and 12 with a straight line and divide by 2			
21	Mark the point 15¢from point 15	[15–15¢] = 1.5 cm	To make the armhole curve	
22	Draw a curve line connecting point 12, 15¢and 11			What is the ideal armhole curve?
23	Square out point 16 from point 1	[1–16] = 5.0 cm		How can we determine the drop measurement?
24	Draw slight tilted line from point 16 and label as point 17	[16–17] = 3.0 cm		Is 3 cm suitable for hook and eye tape? What is the rationale behind the tilting direction?
25	Connect point 17 to point 11 and point 9¢to point 16 with a straight line			Why not use a curved line?
26	Connect point 4″, 9¢with a smooth curve line			

Note: Numbers in square brackets denote the straight line distance between the numbered points shown in line dstance between the numbered points shown in Fig. 4.8. Morris method.

which is the balance point of the pulling force from the bra wing should be defined before drafting. Basic bra size is 34B/75B. The inner bust line from the bust point is 9 cm and the outer bust line from the bust point is 10.0 cm. Breast depth, distance between bust point to the breast root is 8.5 cm. Breast root width is 13.5 cm (Fig. 4.9(a) and (b)). Table 4.4 shows the bra band drafting and measurement used, while Table 4.5 shows the bra cup drafting step by step.



4.9 (a) Morris's bra band drafting; (b) Morris's bra cup drafting.

Table 4.4 Direct drafting of wire bra band

Step	Description	Formula	Purpose	Assumptions/questions
1	Draw a vertical line [0–0¢ and 5 horizontal lines [1¢, [2], [3], [4], [5] which are perpendicular to the vertical line	[1–2] = 0.5 cm, 2–3] = 1.5 cm, [3–4] = 1 cm, [4–5] = 7 cm	To guide the bra band shape	
2	Place wire centre tip and wire balance point to touch guide line [0–0'] and [1–1'] and trace (dotted line)	[A] = cross point of wire and line [0–0¢, [B] = crossing point of wire and line [1],	To find a placement for wire	Inside of wire should touch the guideline since inside of wire touches breast root
3	Open wire to reach the 13.5 cm breast root width	[C] W [D] = new side tip of wire. Straight distance [A] to [D] = 13.5 cm	To ensure that bra band will open with wire	Is 13.5 cm the set measurement for all 34B breast root width?
4	Rotate wire 0.5 cm to side or counter clockwise	[A] W [A¢ [B] W [B¢ [D] W [D¢	To compensate for the rotation when bra is worn	Is rotation necessary?
5	Add 0.5 cm to each wire tip for wire play and draw smooth line to each point	[A¢-A] = 0.5 cm [D¢-D″] = 0.5 cm	To give space for wire movement	What is the maximum and minimum amount for wire play?
6	Draw centre front line [6–2]	[0–6] = 1.0 cm	Half of distance between breasts	
7	Draw line from point A to line [6–6¢		To shape the gore top	
8	Draw a curve line from point 2 to point 7	[B–7] = 2.0 cm		Is it too wide for sewing operation?
9	Draw a curve line connecting point 7 and point 8	[4–8] = 15.75 cm		

Table 4.4 Continued

Step	Description	Formula	Purpose	Assumption/questions
10	Draw a curve line connecting point 8 and point 9	[5–9] = 30.5 cm		
11	Square up from the point 9 and mark point 10	[9–10] = 2.5 cm		Is 2.5 cm right measurement for the pre-made hook and eye tape?
12	Mark point 11 on the line [8–9] and draw a line which is parallel to [9–10]	[11–12] = 6.6 cm	To make U-shape as a design	
13	Draw a curve line connecting point D″ to point 12		To form a smooth underarm curve	
14	Draw a line from point 8 towards underarm curve line, which is parallel to wire channel line	Length of [8–13] varies due to degree of curve [D″–12]		Can angle of [8–13] be different?

Note: Numbers in square brackets denote the straight line distance between the numbered points shown in Fig.4.8 Morris method.

Table 4.5 Direct drafting of wire bra cup

Step	Description	Formula	Purpose	Assumptions/questions
1	Draw a vertical line [14–14¢ and a horizontal line [15–15¢ which is perpendicular to the vertical line	[14–14¢ = 8.5 cm [14–16] = 5.5 cm [16–14¢ = 3 cm	To make balanced bottom cup	
2	Draw straight lines E and F starting from point 14 and meet the line [15–15¢ according to measurements	[E] = 8.5 cm [F] = 9.5 cm		
3	Draw straight line G and H which connects point 15 to 14¢and point 14¢to 15¢ Divide lines E, F, G, H by 2 and label points 17, 18, 19 and 20.			
4	Square out from point 17, 18, 19 and 20 according to the measurements	17–17¢ = 1.2 cm [[18–18¢ = 0.8 cm [19–19¢ = 0.6 cm [20–20¢ = 0.6 cm	To make the right length of curve lines	
5	Draw curve line and label E¢ F¢ G¢and H¢	[E¢ = 9.0 cm [F¢ = 10.0 cm	To match the length of breast measurements	
6	Draw a vertical line [21–21¢ and a horizontal line [22–22¢ which is perpendicular to the vertical line and label crossing point as 23	22–23¢ = 8.9 cm [23–22] = 9.9 cm [23–21¢ = 0.9 cm	To draw a curve line	How to determine the measurement for [23–21¢ (0.9 cm)
7	Draw curve line connecting point 22, 21¢ and 22¢	[22–21¢ = 9.0 cm [21¢-22¢ = 10.0 cm	To match the length of breast measurements	
8	Mark the point 24	[23–24] = 2.6 cm	To make shoulder strap placement	Where is the most appropriate shoulder strap placement?

Table 4.5 Direct drafting of wire bra cup

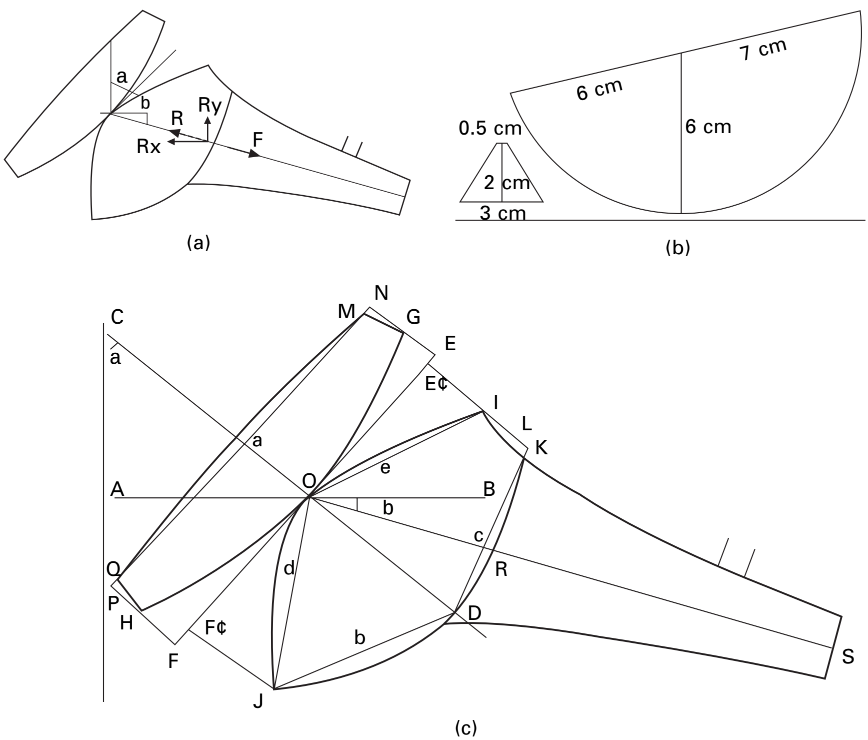
Step	Description	Formula	Purpose	Assumptions/questions
9	Draw a parallel line to [21–21¢] from 24 and mark the point 25	[24–25] = 6 cm		
10	Square up from curve line formed by the point 22 and point 22¢			
11	Mark the point 26 and 27	[22–26] = [A–B¢] – G¢ [22¢–27] = [B¢–D″] – H¢		
12	Draw curve lines connecting point 26 to point 25, point 25 to point 27			

Note: Numbers in square brackets denote the straight line distance between the numbered points shown in Fig. 4.8 Morris method.

4.3.3 Direct drafting of push-up bra

For the pattern construction of a push-up bra, Yu and So [16] recommended a 2D direct drafting method to provide natural projection of the breasts and creation of cleavage. The bra would carry the breasts upwards and inwards. The pattern used no padding but it lifted and supported the bust line, so as to give a natural projection without compressing the breasts.

Four essential features of the push-up bra are (i) bias cup seam, (ii) angled wing, (iii) small underwire and (iv) small gore. A bias cup seam provides a more natural and appealing silhouette than the other designs. When an angled wing is fastened at the back an extension force F, pulling the cup, will generate a reaction force R that gives a push-up vector force Ry that uplifts the breast and a push-in vector force Rx that brings the breast inwards (Fig. 4.10(c)). An underwire for the push-up function should be a small arc curve because a large underwire will restrict the uplifting effect. All push-up bras



4.10 (a) Bias cup seam and angled wing (reprint from Yu and So, *ATA Journal* Jun/Jul 2001 p. 69); (b) small underwire and small gore; and (c) detailed pattern construction of a push-up bra cup and wing for size 75B (reprint from Yu and So, *ATA Journal* Jun/Jul 2001 p. 70).

should avoid using a cradle that keeps the cups too rigidly in place. Instead a very small gore is applied to help achieve maximum cleavage.

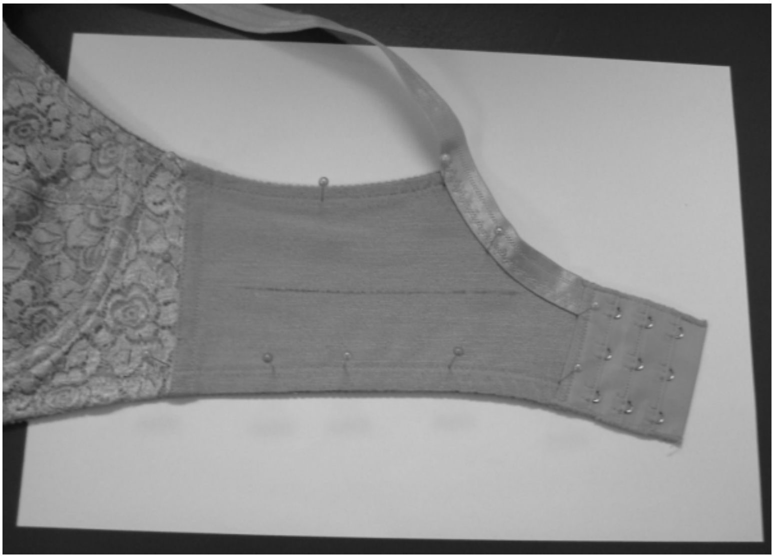
Direct drafting may be suitable for the business of both made-to-measure and mass production, provided that the pattern designer is experienced in accurate fitting. However, the drafting procedures for the different styles are distinct and complicated. When the style changes and the body size alters, the creation of a completely new pattern, with a resultant cost in terms of time, is required. Furthermore, there remain many assumed lengths awaiting verification. The cut lines and curve edges are drawn through experience, artistic sense, and careful observation of the varying proportions of the figure in action and repose [17]. The accuracy of the pattern depends on the precision of the pattern drafting instructions and learning this quickly is clearly beyond a novice's capacity.

4.3.4 Tracing from the sample

When a pattern technician develops the 2D pattern from a garment sample, it may be copied by cutting the stitches along the seams, removing the accessories, and separating the components. Then, one option is to make photocopies of the components to obtain the basic pattern shapes. Another method is to trace the components onto a table using a pencil. This method requires pressing out the wrinkles, smoothing the drawn lines, adding seam allowances and so on. Both methods involve destruction of the garment and are prone to manual handling errors.

Another less accurate option is to measure each garment component using a ruler, and make the pattern based on the overall shape and measurement of each edge. Whilst this option is relatively simple for flat garments such as a camisole, copying 3D garments like bras is a more complicated process. At the very least, the bra sample must be flattened onto a table and require the use of material similar to the sample. In fact, many factors will affect the final measurements and fitting.

Based on Luk's 'unpick garment' [18] method which academically may be regarded as a kind of 'reverse' engineering, we have developed an initial pattern without destroying the bra. The unpicking procedure and the results of pattern tracing are presented in Fig. 4.11. First we remove the bra wire, follow the fabric grain and pin the bra component onto white paper. We ensure the components lie flat without gathers or wrinkles. Then we trace the pattern on the paper. This method was found to be efficient especially for cut and sewn bras. Furthermore, little experience and knowledge is required for this unpicking process, so it provides a good starting point for training new designers. However, it can be more complex for the moulded cup and one-piece bra because it is difficult to flatten a 3D stretchy object onto a table and the bra is easily distorted in shape when being traced.



4.11 Unpicking garment.

4.4 Three-dimensional modelling on the mannequin

Traditional pattern construction is based mainly on manual calculations and human experience. It involves the drawing of 2D blocks of patterns, which are subsequently assembled to form the 3D shape of garment to fit the human body. This 2D approach has a number of inherent deficiencies [19]. It requires enormous manual skill, the lack of which will produce ill-fitting clothes. The 3D modelling method creates the bra pattern by draping toile onto the curve surface of a dress mannequin and adjusting the style lines and fitting by means of pins and tacking stitches. Working directly on the dress mannequin is the first step for developing a three-dimensional concept and understanding of a woman's body figure.

4.4.1 Lingerie design on the mannequin

As the mannequin is supposed to have symmetrical left and right sides, modelling only on one side would be enough. Cloake [20] has introduced the basic modelling techniques for lingerie using woven fabrics in her book. It generally covered eight steps:

1. determining mannequin size
2. padding the mannequin
3. taping essential body positions

4. taping design lines
5. understanding fabric grain
6. preparing fabric for a design
7. controlling fabric grain vertically and horizontally on the mannequin
8. shaping woven fabric to curves by creating darts.

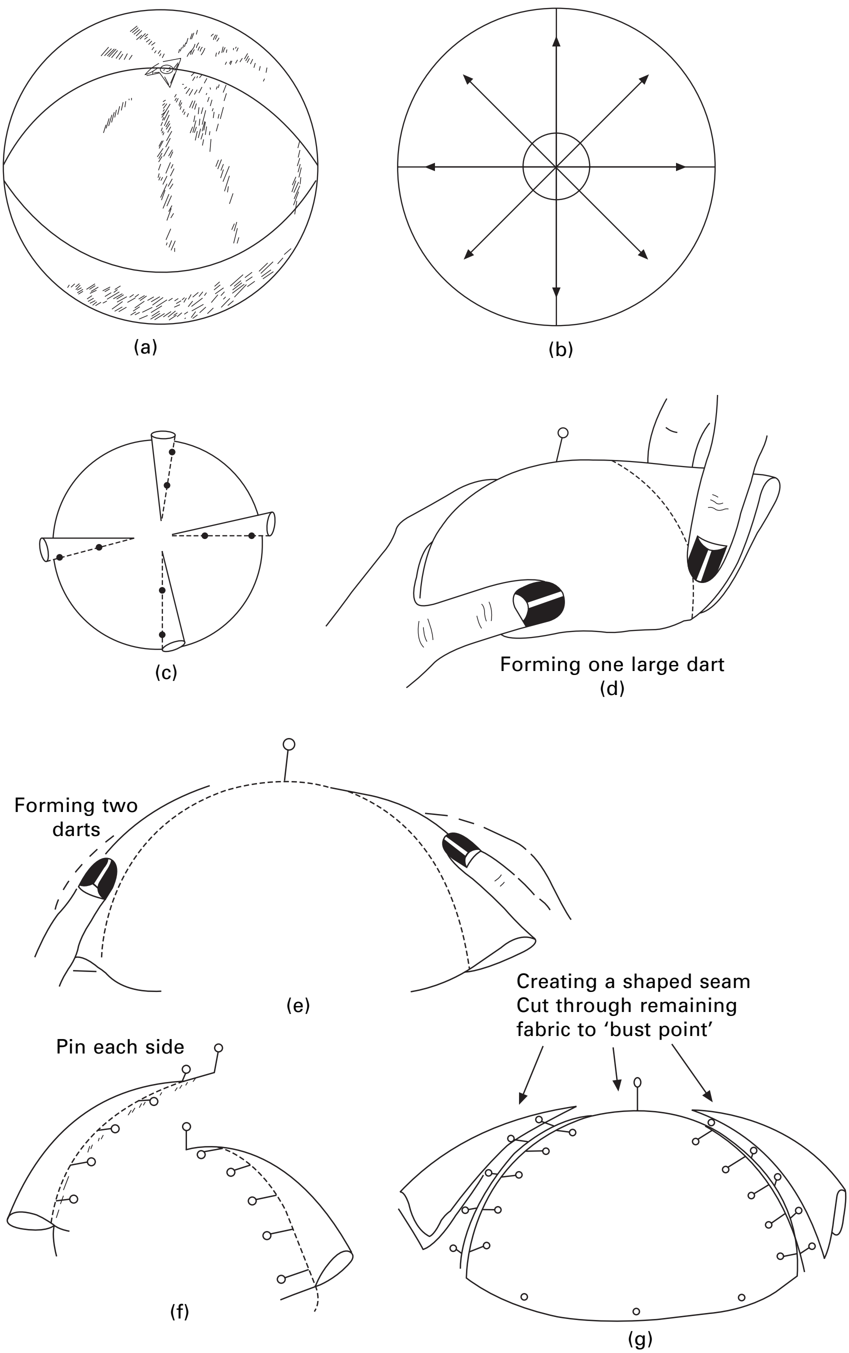
The above modelling procedure was based on a dress mannequin of British size 12, so it required adding pads on the mannequin to make the appropriate size at certain areas. These two steps will not be necessary if a proper lingerie mannequin is available. Step 3, taping essential body positions on the mannequin, is important to fix the body landmarks and reference lines such as the horizontal girths of bust, hip and abdomen. In step 4, narrow tape is used to define temporarily the major design lines such as seams and dart positions. This is the most critical step in the design process. Steps 5 to 7 for handling the fabric grain is similar to the methods used for other fashion items. However, step 8, for shaping the woven fabric around the bust area, would be difficult and requires a high level of skill. The suggested 'grapefruit exercise' (Fig. 4.12) would be interesting and useful for new designers for developing the skill of shaping fabric to curves.

4.4.2 Techniques in 3D modelling of bra pattern

Different techniques have been developed for the 3D modelling of bra patterns. TPC used red strings to define the horizontal bust line and curved cup seam line. Y.K. So applies narrow black tapes (Fig. 4.13) to mark more detailed style construction lines. Both methods use soft paper which is pinned on the mannequin smoothly like a second skin without causing any wrinkle, to just cover the predetermined style lines. After extra fabric is cut away, the so-called 'second skin' is removed from the dummy and laid flat on the table. Then the edges are traced, lines are straightened and curves are smoothed out. The initial bra pattern set (Fig. 4.14) is thus developed.

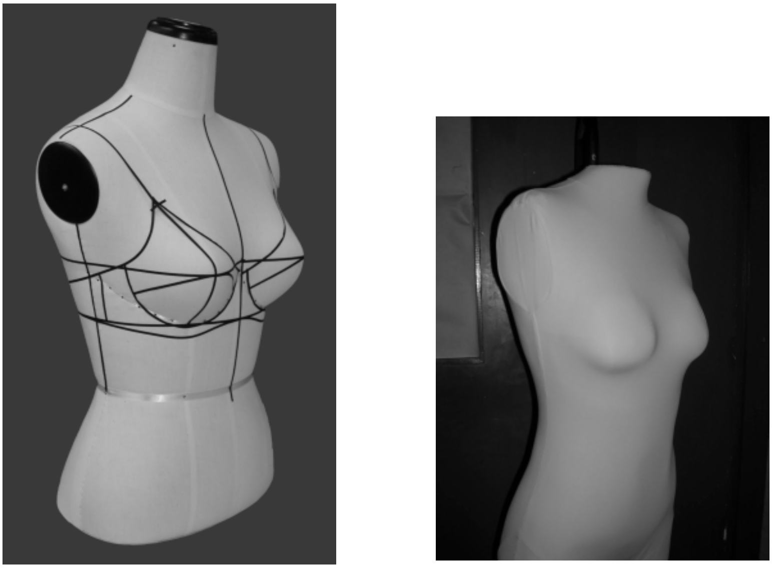
TPC's method appears to be more fashion-based and the lines are simpler. So's method is specialised for bras where close-fitting lines and curves are emphasised. In both respects, the correct fabric grain must be set on the soft paper or toile before draping so as to ensure the proper straining force to provide the desired support for a particular style. With TPC's technique, the initially developed patterns were digitised into a computer CAD system for matching the line length and adding the seam allowance, whereas So did it manually using French curves and rulers.

More importantly, all methods require a mock garment to fit on the mannequin or a live model of the target size. Correct materials with similar, if not exactly the same, stretch factor must be used to ensure a valid fitting result. If there is discrepancy at a certain body region, the pattern will be



4.12 Grapefruit exercise of modelling a 3D shape. (Source: Cloake 2000 p. 26–27).

4.13 So's bra modelling.



(a) (b)

4.14 (a) Conventional mannequin; (b) soft mannequin for intimate apparel fitting.

modified accordingly. According to Luk [21], reducing fabric by enlarging the dart can flatten the shape of a bra, whereas adding a patch to a cut opening can give more volume to the bra. Fitting and modification will continue until the final prototype satisfactorily fits the body. Sometimes, the live model is asked to wear the bra for at least eight hours to test the wear compatibility.

Compared to 2D flat drafting, the 3D modelling method is more realistic and reliable because the characteristics of women's 3D body topography are well matched with the bra pattern. Although 3D modelling needs retracing and smoothing of lines that also create some errors, the required modifications are much less than the 2D approach. Stanley [22] suggested modelling on the mannequin first to overcome the difficulties for the novice acquiring knowledge of the flat pattern-making method. In practice, both methods should be used side by side to develop more accurate 2D drafting.

4.4.3 Soft mannequin for bra modelling

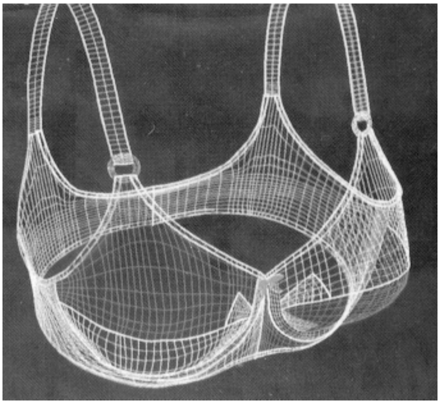
Traditional mannequins are so rigid that they cannot show the body curves created by wearing a bra from the forces asserted on the human soft tissues. Therefore, a soft mannequin would be ideal for 3D modelling of lingerie. A soft mannequin specifically for intimate apparel fitting has therefore been developed [23]. By 3D body scanning of a live model, the mannequin's size and shape was made to be the same as a woman's torso with a full-sized bone skeleton, imitating soft tissue and smooth-touch fabric skin. The soft tissue was made from flexible polyurethane foam of a similar Young's modulus to human skin. This soft mannequin provides a novel tool for evaluating the fitting and tension of intimate apparel without using expensive live models.

4.5 Computerised 3D intimate pattern design

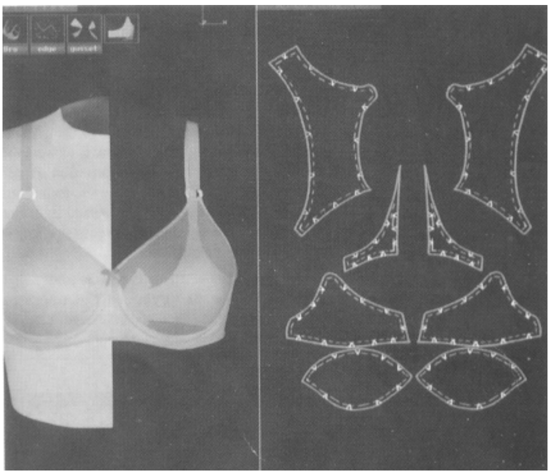
The lack of a clear relationship between different components of the bra pattern blocks makes it difficult to automate bra pattern construction. Any modification in shape or style will require the whole work to be redone, resulting in prolonged product development time. Therefore, computer-aided-design (CAD) is a potential tool for shortening the product development cycle and improving the pattern accuracy. During recent years, many key CAD companies have been are continuing to develop 3D design systems that 'virtually' sew together 2D pattern pieces on the computer to see how they will fit and drape on a 3D displayed person or mannequin. The required pattern modifications are much less than those required in the 2D approach [24].

4.5.1 CDI technology

CDI was the earliest company to show the feasibility of using computer tools to generate, analyse and visualise the 3D surface of a bra being worn on a mannequin (Fig. 4.15) [25]. Based on the polygonal computation of NURBS (Non-Uniform-Rational B-Splines), the system incorporated an automatic feature intended for intimate apparel with considerations of axial changes in



(a)



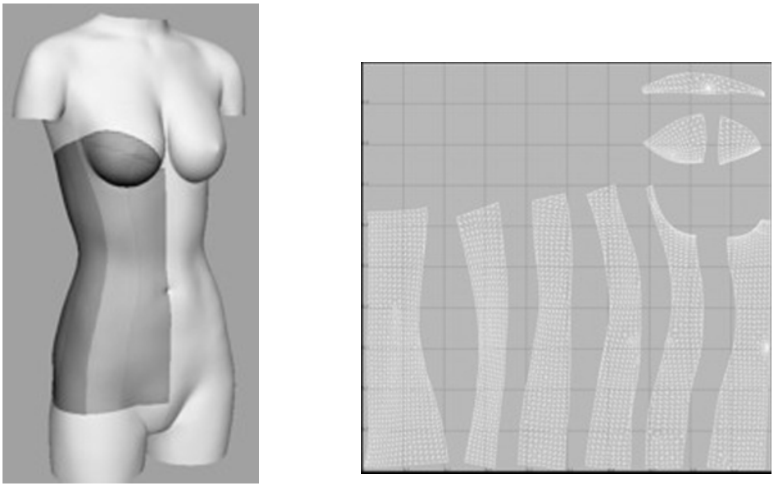
(b)

4.15 CDI's virtual bra pattern. (Source: Tait N., *Apparel International*, Nov 1993, p. 15).

materials relaxation and load-extension characteristics. NURBS represents smoothed 3D curves with variable nodes which can also be inserted retrospectively, relocated and/or deleted.

4.5.2 TPC lingerie software

Institut TPC Paris obtained human body data from a 3D body scanner and treated the image as a 'virtual mannequin' (Fig. 4.16). Reference lines were used for the construction of garment patterns based on the TPC's worldwide patented 3D pattern concept [26]. 3D relational-geometry is used to automatically convert 3D pattern structures into 2D pattern blocks. The pattern



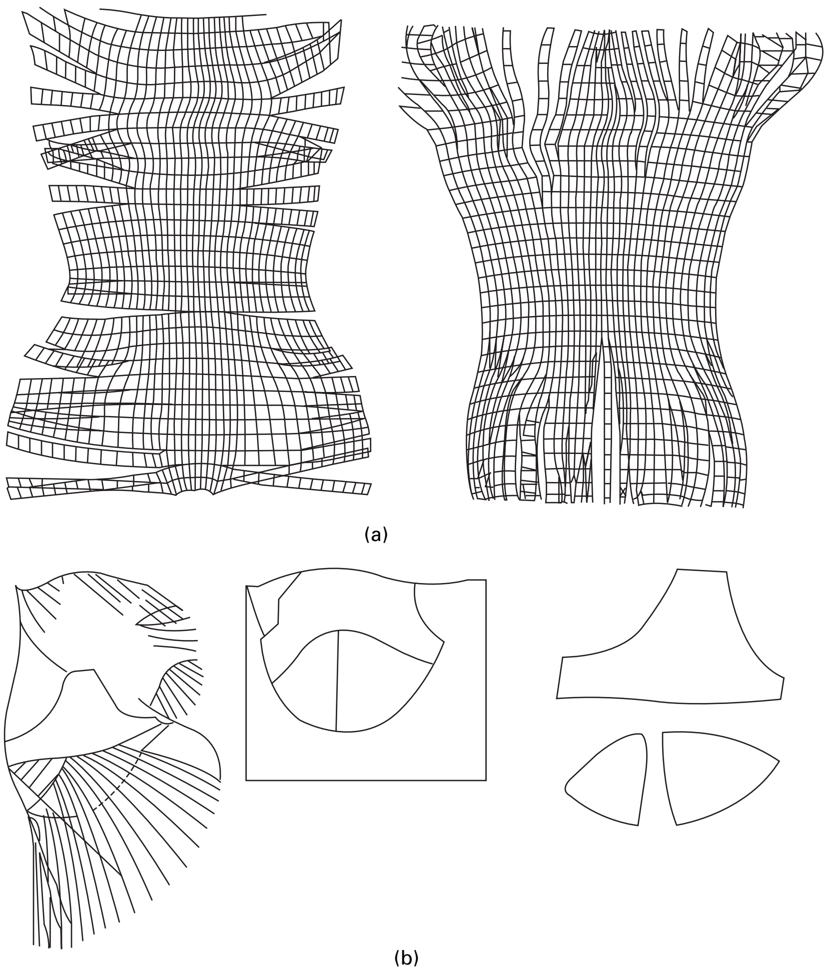
(a) (b)

4.16 (a) TPC 3D CAD software; (b) TPC's developed pattern from 3D virtual mannequin. (Source: http://www.tpc-intl.com./products.asp).

blocks thus created are akin to those stripped from a 3D garment form, making the attainment of 'fit' much easier. The TPC foundation garment technology used the Maya software of Alias Wavefront as a 3D platform to treat the real-time garment fit problem. With 3D visualisation, users can create the garment structure on a virtual mannequin, or manipulate simultaneously the volume and silhouette of the garment. For the development of lingerie, it is difficult to define manually the different characteristics of the bust, such as the cup sizes, under bust and their shapes. The virtual model allows morphological evolution in a virtual space with transformation of posture and attitude. With the feature base design, a user can create the 3D garment directly on a designated virtual body.

4.5.3 Kurokawa and Nishimura's model

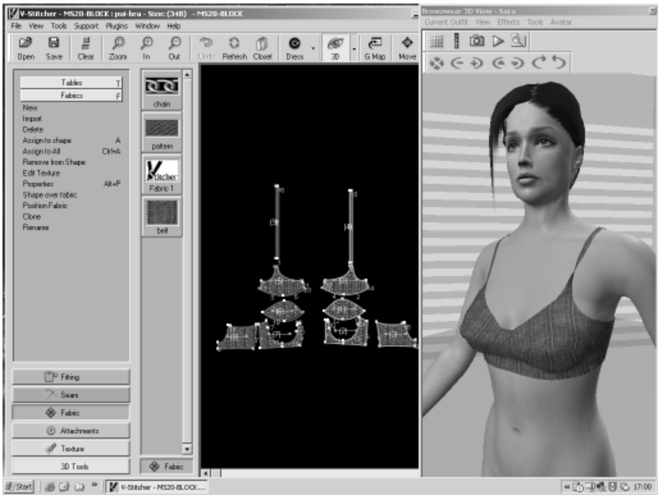
Kurokawa and Nishimura [27] demonstrated the possibility of making a bra pattern based on the style lines drawn by the designer on a 3D digital human model. The model was described using a bi-cubic B-spline surface developed on a plane, connecting small quasi-planar square pieces in shreds from the model surface. The developed bra pattern resembled a picture composed of many strips (Fig. 4.17) placed beside each other. This showed a promising direction for the commercial software developers to create better CAD systems that allow the intimate apparel designers to interact with the computer screen and incorporate their ideas in designing lingerie styles and patterns.



4.17 (a) Examples of planar development of a body surface; (b) planar development of a breast. (Source: Kurokawa and Nishimura 1990, p. 152).

4.5.4 V-stitcher

Browzwear's, V-Styler and C-Me technology can be integrated with CAD systems from Gerber Technology, Santoni and Kopperman. Using the latest upgrade of V-Stitcher (Fig. 4.18) [28], the parametric avatar (virtual body) can be modified from teenager to mature pregnant woman by manually inputting body measurements. However, direct importing of data in DXF format from a body scanner is not yet possible. The 2D patterns input from a CAD system can be virtually sewn together with the identification of the corresponding seams and instructions of sewing steps. The fabric mechanical



4.18 AccuMark V-Stitcher. (Source: http://www.browzwear.com/).

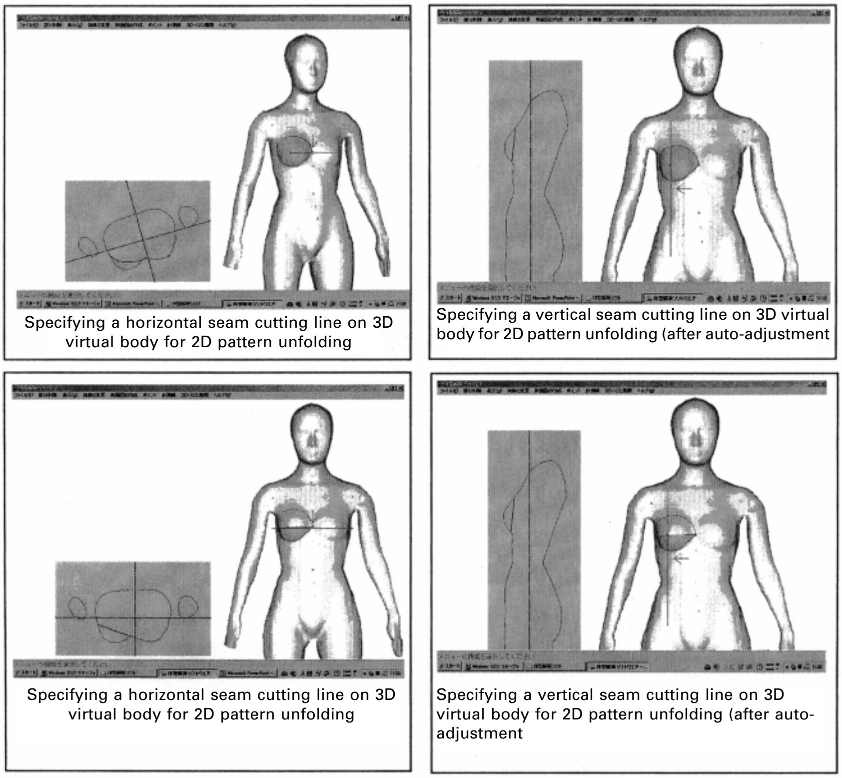
properties can also be specified, so that the stress distribution between the body and the garment is displayed on the virtual fitting model for quick evaluation. With this technology, product development time is much shortened and communications are enhanced among buyers, designers and the technical team.

4.5.5 AGMS's 3D body analysis software

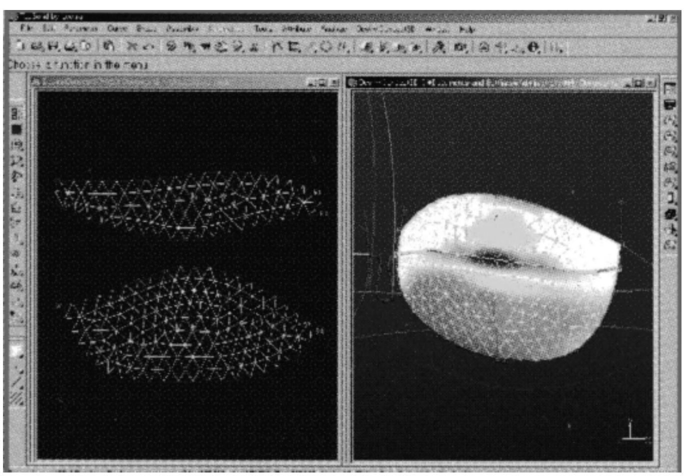
3D AGMS™ body analysis software [29] can import the DXF formatted file of a 3D scanned body and display the virtual mannequin on the computer screen (Fig. 4.19). It allows the designer to draw the wire shape and style lines on the mannequin. The enclosed surface on the mannequin is automatically unfolded to form a flat pattern. Inspecting the design from any angle, users can apply various fabrics and textures to create the 2D pattern pieces from the 3D modelled surface. Adjustment can be made easily when some mismatches or errors are found.

4.5.6 Lectra's 3D design concept

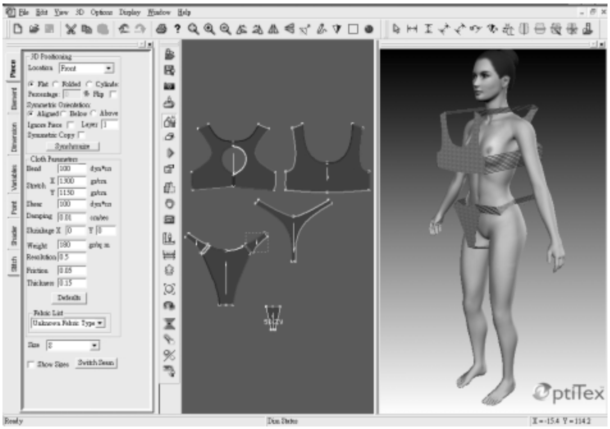
Design Concept3D Advanced Pattern Modelling is Lectra's 3D technology design solution for lingerie and swimwear. This software contains parametric and freeform tools for precision 3D surface generation, surface analysis, visualisation, and lay planning. Moreover a host of data translation tools allows integration of design concepts into existing CAD processes (Fig. 4.20). With Design Concept 3D, drawing brassiere pattern boundaries on the



4.19 AGMS 3D body software. (Source: AGMS 3D body software manual).



4.20 Lectra's Design Concept 3D. (Source: *Design Concept 3D, Lingerie and Swimwear solutions*, brochure from Lectra, 2005).



4.21 Optitex 3D software.

3D model and then automatically flattening them into 2D pattern shapes becomes relatively easy. Bra pattern strain, ease, perimeter and surface area study are feasible. For an easy optimisation process, flat patterns automatically update when any change is made to the 3D shape.

4.5.7 OptiTex's software

Berzon in 2004 reported that OptiTex provided 3D software for visualisation which was based on accurate CAD patterns and real fabric characteristics (Fig. 4.21). The Runway 3D offers the user a suite of tools that will simulate all pre-production activities related to: fitting, visualisation, texture and colour variation. It includes a highly detailed parametric mannequin with over 40 precise adjustable body measurements. Users can create specific base size mannequins (virtual fit models) for virtual fittings. Bra flat patterns can be converted onto adjustable 3D parametric mannequins, so that a true-to-life 3D human image can be carefully critiqued for construction, and fit.

4.6 Comments on various pattern technologies

Basic block drafting is a fast, systematic and cost-effective way of making bra patterns. The principle is easy to learn and often found very convenient. However, the numerical values of the specific lengths used in the block pattern depend much on experience. The drafting principle of dart quantity and distribution is still unclear. The direct drafting method is suitable for made-to-measure wear and is preferred as the basis for tailor-cutting. The accuracy of the pattern depends on the accuracy of the body measurements and the pattern designer's experience. The procedures for different styles are distinct, complicated and time consuming.

While traditional 2D pattern design is based mainly on manual calculations and experience, it requires enormous manual skill. The lack of such skill will produce ‘ill-fitting’ bras. Flat cutting is accepted as reliable only when the garment can pass the fitting test on the mannequin. The interpretation of body measurements and the 2D translation of patterns are difficult to realise and are very time-consuming. The established theories and methods could enable the designers to get more deeply involved in the technological translation of their designs without having to restrict their creativity.

Un-picking from a bra sample is simple, fast and requires less experience, however, accuracy cannot be guaranteed. 3D pattern draping on a mannequin is a more realistic method to roughly form a mock-up to test the fit on the mannequin’s surface and it is well known for its excellence in crafting custom-fit intimate apparel. However, a variety of mannequins is required and skilful operations are involved. It may not be unsuitable for modern mass production. Instead of using either the 2D or 3D technique, leading designers often employ a synthesis of both flat pattern cutting and modelling methods.

Interactive 3D CAD systems are good for the pattern designers to visualise how the bra will look as the pattern develops from the screen. Proportions of the design details can be related to the human body. The flow and drape of fabric is readily apparent as long as the predictive ‘draping’ algorithms are accurate. However, the virtual mannequin is considered rigid so the calculated stress between the body and the garment is not real. Further research is therefore required to establish a relationship between the computed stress value and the realistic pressure measurements.

4.7 Future work

Until recently, there has been only limited research on bra pattern design, bra sizing and assessment of fit. There is no real scientific understanding on the relationships between stretch ratio, wire spring, gore width, cradle depth, wing angle and cup pattern parameters. The complex relationship between pattern engineering, material properties and the body curvature and anthropometry remain largely unknown. The mathematical relationship between the different components of the bra pattern blocks based on body shape needs to be further explored. Through the previous systematic examination of literature, the remaining knowledge gaps may be summarised as follows.

- Traditional bra pattern drafting was based only on the measurements of bust and underbust girth for determining two key lines on the block pattern. Other important detailed body measurements have not yet been considered.
- No research has been found on the interrelationships between body dimensions, bra pattern parameters and body fitting preference.

- There has been no systematic study on the optimisation of dart distribution to fit specific breast dimensions.
- Traditional bra pattern drafting procedures of different styles are distinct and complicated. The cut lines and curve edges are drawn by experience. Verification by systematic experiments is necessary to develop drafting methods.
- The fitting performance of a bra is essential to evaluate pattern accuracy, but there exists no objective standard for the testing of bra fit.
- Literature is always based on a basic style of bra. For different bra styles and shapes, the relationships between the bra pattern and fabric properties in fitting the specific breast forms are not well understood.
- Even if the desired stress-strain properties are defined, it is still difficult to manufacture a knitted fabric with the specific tensile properties for surface forming and dimensional stability after washing or finishing.
- No matter which method is used, seam allowance must be added for assembly. However, literature has not mentioned the determination of seam allowance which is often affected by the seam type, fabric thickness and stretch, lace pattern, size of trims and fasteners, etc.

Clearly there is scope for considerable further works to establish a more scientific basis for the design of a critical and complex item of apparel.

4.8 Acknowledgement

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5
Innovation of girdles

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5.1 Introduction

Throughout history to the present day, women have paid great attention to their body image in the obsessive belief that 'thin is beautiful' – which, to some extent, still prevails nowadays. In a society where the majority of females are pursuing a particular type of body shape, the ideal body and the standard image of beauty will also change accordingly. With the aid of body shapers, women can often enhance their body shape to one that is more desirable.

A body shaper, also known as a girdle, is both a women's undergarment and a pressure garment. In most cases, it is made from highly extensible fabric and fastened with hook and eye closures. It mainly serves the purpose of re-shaping and smoothing the lower torso of a woman's body, thereby producing a more aesthetic appearance and attractive silhouette [1]. A girdle can extend high enough to incorporate a bra and as low as the thighs. Some girdle designs may also include garters to hold up stockings. In order to have a thorough understanding of this sophisticated foundation garment, its historical development, modern classification and innovations in shape-up girdles produced from various materials, health aspects and design features will be reviewed in this chapter.

5.2 Historical development of girdles

Girdles have evolved since the 1940s from the concept of the corset. Although the exact origins of the corset could not be found from any literature, undergarments that forced the waist into a predefined shape were worn by wealthy ladies in France in the 1300s and 1400s. The wearing of corsets became widespread in the 1500s and 1600s as shown in many Renaissance portraits. These corsets were functional but particularly rigid and uncomfortable as they were made from materials such as iron or wood, as well as whalebone. In the 1700s, corsets were long, stiff and essential when ladies were wearing petticoats to make their waists more slender and push their breasts up. Extremely tight lacing became more and more popular towards the end of the 18th century. However, the French Revolution was accompanied by a diminution in the popularity of tight lacing as it was regarded as a symbol of decadent aristocracy, and indeed jeopardized wearers' health [2].

In the first decade of the 19th century, long and tight corsets made a spirited comeback. The invention of the Latex process by Dunlop in the 1930s led to the invention of the two-way-stretch girdle skirt. Such a girdle skirt was made with rubberized stretch fabrics to provide greater comfort, ease of movement and a smoother line under the dress. A girdle at that time was often advertised as a pattern of stitched reinforcements and the use of boning, as keys to successful control. However, rubber rationing in the Second World War temporarily interrupted this trend.

In the early 1940s, with the coming of the Second World War the emphasis was placed on prolonging the life of clothes [3]. There was a tendency for women to look for good quality body shapers so American designers focused on new production technology and research into new fabric materials. In 1941 Elastex, which was a type of elastic fabric was developed specifically for making body shapers. A clean and streamline style of all-in-one body shapers without any embroidery was very popular at that time [4]. This kind of 'body briefer' and 'shapesuit' held a substantial share of the undergarment market at that time, but gradually gave way to the divided bra-and-girdle. In 1945, the popular design was a set of bra-and-girdle with a tight waist.

The post-war period immediately saw a return to the use of elasticized fabrics. The typical body shapers in the 1940s and 50s were firmly constructed, with extensive use of rigid panels and reinforcement. Lycra, an elastic filament invented by Dupont, created highly extensible fabric with good elastic recovery properties and became increasingly popular in the early 1960s, allowing the design of body shapers that were light in weight yet still provided effective figure control. The long-leg panty girdle came to dominate the U.S. market and retained predominance in Europe.

In the 1970s, sport, dance, health and fitness were glorified, clothing was simple and non-hindering so that women had freedom of movement and exercised in the gymnasium. In late 1970s, tight girdles with high clothing pressure faded out of the market to be replaced by control garments which imposed some clothing pressure but were also comfortable to wear and easy to wash and these became the common kind of body shaper for daily wear.

Based on the fashion trend for 'healthy beauty' in the 1980s, women desired girdles that would not only show their outstanding body figures, but were also comfortable to wear. The invention of Spandex made possible the lightweight girdle. Explosive technological growth in fibres and fabrics totally changed body shapers' fashion in the 1990s from tightly laced to light, flexible, and easily cared for. Women's clothes became more fluid, and certainly more comfortable.

Today, the demand for functional girdles made from high-quality materials with a perfect fit is constantly rising. The trend is towards very fine, microfibre fabrics in combination with highly elastic elastomeric threads, such as Dorlastan, Lycra and Lyocell [5]. The growing trend for keeping fit boosted the sale of body shapers in the U.S.A increasing by 127% every month [6]. Most girdles are knitted from nylon and elastane, (elastic filament yarns) such as Lycra or Spandex, to fulfil the requirements for comfortable and lightweight shaping girdles. Moreover, elastane can now be blended with natural and man-made fibres such as silk, cotton, or nylon, in order to create new elasticized material for women's shape wear. Even leather has been blended with Lycra to make exotic lingerie whose applications can only be left to the imagination of the woman wearing it [7].

5.3 Classification of modern girdles

Girdles are classified in terms of their support capabilities – light, medium, or firm control. The difference is usually determined by the weight or thickness of the supporting material. Light-control girdles, emphasize comfort and ease of wear. The main drawback is their limited reinforcement of the abdomen and insufficient support for the hip contour. Medium-control girdles provide greater support to specific parts of the body, typically the abdomen which is the common part to be controlled by pressing it down by using firmer materials. Firm-control girdles apply higher forces to achieve functional control on the abdomen and to raise the hip level. Mostly, the fabrics are used in two or more layers to provide the strength and elasticity to give extra support to the hips. However, this kind of girdle is heavier than the other two and it is difficult for the wearer to put on and remove.

With regard to girdle styles, there are four common types: long-leg panty girdle, open-bottom girdle, control brief and 'all-in-one'. The main charateristic of the long-leg panty girdle, which attained its greatest popularity in 1960, is its all-around smoothing but the demerit is the low narrow waistband which leads to an uncomfortable roll when worn.

The open-bottom girdle was developed and became popular in the 1940s and 50s. Nowadays girdles are worn with gartered stockings in order to extend the beauty to include the legs. Attention must be paid when wearing trousers as the garter tabs can be easily seen.

The control brief is the most popular shaping garment today. It typically provides lightweight smoothing, although firm control models are also made. Abdomen panels, as shown on the front side of the brief, are a common feature.

The all-in-one is a one-piece undergarment combining both girdle and bra. Light-control versions are often sold under the term bodysuits or bodybriefs, but the sizing is difficult to fit both the body length and circumference.

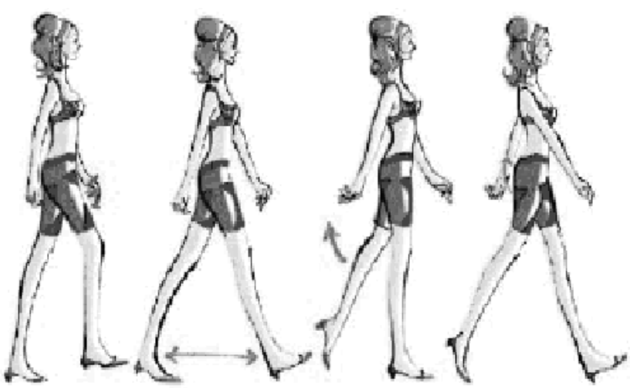
5.4 Innovations of shape-up girdles

Although the girdle is designed primarily as a functional garment, there is no reason why comfort, health, aesthetics and durability should be sacrificed. Therefore, girdle design has become highly specialized. For the developed market, especially in Japan, girdle products with shape-up performance must demonstrate innovative technology. Customers are more and more demanding, they expect that the new product should offer special functions and smart technology.

Wacoal is probably the major inventor of this particular kind of intimate apparel. Based on its research on body sizing, biomechanical study and sensory engineering, Wacoal has invented many special designs for underpants and girdles. Over 300 relevant patents were granted in Japan and more than 40 patents were obtained from the United States. Some interesting examples have been selected for presentation in the following sections.

5.4.1 'Hip training bottom'

Based on a biomechanical study of the joint and muscle movements that occur when women walk, Wacoal's Human Science Research Centre developed a new product called the 'hip training bottom' which was launched in 2005. As shown in Fig. 5.1 the cross structure of the seamless knitting pattern provides power to the anterior thigh muscle with moderate tension when a woman walks. Thus, it stimulates the wearer to extend the knee and her rear leg naturally kicks in a bigger step during walking. It was claimed that this repeating movement could pull up the hip to a higher position to achieve a more beautiful shape, if a woman walks 6000 steps or more wearing this 'hip training bottom' everyday.



5.1 Training of hip and leg muscles. Source: http://www.wacoal.co.jp/news/pdf/13161_1.pdf.

5.4.2 Warp knitted shape-up girdle

A shape-up girdle is expected to enhance the beauty of the female figure. Many innovations in girdles have focused on smoothing and shaping body figures to make the appearance firm, compact and trim.

5.5 Inventions of health-promoting girdles

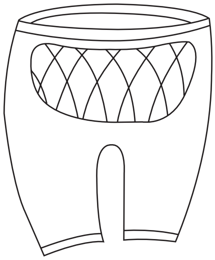
Following the continual improvement in manufacturing technology for girdles, the trend in health-promoting girdles has been full of invention. The development of functional health girdles is becoming particularly topical. Examples of the health functions are given in the following sections.

5.5.1 Reduce fat

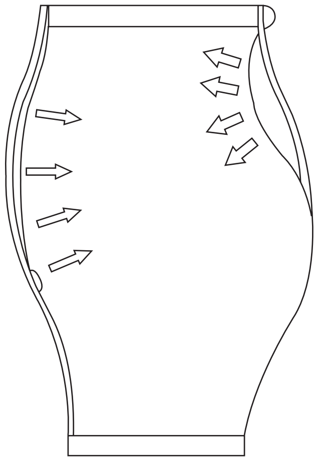
In 2003, Kevin *et al.* [8] invented a garment configuration which claimed to achieve weight reduction and muscle-building function (Fig. 5.2). It provided both electrically conducting portions and insulating portions that altered the electrochemical signal messaging system in the wearer's body. The redirected currents triggered a release of stored fatty tissues, and, hence a reduction in weight. The electrically conductive portions were configured to permit safe and effective use.

5.5.2 Relieve pain

To relieve discomfort induced by menstruation, Scott *et al*. [9] developed a panty girdle with a distensible bladder which applied pressure to one or both of the sacral areas of the female body (Fig. 5.3) for relaxation. The pressure could be varied through the manual manipulation of a squeeze pump that was built into the waistband of the garment. The elastic foundation panel was shaped and designed to reduce bloating and create a trimmer appearance.



5.2 Electrically conductive weight reduction girdle. Source: Kevin R.O.



5.3 Panty girdle with distensible bladder. Source: R. Scott Smith.

A special girdle called the 'Relief Brief' [10] has latex foam components called acupads embedded in the lower abdominal and lower back regions of the garment. These acupads apply pressure on the wearer's acupressure points to try to relieve dysmenorrhea. Dysmenorrhea is defined as excessive pain experienced during menstruation. About 90% of menstruating women are affected by menstrual pain [11–13]. Symptoms associated with primary dysmenorrhea include abdominal cramps, headache, backache, general body aches, continuous abdominal pain, and other somatic discomforts [14].

A study examined the effectiveness of the Relief Brief acupressure panty, for relief of pain and distress symptoms associated with dysmenorrhea in 61 women with moderately severe primary dysmenorrhea [15]. Thirty-three women were assigned to the treatment group and 28 to the control group. Assessments were made before treatment to establish a baseline, and during two menstrual cycles when the subjects were wearing the 'Relief Brief' as garment treatment. Most of the women (90%) who wore the Relief Brief experienced at least 25% decrease in pain severity (2–3 points drop on a 0 to 10 scale) compared to an 8% drop in the control group ($p < 0.05$).

5.6 New materials for girdles

For a few years now, a revolution in materials used for intimate apparel has been taking place. New materials have been invented that are designed to enhance the wearer's comfort and hygiene. Material innovation encouraged the development of new designs and created the new market for value-added and high-quality products. This section reviews some of the latest materials developed specifically for girdles.

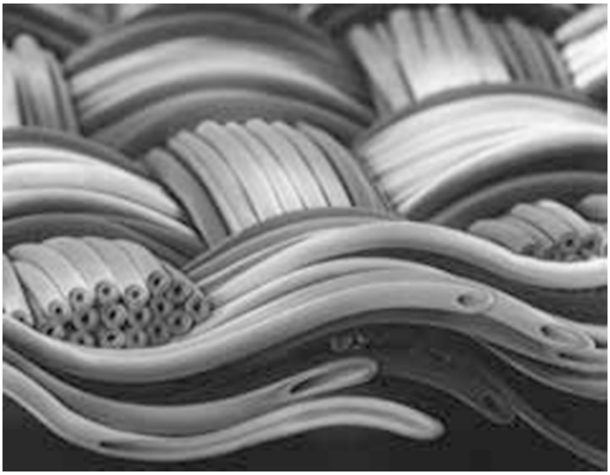
5.6.1 New materials for thermal and moisture comfort

Conventionally, girdles are made of synthetic fabric with high extensibility and recovery to enable it to exert strong 'power' which is why they are called 'power' garments. They are generally not moisture absorbing. To improve thermal and moisture transfer, fibres such as hollow fibres, modified cross-section fibres and breathable fibres have been developed with the aim of enhancing the wearer's comfort.

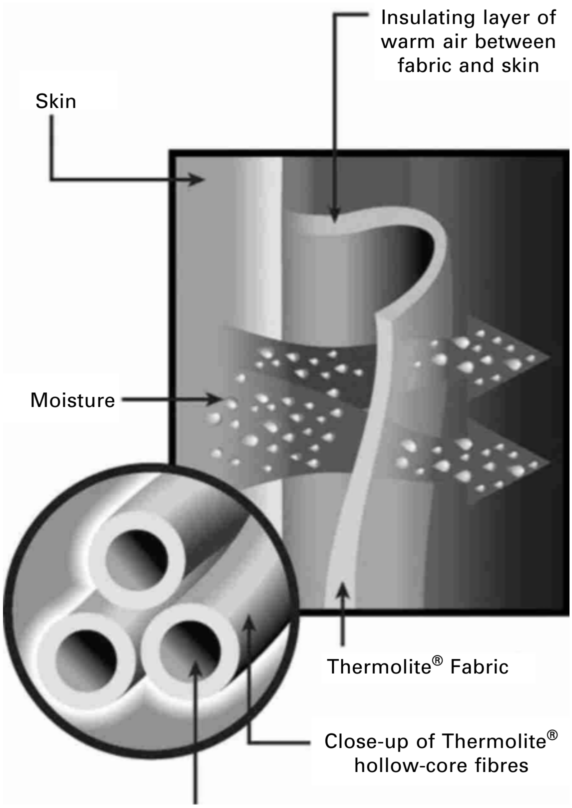
Hollow fibres are designed to promote natural climatic regulation, Meryl® Nexten® is the first European-made hollow polyamide fibre [16]. Figure 5.4 shows a fabric woven using yarns containing Meryl® Nexten® fibres [17]. This fibre is claimed to produce garments that are 25% lighter than conventional polyamide garments of the same thickness and 25% greater insulation than those produced using other hollow fibres [18].

Thermolite Base® fabric is made from hollow core fibres which are similar to the hairs of a polar bear [19]. Figure 5.5 illustrates how the Thermolite® hollow fibre entraps insulating air and how moisture is transported through the fibre. The Thermolite Base® fabric dries 20% quicker than other insulating fabric and 50% quicker than cotton [20]. By modifying the cross-sectional structure, the physical properties of the fibre can be changed significantly. Similar to Coolmax® fibre, the highly functional Aerocool® polyester fibre developed by a Korean firm, Hyosung Corporate, absorbs and evaporates sweat quickly and dries fast. Its 'four-leaf clover' cross-section (Fig. 5.6) helps the movement of moisture through four capillary tubes [21].

Dryarn® developed by the Aquafil division of the Italian group Bonazzi, is a breathable fibre called 'isostatic polypropylene microfibre' which offers



5.4 Morphology of Meryl® Nexten® fibre used in a woven fabric.



5.5 Morphology of Thermolite® hollow-core fibre.

5.6 Cross-sectional view of Aerocool® polyester fibre.

interesting performances in terms of lightness, drying and wicking of moisture, without losing the thermal insulation properties inherent in polypropylene. It also has a higher capacity for removing moisture compared to polyester [22].

Microencapsulated fabrics can be either cosmetic textiles that gradually release active or volatile microcapsules, or climatic fabrics containing phase change microcapsules which provide a thermal effect [23]. The former has been widely applied in lingerie using microencapsulated active ingredients with various properties such as scents, cosmetics and therapeutic materials [24–26]. The latter are known as phase change materials (PCMs) that store, release or absorb heat as they oscillate between solid and liquid form. Some PCM's change their phases within a temperature range that is just above or below human skin temperature. This property is now being used in fabric to store body heat when it is cold or release heat when it is too warm [27]. The value-adding functions of these new materials sound useful to intimate apparel.

5.6.2 New materials for hygiene

Demand for anti-microbial-treated clothing is growing as consumers become increasingly aware of hygiene and of the potentially harmful effects of micro-organisms [28–30]. Fabrics known as bacteriostatic prevent the proliferation of micro-organisms. They halt or slow down the formation of fungal growth and the production of unpleasant odours following the incidence of perspiration.

Bacteriostatic fabrics can be either natural or synthetic. Natural materials are naturally antibacterial on account of their intrinsic properties, for example, bamboo. Scientists have found that a bio-agent named 'bamboo kun' inside a bamboo fibre makes it naturally bacteriostatic [31]. The structure of bamboo fibre comprises numerous microscopic holes which produce fabric with unique breathability and lightness [32]. Bamboo fabrics have comfortable hand, special lustre and allow bright colouration and good water absorption characteristics which are particularly suitable for making intimate apparel.

Crabyon®, a new fibre based on the technology of making chitin/chitosan into fibre is another example. Chitin/Chitosan is a white and porous polysaccharide that forms a base for the hard shell of crustaceans like crabs, lobsters and squids. Because Chitin/Chitosan is a built-in part of Crabyon®, its antibacterial function remains, unchanged against prolonged washing or abrasion. Crabyon® prevents the skin from drying out because its moisture-retention property is claimed to be better than any other cellulose fibre. At the same time it has a velvet touch and causes no irritation to the skin which is why it is recommended for use in intimate apparel [33–35].

Antibacterial agents like Triclosan® by Ciba [36], Bioactive by Trevira [37], Bactekiller® by Kanebo [38] and Amicor® by Acordis [39] may be applied as chemical finishes in the last stage of textile production. Grafting is a new technique that involves electron bombardment with charged molecules carrying an antibacterial agent [40] that is achieving good results.

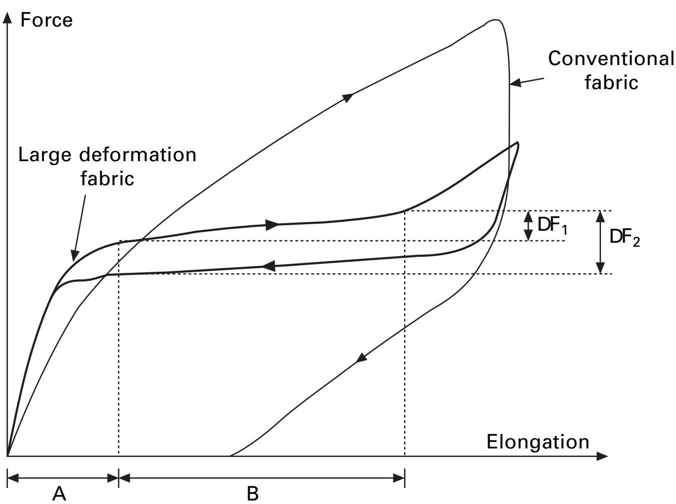
5.7 Considerations of fabric properties in girdle design

According to Zhang *et al*. [41], 82% of 200 women ranked 'fitting' as the most important attribute of a girdle. The fabric has to support contours and give freedom of movement in any direction. For the product development of girdles, consideration of fabric stretch and shrinkage is particularly essential to achieve an acceptable fit with the required functional performance.

5.7.1 Fabric stretch

As intimate apparel is often made from elastic materials, the patterns are made smaller than the body dimensions. When being worn, the material stretches to fit the body. Therefore, the fabric mechanical properties as well as body measurements are crucial parameters for pattern making. Among various mechanical properties, the most apparent property of intimate apparel is its good extensibility at low forces. Large deformation fabric [42] as shown in Fig. 5.7 not only provides a certain tension when stretched to fit the body, but also ensures comfort for body expansion during breathing and after meals. Moreover, it is easy to extend the garment with little force when putting it on or taking it off.

As already mentioned, intimate apparel is often made of knitted fabric and elastic materials. Their stretch ratios can significantly affect the garment fit. In our work, we used an Instron tensile tester in accordance with ASTM D4964-96 method (tension and elongation of elastic fabrics) to measure the



5.7 Force/elongation diagram of large deformation fabric in comparison with conventional fabric.

fabric extensibility. A 350 ¥ 100 mm specimen was sewn to form a loop with a circumference of 250 mm which was extended by applying a tension up to 100 N at a speed of 300 mm/min for three cycles. The extension was recorded for the third cycle. The upper force limit should not be substantially higher than the wearing strain because most of the knitted fabrics are not 100% elastic. Even with the use of elastane yarns, the fabric loses energy and retains some residual extension after the loads are removed. Both length and width directions should be tested because the fabric length contracts when the fabric is being stretched along the width due to displacement of structure and yarn from a relaxed condition to a strained status. These properties should be taken into account in pattern construction of close-fitting knitwear such as intimate apparel.

In the industry, a cruder, simpler method may be used. Designers usually test the stretch of fabric along a ruler manually. They fold the fabric sample widthwise, measure a standard length, say 20 cm, hold the ends and stretch it. The distance that the fabric can be stretched easily is defined as the stretch ratio. For example, if the fabric can be extended to 30 cm easily under a comfortable tension, its stretch ratio along the width is defined as 50%, i.e., the percentage increase from 20 cm to 30 cm. Then the pattern should be made smaller than the body dimension by this amount, so that it fits and allows comfortable movements. As many fabrics have different stretch ratios in the wale and course direction, such tests must be done in both the lengthwise and widthwise directions. The fabric used for the pattern is specified by its specific stretch ratio, so each pattern needs to be adjusted accordingly when a new fabric is used.

5.7.2 Optimization of fabric tension leading to tactile comfort

The requirement for a garment to be 'close-fitting' may be expressed in terms such as body-hugging, forming, etc. In this context, it is necessary to define precisely the pressure acting on the body [43]. Roedel *et al.* [44] suggested that the optimal blood circulation occurred at a pressure range of 15–25 mmHg for the lower arm tube. For men's underwear, Kristein *et al.* [45] found that the strain for optimal wearing comfort was between 1.5 N and 2 N per 5 cm fabric width. This value may also change for different parts or different functions of the garment. Undershirts need less material tension in the upper sleeve to improve freedom of movement, while a sports bra requires firm materials for the bra cups to reduce breast displacement during exercise.

Since the human figure is very complex, the interaction between the garment and the body in terms of force and deformation varies from one place to the other. Yu's preliminary studies [46] aimed at finding the optimum fabric tension for a comfort pressure girdle at three main body parts: waist, abdomen and hip. Women subjects with four different body shapes were invited to adopt three different postures: mannequin, sit and squat. At each posture, the subjects were measured around the waist, abdomen and hip using a tape measure. Two measurements were taken in a single day for each subject. One reading was recorded when the subject had an empty stomach. The other measurement was taken after a meal when the stomach was 'full'. Therefore six measurements were obtained for each body part. The change in extension i was calculated using eqn 5.1.

$$i = \frac{i_2 - i_1}{i_1} \text{ ¥ } 100\% \qquad 5.1$$

where i_1 and i_2 are the minimum and maximum measurements respectively at the particular parts of the body.

The minimum sizes for waist and abdomen were observed in the standing position with an empty stomach. The maximum extension was in the sitting or squatting positions when the stomach was full. The changes in extension percentages at different parts of the body are shown in Table 5.1. The experimental results for the participants showed that the maximum changes in body dimensions were 12.7% at the waist, 8.3% at the abdomen and 11.9% at the hip respectively.

The variation in body positions and postures will clearly affect the fabric extension and deformation. An increase in material extension normally means an increased pressure on the wearer's body. If this pressure value exceeds the threshold value of pressure comfort, sensation of discomfort will occur. This work examined the relationship between the pressure level and the fabric tensile properties in achieving comfort for all these variations.

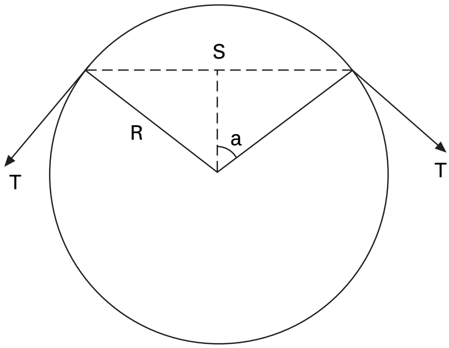
In the wearing test, the subjects were invited to wear five different styles of girdles for pressure evaluation using Flexiforce ELF pressure sensors. A detailed description of the sensor will be given in Chapter 7. The wearer trials were performed both over short periods (15 minutes) and long periods (12 hours). Then the subjects gave a rating from 1 to 7 in a questionnaire relating to pressure comfort. By correlating the measured pressure and the ratings, the tolerable comfort pressure range was found (Table 5.2).

Table 5.1 Change in fabric extension of girdle pants in different body parts

	Average extension level of		
Body type	Waist (%)	Abdomen (%)	Hip (%)
A	5.2	3.9	5.1
B	3.5	4.9	11.9
C	11.6	7.0	4.7
D	12.7	8.3	9.0

Table 5.2 Pressure range of different parts of body

Parts of body	Comfort pressure range (mm/Hg)
Waist	12.2–19.4
Abdomen	4.9–11.8
Hip	10.6–18.2



5.8 Tension model of girdle on a cylindrical surface simulating the human body.

According to the comfort pressure range, the corresponding fabric extension force can be calculated, taking into account the body geometry and curvature. Assuming that the human body is a cylindrical shape [47] covered by a girdle, the top view of a body and the tension applied by the garment is depicted in Fig. 5.8. S is the arc length at an angle 2α, L is the fabric width, R is the radius of the cylinder, P is the pressure exerted on the body and T is the force applied to the fabric. Then,

$$2T \sin \alpha \, L = 2 \int_0^{\alpha} P \cos \theta \, R \, d\theta \, L$$

$$2 T \sin \alpha \, L = 2 P r \sin \alpha \, L \qquad 5.2$$

$$T = PR$$

While the pressure P is given in Table 5.1, the curvature radius R can be obtained based on the breadth and thickness of a human body. We assumed the cross-section of the waist, for example, as an ellipse. Then the long axis b of an ellipse is the body breadth and the short axis a is the thickness. A calculation for one subject is shown in Table 5.3

By substituting the pressure value (Table 5.2) and curve radius (Table 5.3) into eqn 5.1, the desirable tension of fabric for different parts of the girdle was obtained and is shown in Table 5.4 where 1 mmHg = 0.0133231 N/cm^2,

Table 5.3 Calculation of curvature radius

Body position	Breath (cm)	Thickness (cm)	Curvature radius (cm)
Side waist point	12.5	10.0	$R_w = 7.9$
Abdomen centre point	15.7	11.6	$R_a = 21.3$
Hip outermost point	15.8	9.3	$R_h = 5.4$

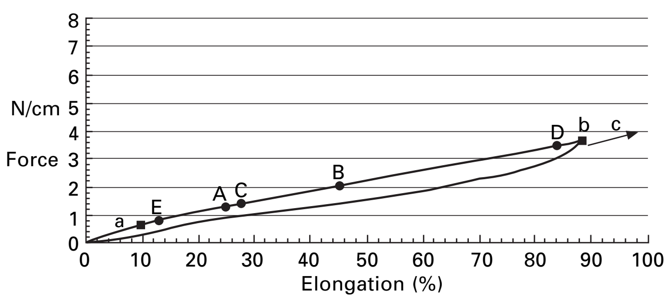
Table 5.4 Desirable fabric tension of girdle pants

Body part	Pressure range (mm/Hg)	Tension range (N/cm)
Waist	12.2–19.4	1.3–2.0
Abdomen	4.9–11.8	1.4–3.4
Hip	10.6–18.2	0.8–1.3

the desirable tension on the waist and $T = PR_w$ = (12.2 ~ 19.4) ¥ 0.0133231 N/cm^2 ¥ 7.9 cm = 1.3 ~ 2.0 N/cm.

To identify the appropriate fabric stretch for the girdle, over thirty commercial knitted elastane fabrics were tested for tensile and recovery properties in the wale and course directions. Among them, Lycra® Soft which has a special characteristic of large deformation, meets the optimum tension range. Figure 5.9 shows the load-elongation curve of Lycra® Soft. It possesses a particularly flat load-elongation part compared to conventional Lycra®. This fulfils the requirements for tight-fit pants because the pressure changes very little over a large deformation and has good elastic recovery.

With reference to Fig. 5.9, when the fabric is subjected to initial loading, the elastic fibre component deforms readily, and the non-elastic fibre (nylon) will change from a relaxed state to straight. At this stage, deformation increases as the force increases. At point a, the non-elastic yarn is already in tensioned state. With the elastomeric yarns interlacing throughout the fabric construction,



5.9 Stress strain curve of Lycra® Soft.

the yarn continues to extend without yarn segment distortion occurring, thereby providing satisfactory extensibility. The deformation increases rapidly with little rise in force from point a to b. After removing the force, the fabric recovers completely with little hysteresis.

Based on the required pressure and tension ranges on the body waist, the range of pressure comfort is within 12.2–19.4 mmHg and the corresponding fabric tensile load is 1.3–2.0 N/cm. This range is between point A and B as indicated in Fig. 5.9 Assuming that i_A is the extension value at point A and i_B is the extension value at point B, the difference in the extension from point A to B is $\Delta i_{waist} = i_B - i_A = 45.2\% - 25.2\% = 20\%$. Since $\Delta i_{waist} > 12.7\%$, which is the maximum extension level measured on the waist as indicated in Table 5.2, the fabric fulfils the requirement for girdle extension at the waist.

Using similar analysis, section CD in Fig. 5.9 conforms to the requirements for the abdomen that needs a pressure range of 4.9–11.8 mm Hg or 1.4–3.4 N/cm and achieves an extension $\Delta i_{abdomen} > 8.3\%$. At the same time, section EA fulfils the criteria for the hip where the pressure ranges from 10.6–18.2 mm Hg or 0.8 N/cm–1.3 N/cm, and the extension Δi_{hip} is over 9%.

5.7.3 Fabric shrinkage

Since intimate apparel is expected to be worn and washed repeatedly, the most significant properties affecting pattern construction are dimensional changes and elongation during wearing and after washing. Based on the AATCC 135-1995 Method (dimensional changes in automatic home laundering of woven and knit fabrics), a full width of 80 cm long specimen is marked with three pairs of benchmarks of 50 cm parallel to the length, and another three pairs parallel to the width direction. It is washed with ballast to make up a load of 1.8 kg at 49 °C under a permanent press cycle and low water level. Then the full load is tumble-dried under a permanent press cycle. The cycle is repeated five times.

The garment patterns should be developed to incorporate the required load for correct fitting. One possible way is to use Kirstein's elongation factors [45] L and Q in different directions as shown in eqns 5.3 and 5.4.

$$L = \frac{1}{1 - e_{l,d} \cdot (1 - e_{l,w}) - e_{l,w}} \text{ along the length direction,} \qquad 5.3$$

and

$$Q = \frac{1}{1 - e_{q,d} \cdot (1 - e_{q,w}) - e_{q,w}} \text{ along the width direction} \qquad 5.4$$

where $e_{l,d}$ is length reduction and $e_{l,w}$ is shrinkage in the length direction; $e_{q,d}$ is elongation and $e_{l,w}$ is shrinkage in the cross direction. Based on the aforementioned factors, the parameters for pattern construction could be calculated from the body measurements. For example, Garment length = (waist length + waist to hip) ¥ *L*

Chest size = (chest girth ÷ 4) ¥ *Q*

Neckhole depth = 3 cm ¥ *L*

Shoulder length = body shoulder ¥ *Q*

Shoulder slope = shoulder length ¥ sin (shoulder angle in degree).

5.8 Conclusion

Most of the research literature has focused on corsets and their fashion implications. However, the technological advances in body shapers such as girdles and their performance have received little publicity. Some major historical innovations and modern technological breakthroughs have been reviewed in this chapter to provide a useful reference to emphasize the importance of fabric properties and body characteristics in the construction of patterns and the selection of materials for making a pressure girdle that is both comfortable to wear and enhances the body figure.

5.9 Acknowledgement

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6

Physical and physiological health effects of intimate apparel

S HO, Y LUO, W YU and J CHUNG

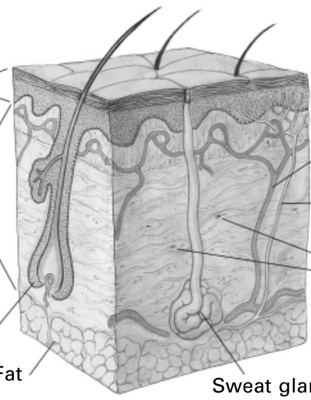
6.1 Introduction

Clothing is depicted as our 'second skin', our most intimate environment [1,2]. Intimate apparel truly creates a bona fide intimate environment for a woman, which has its own climate within the larger climate of our surroundings, and is carried everywhere by the individual [1]. Underwear has increasingly come into vogue. Women wear intimate apparel such as bras, panties, pantyhose and perhaps corsets or girdles every day.

As an example of fashion design, intimate apparel exercises the creative expression of glamour, passion, eroticism, intimacy, exoticism, a sense of luxury and even a sense of humour [3]. As an example of industrial design, it exploits materials, construction and engineering in pursuit of comfort and economical production. In the healthcare sector, the concern is that intimate apparel should provide both health benefits and eliminate health risks for the wearer [4]. This chapter provides a comprehensive review of the beneficial and detrimental effects of intimate apparel on women's health.

6.2 Definition of health

Health encompasses physical, emotional, social, intellectual and spiritual dimensions. As society advances, people have new and ever-changing ideas for the concept of health. Early in the 1940s, the World Health Organization (WHO) defined that health is a state of complete physical, mental and social well-being and not merely the absence of disease and infirmity [5]. In the 1970s, the WHO provided an alternative but more inclusive definition of health. Health is regarded as a resource for everyday life, not the object of living. It is a positive concept emphasizing social and personal resources, as well as physical capacities [6]. Humans should possess not only biological health but also psychological and social well-being [7].



6.1 Human skin structure. (Source: http://www.nigms.nih.gov/news/features/skin.html).

6.3 Skin health

Skin is the largest organ of the human body. It provides a useful barrier that protects the body (Fig. 6.1). Its functions include preventing damage from the external environment, prohibiting pathogens entering into the body, and maintaining body temperature. The multiple sensory nerve endings embedded in the skin are responsible for the sensations of pain and ambient temperature that trigger the responsive mechanisms to external stimuli to prevent further serious damage. Because intimate apparel is worn very close to the skin, it is desirable to wear soft breathable materials with optimal heat and moisture transfer that can provide maximum comfort and protection to the wearer.

6.3.1 Thermal comfort

Breathability is the degree to which a fabric permits air and moisture to pass through it. Heat and moisture can accumulate in the microenvironment inside the intimate apparel of poor breathable fabric [8]. The evaporative properties of the materials influence the level of heat and favourable moisture transfer can lessen the thermal sensation of wetness [9]. Studies have shown that perception of discomfort ratings is significantly associated with increases in skin temperature and sweat rates [10] whereas subjective perception of comfort in clothing is related to thermal comfort. Wearing intimate apparel made from poor-heat-transfer material causes discomfort, with an increase in the subjective sensation of warmth and sweating which might induce a deterioration in the wearer's performance [11]. Studies have found that thermal stress can influence mental performance [12,13,14,15,16], cognitive performance [12,15], and limit ability in physical work performance.

6.3.2 Skin infection

Non-breathable underwear with poor vapour permeability can cause various bacterial or fungal infections of vulvar skin. The skin climate can be impaired by a poor-vapour-permeability fabric which leads to altered temperature, humidity and pH, that become a favourable environment for promoting the growth of skin microflora [17]. The vulvar skin is more vulnerable for microbial risks compared to other normal skin because of the high density of vaginal flora [18,19], and its vicinity to vaginal, urethral and rectal orifices. Although there is scant literature on the microbiology of vulvar sites, it is known that the normal vaginal flora changes dynamically with the different stages of the menstrual cycle [20].

A recent study compared the impact of vapour-permeable versus vapour-impermeable panty liners on skin climate and skin microflora in 102 healthy caucasian women with regular menstruation [17]. Women who had used antibiotics and vaginal medication in the previous four weeks, or had current abnormal discharges, bleeding, itching or irritation in the vulvar area were excluded. Factors such as genital hygiene habits, use of contraceptives and hygiene products, past yeast infections and skin diseases were controlled in this study. The results showed that the skin temperature, pH and total number of microorganisms were significantly lower for those who were using vapour-permeable materials than those wearing vapour-impermeable ones ($p < 0.05$, $p < 0.001$, and $p < 0.001$ respectively).

The cause of vulvar infections related to vapour-impermeable underwear is likely to be the elevated pH in the microenvironment, which is probably due to the increase in skin surface humidity [17]. Numerous studies have reported similar effects of pH and occlusion-caused humidity on skin microflora and skin reactions [21,22,23,24,25]. Also, while prolonged occlusion of forearm skin has increased the skin pH and bacterial growth [22], a drying process of vulvar skin has led to a reduced vulvar pH [26]. On the other hand, the effects of breathable materials on skin have also been examined [21,17,27]. Vapour-permeable materials are able to reduce over-hydration of skin [27] and the occurrence of Candida infection and dermatitis [21]. However, tight-fitting underwear does not seem to affect the vulvar skin microclimate (including the skin surface temperature, humidity, and pH, and aerobic microflora) measured at the labium majoris and perineum [28].

6.3.3 Irritation and allergy

Contact dermatitis or eczema is an inflammation of the skin that can be caused by direct contact with many substances, particularly for those who have sensitive skin or a history of any type of allergies. Wearing intimate apparel with irritating or allergic substances can precipitate skin reactions.

Skin inflammation varies from mild irritation and redness to open sores, depending on the type of irritant, the body part affected, and the sensitivity of the individual. Other symptoms include itching (pruritis), skin redness or inflammation (localized swelling and warmth), tenderness, and skin rash or lesions in the exposed area. Contact dermatitis usually clears up within two or three weeks after avoiding contact with known allergens. The most common type of contact dermatitis is caused by exposure to a material to which the person has become hypersensitive or allergic. Literature has shown that latex allergy problems are not only confined to rubber gloves, but also to articles of clothing [29]. Other allergens to skin include fabrics such as laces, nickel [30] or some metallic buttons. Intimate apparel should be designed in such a way that the laces or buttons do not directly contact the skin.

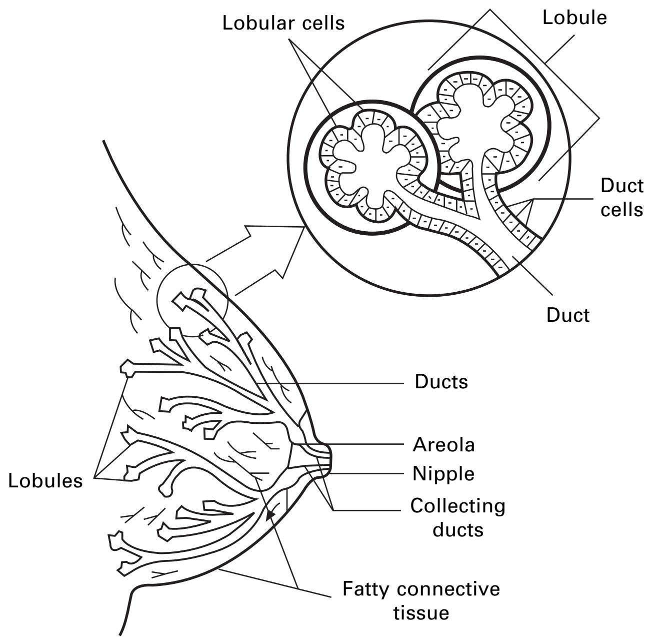
6.4 Physical support from intimate apparel

6.4.1 Breast anatomy

The development of female breasts starts as early as the first few weeks of embryonic life, and throughout early childhood, during which the blood supply, nipples, and milk ducts start to form [31,32]. The major development of female breasts occurs at puberty. Female adult breasts are situated on the chest wall within the superficial fascia, between the deep layer of the fascia (posterior boundary) and the superficial portion of the fascia (anterior boundary). Women's breasts lie over the surface of the anterior major muscles covering the area from the second rib to the sixth intercostal cartilage. In the horizontal plane, the breast covers the area between the mid-axillary line and the sternum.

The size and shape of female breasts vary. The differences in size are attributed to the amount of adipose tissue in the breast. Generally, breasts measure 10–12 cm in diameter and 5–7 cm in central thickness. The weight of an adult female breast is approximately 200 g. The size and weight of the breast increases during pregnancy and lactation, weighing between 400–600 g and between 600–800 g respectively [31]. Often, the left breast is slightly larger than the right breast. The reason for this bilateral asymmetry in breast size is not fully understood, however, fluctuating asymmetry is suspected to have health implications [33]. In general, breast cancer is more common in the left breast, possibly because the breast is usually slightly larger [34].

The major structural component of female breasts is the skin, the subcutaneous tissue and the mammary glands. The female breast (Fig. 6.2) is made up mainly of lobules (mammary glands), ducts (milk passages connecting the lobules to the nipple) and stroma. The stroma includes fatty tissue, connective tissue surrounding the ducts and lobules, blood vessels, and lymphatic vessels. The connective or fibrous tissue in the breast usually refers to the Cooper's ligaments. These ligaments are thin sheets of fibrous



6.2 Major structures of female breast. Source: http://www.nlm.nih.gov/medlineplus/ency/imagepages/1075.htm.

bands but their mechanical properties have not been reported [35]. These ligaments are easily stretched by repeated loading during physical activity which may lead to breast sagging.

6.4.2 Breast hypertrophy and associated health problems

Nowadays, breasts are getting bigger as reflected by the USA and UK bra manufacturers who are producing larger bust sizes, especially for the teenage market. In Britain, the most commonly purchased bra size has increased from 34B to 36C during the past ten years. In 2001, 27% of British women bought a D cup or larger [36]. Ill-fitting bras may cause breast hypertrophy [37]. Common symptoms of breast hypertrophy are mastalgia or mastodynia (breast pain or tenderness), headache, pain symptoms in the neck, shoulders, upper and lower back regions, intertrigo (an inflammation of the skin under the breasts caused by moisture, bacteria, or fungi), bra strap grooving, and numbness and tingling of fingers [38,39,40,41]. Psychosocial effects include difficulty in exercising and finding suitable size clothing, extreme embarrassment in public and social settings, and poor self image due to excessive bust size [42].

Women with breast hypertrophy report varying pain symptoms all or most of the time [43]. The pain symptoms may affect the level of functions and quality of life, and heightened dissatisfaction with body image will drive women to pursue reduction mammaplasty [42,43,44]. Currently, most of those women who seek medical attention and undergo breast reduction surgery for pain relief are middle-aged and overweight or obese. Younger women tend to have the operation for psychological or cosmetic reasons. Although reduction mammaplasty has one of the highest patient satisfaction rates of all plastic and reconstructive surgery [42] and improves the preoperative pain symptoms substantially by 80–100%, [40,43] ongoing research continues to investigate whether conservative measures can be applied for symptomatic relief. Correctly fitted bras may improve anatomical, physiological and psychological parameters.

A group of surgeons and specialists in the UK suspected that women seeking reduction mammaplasty often wear ill-fitting bras, which may exacerbate some of their symptoms. Normal breast size is bra cup size A, B or C. Women with breast hypertrophy wear bra cup size D or larger. They conducted a study to investigate the suitability of bra fit in women referred for reduction mammaplasty [37]. Women were recruited from a pre-assessment clinic and asked their current bra size. Their back (underband circumference) and cup (overbusts) sizes were measured to see whether their bra size was correct. Bra manufacturers, designers and shop bra fitters were also interviewed about bra manufacture, sizing and fitting techniques.

Of 102 women aged between 18 to 64 years interviewed, almost all claimed to have their bra fittings professionally measured and fitted. The mean 'claimed' back size of the bras was 91 cm (range 76–106 cm) and the mean 'claimed' cup size was F (range C–J). These 'claimed' sizes and the subjects' measurements were then compared with sizing charts used by the major manufacturers in the UK, Europe, and North America. The results showed that not a single one of these women was wearing the correct size of bra as recommended by the manufacturers.

The mean shortfall in back size was 10 cm (range 5–25 cm) and the mean overestimate of cup size was three sizes (range: one size smaller to seven sizes larger) i.e., most women wore undersized backs and oversized cups. The data was comparable with those of the general population of the same age range using anthropometric data sources [37]. The mean ± SD underband circumference in the British general population is 85.5 cm ± 7.3 cm, and in the American population is 88.7 ± 12.6 cm. The mean ± SD British overbust is 100.8 cm ± 11.3, and the American is 104.7 cm ± 19.6. As expected in a subpopulation seeking breast reduction, these women had larger overbusts (108.9 cm ± 8.6 cm) than the general population.

6.4.3 Prevention of breast sagging

Wearing appropriate external support has been suggested to prevent stretching of the Cooper's ligaments and the skin during activity, thereby reducing the risk of breast sagging. Ashizawa *et al.* [45] conducted a longitudinal study in Japan to examine breast shape changes after wearing bras. Eleven adult females, aged 22–39 years, were asked to wear a bra for three months, and then not wear one for another four months. Breast form changes were monitored by weekly anthropometry measurement and moiré fringe photographs. Women with pendant breasts showed the greatest degree of breast form change when wearing the bra. After wearing the bra, all the subjects had a smaller underbust measurement, but a larger overbust measurement. The distance between the two nipples became wider, and sagging of the breasts was more marked in obese women with pendant breasts. However, there is limited literature to underpin these findings.

In fact, little scientific research has been conducted to support the view that wearing bras prevents breast ptosis. So, does wearing a bra actually cause breast sagging or does the bra prevent it? Although some research has shown that weight-bearing and movement is necessary to the maintenance of healthy ligaments [46,47,48,49], none of these studies investigated the breast ligaments. More research is needed to understand the mechanical properties of the breast tissues and ligaments that offer anatomical support.

6.4.4 Reduction of breast movement

Due to the lack of intrinsic anatomical support in the breast structure and the movement that it allows, female breasts require some form of external support. Exercising females may benefit from wearing an appropriate sports bra during exercise and sports activities. However, the effectiveness of different bra types on controlling breast motion in females with varying breast sizes who exercise has not be confirmed by any comprehensive research [35].

Excessive breast motion during exercise may cause breast pain, and often leads to embarrassment when participating in exercise [35]. Wearing a good supportive bra during exercise and physical activity may limit breast momentum by limiting the boundaries through which the breast can move. Mason *et al.* [50] compared breast movement and the resulting pain in four conditions of breast support (sports bra, fashion bra, crop top and bare breasted). The fitted sports bra provided superior support for the breasts in relation to the amplitude of movement, deceleration forces on the breasts, and perceived pain reduction. While most sports bras are designed to limit breast motion, there is a range of sports bras specifically designed to prevent trauma to the breasts during certain sports (for example, netball) [51]. These sports bras protect the breasts with extra padding in the cups.

6.4.5 Relief of breast pain

Although there are several measures to relieve breast pain, such as weight reduction, regular exercise, caffeine intake reduction, and a variety of pharmacological treatments, wearing a well-fitting bra is a useful option to manage mastalgia [52]. Mastalgia is a common symptom experienced by women of reproductive age. A painful breast is one of the most common symptoms for which women seek medical advice [53]. Ader and Shriver [54] reported that 30% of premenstrual women suffered from cyclical mastalgia lasting for more than five days a month. The pain can be so severe that it interferes with physical, social, work-related and sexual activities.

Hadi [55] conducted a prospective study in 200 women with mastalgia from an outpatient surgical department. One hundred women were assigned to a treatment group while the other 100 were asked to wear sports bras for 12 weeks during their regular daily activities. Both groups were requested to answer structured questionnaires at a specified time on a daily basis; 58% of the women who took danazole enjoyed pain relief but symptoms recurred after the treatment ceased. Furthermore, 42% of the women discontinued the drug because of side effects which include nausea, vomiting, and dizziness. Hadi [55] reported that 85% of the women wearing sports bra enjoyed pain relief despite an initial period of discomfort. These women also experienced comfort during daily activities and a remarkable improvement in their quality of life.

6.4.6 Respiratory health

While sports bras are effective in reducing breast motions and related breast pain, some women perceive them to be too tight and may impede their performance during physical activity. Bowles *et al.* [56] conducted a study to determine whether wearing a sports bra impedes respiratory function at rest and during physical activity. In the study, 22 women participated in standard resting spirometry manoeuvres without wearing a bra, then all women were asked to complete maximal cycle ergometer tests while wearing and not wearing sports bras. Finally, standard spirometry, bra pressure and comfort were measured in all women during treadmill exercise tests under three breast support conditions (sports bra, no bra, and fashion bra).

Significantly more pressure was exerted by sports bras on smaller-breasted women, however, lung volumes and comfort scores were not influenced by this pressure increase. No significant difference was found in the lung volume measurement under the no-bra and bra conditions. Bowles *et al.* [56] concluded that the sports bras did not significantly restrict exercise performance or respiratory mechanics in these women.

6.4.7 Support for breast prosthesis

A surgical recovery bra has recently been developed as described in US Patent 6,390,885 [57]. The new invention is claimed to accommodate postoperative lymphatic drainage tubes (minimizing the tubing outside the garment), store fluid collection bulbs under the breast, and provide breast surgery patients with the ability to don a prosthetic bra. The garment can be worn immediately after breast surgery, particularly mastectomy.

6.4.8 Compression stockings to prevent varicose veins

The varices of the lower limbs and its complications are very common and are usually treated by surgery. Compression stockings are useful in preventing secondary bleeding and above all, the development or recurrence of thrombosis. Patients wearing compression stockings following surgery have no signs of venous insufficiency for a long period of time [58].

6.4.9 Maternity support garment to relieve low back pain

Pregnancy is a joyful, but often painful experience. It is estimated that between 50% and 80% of women experience some form of back pain during their pregnancy which contributes to impaired functions [59]. Pain symptoms can range from mild pain (45%), to very serious (25%), and some (8%) are severely disabled because of pain. There are four main types of commercially available maternity support garments: panties or briefs, belts or girdles, cradles and torso supports, that have been widely used to prevent and treat low back pain. However, scientific evidence is lacking to support the design principles and efficacy of maternity garments.

Further research conducted by Yu *et al.* [60] aimed to develop scientific principles for the design of a therapeutic maternity garment with respect to sensory comfort and aesthetics and to evaluate, through a clinical trial, the effectiveness of a maternity garment protocol in relieving low back pain. A multidisciplinary team of researchers is involved studying the mother's anthropometry and biomechanics, psychology, subjective comfort sensation, pain perception and pregnancy outcome. Novel garment designs, through multidisciplinary research, have promising future potential in promoting health and well-being.

6.5 Physiological effects of constrictive intimate apparel

While intimate apparel functions well to protect human skin and support body weight, critical medical concerns of constrictiveness of bras and corsets have been voiced [61]. The use of the corset has long been thought of as having adverse effects on health. Williams published a paper to report injurious pressure exerted by corsets on the female body over the abdominal viscera, the lower ribs, and the skeleton. The effects asserted included interference with digestion and assimilation, compression to the base of the thorax leading to abnormal and insufficient respiration and spinal deformity [62]. Some corsetry has been claimed to cause abdominal discomfort, fainting, and a pale complexion. There was evidence that 16th-century corsets caused permanently overlapped ribs [63]. Despite many years of improved designs, there are still a number of physiological effects that constrictive intimate apparel may cause.

6.5.1 Shoulder pain

Compression from tight, narrow bra straps is a common cause of neck, shoulder, and arm pain in obese, heavy-breasted, middle-aged or elderly women [64]. Pectoral girdle myalgia, or shoulder pain, may result from breast weight carried at the shoulders through bra straps. The deep grooves in the acromion region under the bra straps in some women suggested that breast weight could cause long-term dragging on the elevators of the scapula. Some women may have permanent grooves developed in their shoulders [41]. The direct compression may lead to impairment of nerves going down the arms to the hands resulting in paresthesias [64]. Symptoms of paresthesias include abnormal sensations, often described as numbness, prickling, or tingling, usually felt along the fingers.

In a five year study, Ryan [65] studied women workers and nonworkers to determine whether breast drag on the shoulder or pectoral girdle muscles of women contributes to pectoral pain. The women were asked to remove breast weight from the shoulders for a two-week trial by choosing to wear either a strapless bra or go braless. All except one woman chose bra removal. The sites of pain and tenderness, and breast weight were documented. Long-term outcome was the presence or absence of muscle pain and tenderness. 79% of patients found pain relief after removal of breast weight from the shoulder. Other simple treatment measures include the use of a shoulder pad [64].

6.5.2 Defecation

Lee *et al.* [66] investigated the effects of skin pressure of a body compensatory bra on defecation. Seven healthy females (11–41 yrs) volunteered as participants. The study lasted for three weeks, in which the participants wore the bra while awake during the second week, and did not wear it during the first and third week. All participants followed a scheduled diet and meal time, a specified time to rise and retire, a work schedule and intensity. The amount of faeces was significantly smaller (less weight) during the week when they wore the bra. It was suggested that it may be due to the suppression of the parasympathetic nervous system and intestine motility and the delayed transit time in the large intestine.

6.5.3 Increased body temperature

Skin pressure can suppress central thermoregulatory activity and contribute to a rise or fall in body temperature in a hot or cool environment respectively. Pressure on the body surface can inhibit sweating in that body area. Ogawa *et al.* [67] examined the effect of skin pressure on the bilateral subaxillary regions. Body heat balance was monitored by continuous recordings of total sweat rate and local sweat rates in various areas. Skin and rectal temperatures, and measurements of metabolic rate were also assessed. A range of pressure was applied up to 5 kg/50 cm^2. It was reported that women wearing foundation garments had rectal temperatures that were significantly higher throughout the day and night when wearing foundation garments [68,69].

6.5.4 Depressed sweating

There was a tendency that the stronger the pressure, the more depressed was the total sweating. On the other hand, a weaker pressure facilitated total sweating. The changes in skin and rectal temperatures and metabolic rate measurements were minimal. Ogawa *et al.* concluded that skin pressure up to 5 kg/50 cm^2 does not affect central body temperature regulation, but it may exert a sweat-inhibitory effect. Elevated breast temperature associated with wearing heavier bra material has been linked to the occurrence of breast cancer [70,71]. However, there is a paucity of literature relating the temperature factor to breast cancer risk.

6.5.5 Suppression of salivary melatonin

A group of researchers in Japan [68] investigated the effects of skin pressure exerted by foundation garments (bra plus girdle) on the circadian rhythms of salivary melatonin. Before the experiment, ten healthy females aged between 18 to 23 years were asked to maintain regular sleep-wake cycles for one week. During the three-day experiment, the women wore the foundation garments according to the time schedule in a light, temperature and humidity controlled chamber. Skin pressure applied by the foundation garments was in the range 11–17 gf/cm^2 at the regions of chest, abdomen, hip, and back. The results showed that wearing a foundation garment could markedly suppress the nocturnal levels of the hormone melatonin by 60%. However, evidence of this link is limited and has yet to be confirmed [72].

6.5.6 Risk of breast cancer

Hsieh and Trichopoulos [34] conducted a large sample study to examine the possible risk factors for breast cancer. The relationship between bra cup size and breast cancer risk was also examined. Pre-menopausal women who did not wear bras had half the risk of breast cancer compared with bra users, but possibly this was because these women were thinner and had smaller breasts. Among bra users, larger cup size was associated with an increased risk of breast cancer. However, this association was found only among postmenopausal women and was largely accounted for by obesity. Furthermore, numerous studies have shown evidence that bra cup size is not related to breast cancer risk [73,74,75,76]. Although internet e-mail rumours and the book, *Dressed to Kill: The Link between Breast Cancer and Bras* [77] have reported that bra wearing may be a major risk factor associated with breast cancer, there is no credible scientific research or clinical basis to validate that claim [78].

6.5.7 Vaginal and urinary tract infections

Several gynaecologists have anecdotally reported an increasing number of women with recurrent urinary tract and vaginal infections who regularly wear thongs [4]. Rabin explained that the thong is like a little subway car that carries the bacteria from the rectum to the vagina and to the bladder, in those who are more susceptible to infection. However, other gynaecologists do not agree with the observation and have reported that thong underwear has improved their patients' hygiene and body awareness. To date, no scientific studies have been conducted to link thong underwear with infections.

6.5.8 Lengthened digestion time of food

Sone *et al.* [79] examined the absorption of dietary carbohydrate and oroecal transit time of food in the gastrointestinal tract in women wearing tight-fitting and loose-fitting girdles. Seven healthy young women wore loosely fitted girdles then tight-fitted girdles on the next day. The pressure applied on the waist, abdomen and hip region was 15.5 ± 0.4 mmHg (mean ± SE). Breath samples were taken to measure the absorption of dietary carbohydrate in the small intestine. Significantly higher breath hydrogen excretion was noted in the tight-fitted garment condition. However, the transit time of the test meal was not significantly different in the two conditions. The findings showed that a tight-fitted girdle had an inhibitory effect on the digestion of carbohydrate, but no effect on the orocecal transit time of food.

Okura *et al.* [80] studied the effect of skin pressure around the abdomen, thighs and legs (similar to wearing pantyhose) on resting salivary rate and the digestive function of saliva. Nine healthy female students, aged between

18 to 33 years, sat in a reclining chair throughout the experiment in a room with controlled temperature and humidity. The study was conducted in three sessions: ‘no pressure’, ‘pressure’ and then ‘no pressure’. While the subjects rested for 90 and 45 minutes respectively in the first and third sessions of ‘no pressure’ periods, during the ‘pressure’ period, the subjects had pressure applied by inflatable cuffs on the abdomen (40 mmHg) and thighs (40 mmHg), then to the legs (60 mmHg). The resting salivary flow rate was significantly suppressed during the ‘pressure’ period. The digestive time for starch was longer with skin pressure measured using the iodine starch reaction. The findings suggested that the pressure applied on the body can influence the digestive response by decreasing the amount of saliva released, stimulated via the autonomic nervous system.

6.5.9 Influenced stress hormones

Noradrenaline (norepinephrine), often referred to as one of the ‘stress hormones’ that normally causes an increased heart rate, increased blood pressure, dilation of pupils, dilation of air passages in the lungs, vasoconstriction (narrowing of blood vessels) in non-essential organs and strengthens the force of the heart’s contraction. Lee *et al*. [69] studied the effects of skin pressure by wearing foundation garments (bra plus girdle) whilst awake on the circadian rhythms of urinary noradrenaline. The urinary noradrenaline level was lowered whilst wearing foundation garments throughout the day and night. Wearing foundation garments during wakefulness and sleep was suggested to influence the noradrenaline secretion.

Sugimoto [81] found that urinary norepinephrine was increased by wearing a girdle regardless of the type or the pressure of girdle. A girdle with a larger area of body compression resulted in a greater increase in urinary norepinephrine than a narrow area of compression. The urinary epinephrine level did not change when wearing a girdle. The results indicated that the girdles had a stimulating effect on urinary norepinephrine, suggesting some level of stress on the body [81]. The findings showed inconsistent results in the effect of girdles on urinary stress hormone, therefore future research is needed to establish the effect of wearing girdles.

6.5.10 Disturbance to menstrual cycle

Investigations have indicated that the skin pressure exerted by foundation garments worn daily could disturb the duration of the wearer’s menses from 30 to 45 days [82]. As yet, the garment pressure effects on the women’s menstrual cycle period, duration, ovulation, other menstruation related symptoms and the mechanisms that influence them are not well known. There are a great number of factors that may cause menstrual cycle disorder.

Potential factors include low body weight, rapid weight loss, sudden onset of vigorous exercise, nutritional deprivation, disordered eating and energy imbalance, as well as psychological and physical stress.

Yu[81] has been developing a protocol to monitor these confounding factors in a study into the effects of foundation garment pressure on women's menstrual cycle. The project aims to explore the effects of foundation garment pressure on the irregularity of the wearer's menstrual cycle, the ovulation day, the duration of menstruation and the other menstruation-related symptoms. The subjects are single healthy women in Hong Kong. The whole experiment is conducted in a controlled environment to maintain a consistent mood, food, body weight and life style. All the subjects are required to maintain regular meal, body weight, mood situation and sleep-awake cycles during the whole experimental period. The garment specimens are tailor-made to fit individual subjects with pre-determined pressure.

The subjects are required to collect their urine samples as soon as they wake. For urine samples, a quantitative method, the enzyme-linked-immomo-sorbent-assay (Elisa), is used to measure the change in hormonal level. By determining different hormonal changes, the irregularities of women's menstrual cycle and the menstrual-cycle-related symptoms are analyzed. So far, the experimental results have revealed that the garment pressure disturbed the regularities of the wearers' menstrual cycle after wearing the tight-fitting foundation garments for a few months. It changed the duration of any wearers' menstruation as well as the amount of the menstruation. On the other hand, some subjects reported that the degree of their cramp pain was lightened and some changes on their leucorrhea have been observed. The research findings are expected to have a large impact by alerting women to the health concerns associated with their choice of fashionable foundation garments.

6.6 Future developments in health-promoting intimate apparel

With the use of different technologies, garments are increasingly being designed to meet specific needs such as personal protection, safety, leisure or health. Wearable health systems are products created and developed based not only on design, fashion, and comfort concepts, but also in terms of unique health monitoring functions. Market research related to biophysical monitoring utilizing smart fabrics or interactive textiles shows an increasing level of commercial activity.[83] Medical applications focusing on the aged, infant and critical patient care are taking the lead. For example, a 3-D bra cup geometry, a new technology, integrated and co-optimized with fluorescence tomography imaging techniques has been developed.[84] This new breast-imaging device has the potential to detect breast cancer, monitor tumour-targeting, deep tissue photodynamic therapies, by providing information about the biochemical environment of breast tissues. Before you know it, the next time you buy a new sports bra, it might have a cardiac-monitor cleverly ingrained inside the bra cup to tell you to slow down because you are reaching your maximum optimal heart rate!

6.7 Acknowledgement

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7 Pressure evaluation of body shapers

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7.1 Introduction

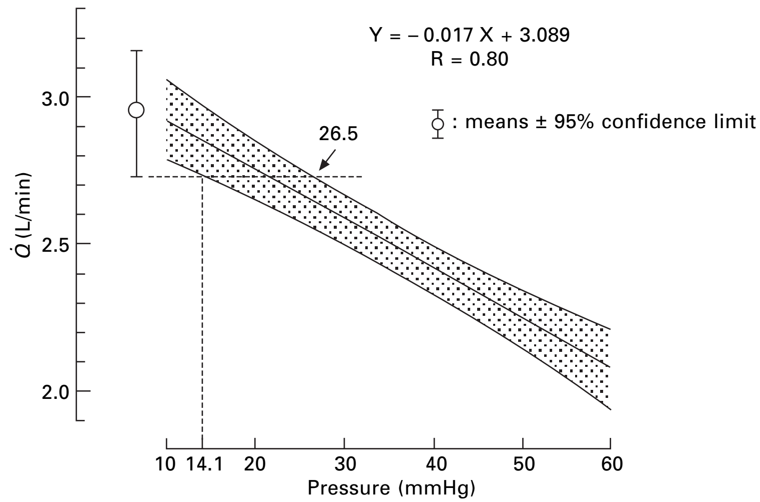
Most body shapers are designed to beautify the figure of a woman by compression on different body parts to the required shapes. The shapers comprise elasticated panels that apply pressure onto the skin. Excessive clothing pressure has been regarded as a problem not only from the view of sensory comfort but also in terms of the detrimental physiological effects caused by the oppressiveness. Therefore, the evaluation of clothing pressure using direct or indirect methods is important to investigate the functional performance and effects of body shapers. In this chapter, the physiological effects of clothing pressure, different pressure-sensing methods and the confounding factors affecting girdle pressure absorption are reviewed.

7.2 Physiological effects resulting from clothing pressure

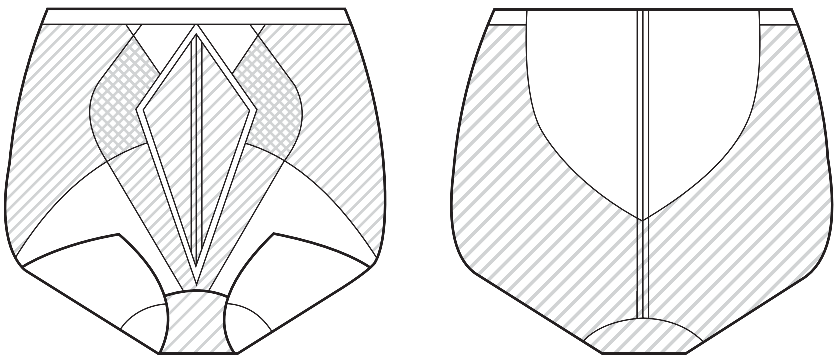
Preventive measures against blood flow disturbance induced by clothing pressure are essential for the design of a healthy and comfortable body shaper. Studies concerning the effect of clothing pressure on cardiac output, cardiovascular response and capillary blood flow are summarized in the following sections.

7.2.1 Cardiac output and cardiovascular response

The influence of clothing pressure on a wearer's cardiac output can be investigated by measuring the amount of blood pumped from the ventricles in a given period of time. Watanuki [1] found that the cardiac output of girdle wearers was significantly decreased whilst in the supine and sitting positions, and clothing pressure was the highest at the groin. Therefore, the relationship between the pressure applied to the groin and the cardiac output was further investigated. The relationship between girdle pressure and cardiac output



7.1 The relationship between girdle pressure and cardiac output. Source: Watanuki [1].



7.2 Three layers of girdles. Source: Nagayama *et al.* [2].

($\dot{Q}$) is shown in Fig. 7.1. It can be observed that the cardiac output decreased linearly with an increase in pressure, and the estimated minimum pressure level leading to some adverse effects on blood circulation was determined to be 14.1 mmHg with an upper confidence limit of pressure of 26.5 mmHg.

Nagayama *et al.* [2] also investigated the effect of a firm-control girdle (Fig. 7.2) in a standing position on the wearer's cardiovascular function in eleven non-smoking female subjects, who had no cardiovascular disease. The entire experiment was divided into four sessions. For the first session (control), all subjects were tested without wearing the girdle. The second (G1) and third (G2) sessions required them to wear one and two girdles respectively having removed all girdles worn in the previous session (recovery).

Table 7.1 Heart rate variability and blood pressure values during steady state of each session for five minutes. Source: Nagayama *et al.* [2]

Variables	Control		G1		G2		Recovery	
RRI (msec)	741.1	(93.7)	776.7	(100.1)**	804.7	(102.9)**	743.1	(103.6)**
SD of RRI (msec)	34.1	(11.9)	40.5	(14.2)**	45.5	(15.1)**	36.3	(11.1)**
HR (beats/min)	82.5	(11.3)	78.7	(10.9)**	75.9	(10.1)**	82.5	(12.2)**
SBP (mmHg)	104.7	(8.8)	107.7	(9.2)*	111.7	(12.9)*	105.9	(13.5)**
DBP (mmHg)	71.3	(6.0)	70.4	(6.6)	71.0	(6.7)	69.0	(7.4)*
MBP (mmHg)	82.4	(6.2)	82.8	(6.6)	84.5	(7.8)*	81.3	(8.8)**

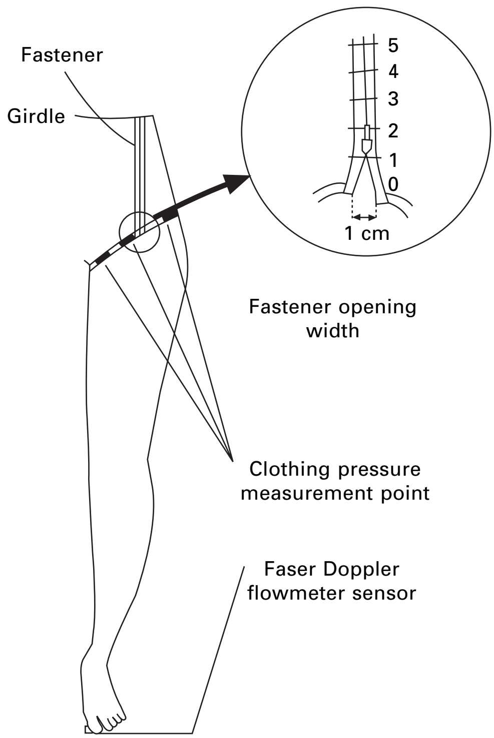
Remarks: RR: respiratory rate, RRI: RR interval, HR: heart rate, SBP, DBP & MBP: systolic, diastolic and mean blood pressure respectively ** and *: significantly different from before session at $p < 0.01$ and $p < 0.05$ respectively.

Their heart rate variability was measured by using the power spectral analysis (maximum entropy method) and the results are shown in Table 7.1. The mean values are shown with their standard deviations in parentheses. The study showed that the systolic blood pressure was significantly higher and the heart rate was significantly decreased when wearing the girdles. The authors also suggested that wearing girdles produced cardiovascular responses accompanied by a change in the balance of sympathetic (SNS) and parasympathetic (PNS) nervous activity, presumably due to a shift of the body fluid.

7.2.2 Capillary and arteriolar blood flow

Tanaka *et al.* [3] investigated the effect of clothing pressure on the change in skin blood flow. In their experiments, three healthy subjects aged between 18 and 22 years old were asked to wear girdles with adjustable fasteners as shown in Fig. 7.3. The clothing pressure measurement points were underneath the cuff at the groin. By adjusting the fastener opening width the clothing pressure exerted on the wearer was varied accordingly. The effect of fastener opening width on mean values of clothing pressure and change in skin blood flow is shown in Fig. 7.4. The results showed that the skin blood flow increased when the clothing pressure was within the range of 20.4~34.0 gf/cm^2. If the clothing pressure attained a value of 54.4 gf/cm^2, high-frequency cardiovascular responses occurred and the blood flow in the toe increased.

Nakahashi *et al.* examined the influence of skin blood flow on a compressed region of the lower leg as depicted in Fig. 7.5 [4]. The skin blood flow tended to decrease with increasing pressure and such a decrease depended on the area of the compressed region on the lower leg. The larger the compressed region, the greater was the pressure and hence the greater was the decrease in the skin blood flow that would be caused. When the compressed region on the lower leg covered about 65% of the lower leg, the decrease in the skin



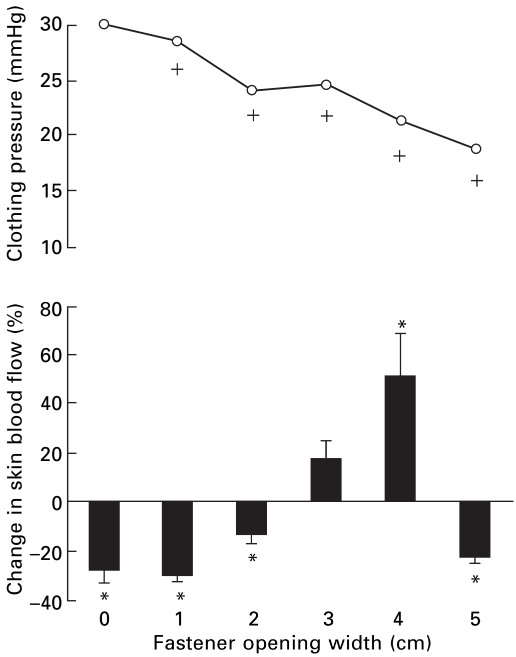
7.3 Processed girdle and physiological measurements. Source: Tanaka *et al.* [3].

blood flow was negligible. However, when the compressed region was about 70 to 80% of the lower leg, the blood flow tended to decrease rapidly with increasing pressure.

7.3 Studies using direct pressure sensing systems

Clothing pressure is measured by either direct or indirect sensing methods. In direct sensing methods, the clothing pressure is measured directly using sensors or gauges while the clothing pressure is derived from measurements of independent variables, such as curvature, fabric tension, body weight, etc., in indirect sensing methods. Indirect methods are favored in some circumstances as they are inexpensive and require no additional hardware. On the other hand, according to previous research results, a shortcoming of this kind of method is the inability to measure accurately the pressure at the concerned region. Therefore, the indirect method is considered to be less effective than, and not as, reliable as the direct method.

Different direct pressure-sensing devices including electrical pressure transducers, hydrostatic pressure sensing methods and pneumatic pressure



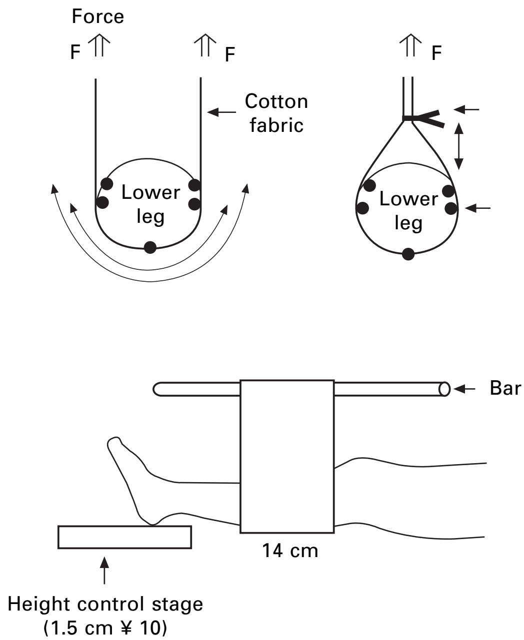
I: standard error of means after the clothing pressure period for five minutes.
* : significantly different from the corresponding value of pre-pressure period at $p < 0.05$
+ : significantly different from the value at 0 cm fastener opening width at $p < 0.05$

7.4 The effect of fastener opening width on clothing pressure and change in skin blood flow. Source: Tanaka *et al.* [3].

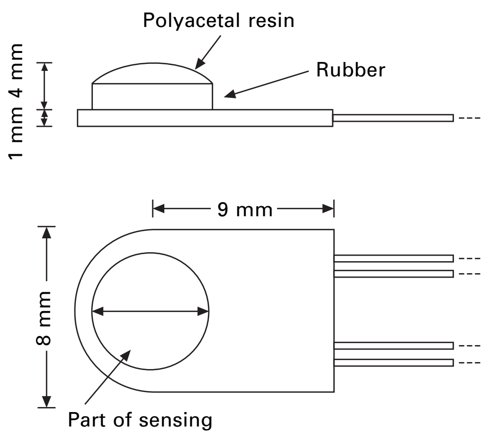
sensing methods are described in the subsequent subsections whereas the indirect methods are described in section 7.4. Some of the methods described relate to the clothing pressure on the wearer's skin whereas others relate to more general pressure measurement applications.

7.3.1 Electrical pressure transducers

In a study by Shimizu *et al.* [5], semiconductor pressure sensors were used to measure the distributions of the clothing pressures on the knee and hip in slacks when performing repeated actions. The sensors used in the experiment were very small and they were multi-sited on given parts of the body. As shown in Fig. 7.6, the diameter and thickness of sensing devices were only 6 mm and 1 mm respectively. When the sensing part experiences uniaxial stress, the electrical resistivity is changed accordingly and the signal will



7.5 Compression method on lower leg. Source: Nakahashi *et al.* [4].



7.6 Dynamic pressure sensor. Source: Shimizu *et al.* [5].

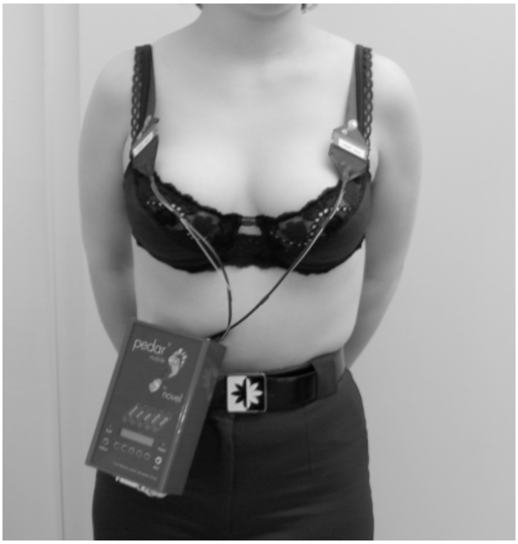
then be transferred to the pressure-sensing system. In order to increase the evenness of garment pressure that was detected by the sensor, the sensor was coated with a layer of polyacetal resin to soften the surface of the sensor and reshape it to follow the body curvature. Based on the results from calibration, the sensor had high sensitivity and repeatability. The sensor could detect pressure below 2 kg/cm^2, therefore it was suitable to measure small values of garment pressure. Their findings showed that the clothing pressures at different locations varied greatly and attained their peak values during motion. When the motion ended, the clothing pressure dropped back to a constant value at the static state. The clothing pressure on the knee was much greater than that on the hip. This was attributed to the dependence of the pressures on the degree of skin stretching during motion and its local curvature.

Flexiforce [6], a commercially available sensing system for garment pressure measurement, combines Tekscan's FlexiForce® single element force sensors with advanced electronics to produce a simple force measurement system. The FlexiForce sensor is an ultra-thin (0.008 inch) flexible printed circuit which is able to detect a relative change in force or applied load and measure the contact pressure. The force sensors are constructed of two layers of substrate polyester/polyamide film. On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. Adhesive is then used to laminate the two layers of substrate together to form the force sensor. The active sensing area is defined by the silver circle on top of the pressure-sensitive ink.

The FlexiForce sensor acts as a force-sensing resistor in an electrical circuit. When the force sensor is unloaded, its resistance is very high. When a force is applied to the sensor, this resistance decreases. The resistance can be read by connecting a multimeter to the outer two pins, then applying a force to the sensing area. One way to integrate the force sensor into an application is to incorporate it into a force-to-voltage circuit. A means of calibration must then be established to convert the output into pressure. Depending on the setup, an adjustment could then be made to increase or decrease the sensitivity of the force sensor.

Lim [7] used an ELF sensor to measure girdle pressures on subjects' bodies with body motion. Human bodies contain thick and soft tissue, especially the area around the girth of the human abdomen. Her investigations showed that this could cause some of the force to be absorbed such that only a small component of force is exerted on the sensor even when the real girdle pressure is very large.

Another commercially available pressure-sensing system is the Novel's Pliance [8] system which offers pressure distribution measurement between soft and curved surfaces (Fig. 7.7). The system consists of flexible measuring sensors, a multi-channel analyzer, a calibration device and a software package for a personal computer. The Pliance system works with capacitive transducers in a matrix configuration. Several sizes of novel standard sensors can be configured as single sensors or arranged in a matrix to fit different measuring surfaces. In addition, a pilot study of clothing pressure exerted by a bra and girdle was conducted by the authors recently and it was found that the elasticity of the sensor permits perfect conformability around highly contoured sites without wrinkling. The pressure analysis can be done on or off-line by



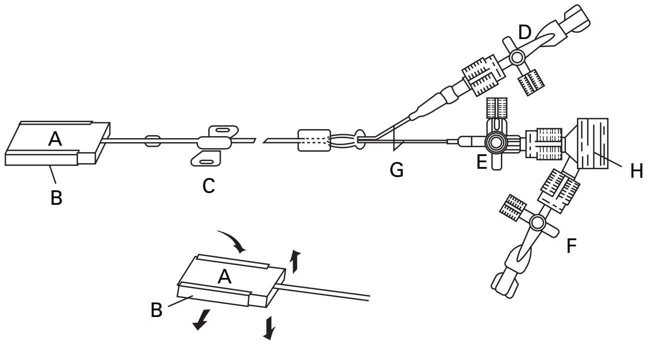
7.7 Novel pliance-sensor pressure strips. Source: Novel's Pliance [8].

a personal computer or a handheld personal digital assistant. All sensors are individually calibrated and supply accurate and reliable signals. The software also allows continuous data storage in online mode and data handling with a configurable SQL database.

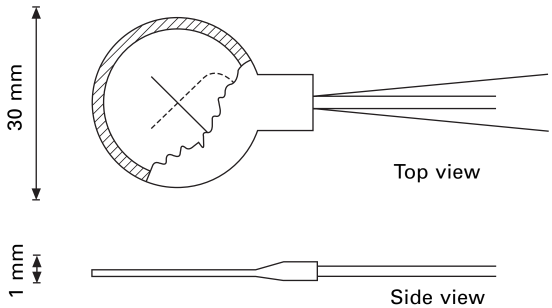
7.3.2 Hydrostatic pressure-sensing methods

Mitsuno *et al.* [9] measured the clothing pressure using a hydrostatic pressure-balanced method as shown in Fig. 7.8. This method employed a small, flat pressure detector (pouch), which is made of an inelastic polyethylene membrane filled with distilled water. The pouch was able to establish flat contact with clothes in the measuring region of the human body. The pressure developed at the pouch was transmitted to a pressure transducer through a slender tube. The authors reported that subjects did not experience an extraneous feeling and full loading of the pouch did not inhibit their movement. No hysteresis effect was observed over a pressure range from 46.25 to 277.48 gf/cm^2. This device was used to measure waistband pressures whilst standing erect under natural respiration conditions. Each subject wore a waistband that reduced the waist girth by 5%; the waist pressure was 23.8 ± 2.9 gf/cm^2 on average. The pressure amplitudes measured were observed to change according to the rate of respiration. [10]

Makabe *et al.* [11] invited subjects to wear girdles of various designs in designated positions to induce clothing pressure. The girdle pressure during body motion was measured by using multipressure sensors with a liquid



7.8 Pressure-detecting system. A: pouch (detector), B: case for fixing a water volume in the pouch, C: fixture wing, D, E, F: 3 way stop cock, H: pressure transducer. Source: Mitsuno *et al.* [9].



7.9 Rubber air cushion. Source: Tokuda *et al.* [12].

pack manometer sensor. The induced clothing pressure caused a hydrostatic pressure difference of the liquid inside the pack which was measured by the manometer. Subjective sensory tests found that most of the subjects complained about discomfort at the front waistline, the thigh base and the thigh front, especially when the clothing pressure reached more than 40.8–54.4 gf/cm^2.

7.3.3 Pneumatic pressure-sensing methods

Tokuda *et al.* [12] used a small rubber air cushion as a pressure sensor as shown in Fig. 7.9. Two electrified pieces of platinum wire were attached, at right-angles, to each other inside an air cushion. The air cushion was inserted between the clothes and the human skin and inflated to such a state that the pneumatic pressure just broke the electrical contact. Hence, the pneumatic pressure inside the air cushion was able to indicate the clothing pressure.

The use of a pneumatic tourniquet is potentially associated with injury to underlying muscles, vessels, and nerves if excessive pressure occurs beneath the tourniquet. Therefore, the appropriate tourniquet pressure should be determined to minimize the risk of soft-tissue injury. According to Shaw and Murray, [13] soft-tissue pressure in specimens, obtained following hip disarticulation, were measured directly beneath a pneumatic thigh tourniquet using a Hewlett Packard pressure transducer with a pressure probe. The tissue pressure was consistently lower than the tourniquet pressure reflected in the underlying tissue and varied inversely with the circumference of the thigh. In addition, the pressure decreased with increasing thickness of the soft tissue.

Isherwood *et al.* [14] developed the Puddifoot dressing which is a kind of pneumatic bandage capable of producing a relatively narrow range of pressures between capillary and arteriolar blood pressures. They claim that the Puddifoot dressing is safe and is less likely to produce a tourniquet effect and minimizes the effects of skill differences between bandagers.

7.4 Indirect pressure prediction

Commercially available pressure sensors allegedly suitable for the pressure ranges normally exerted by garments during wear may not be reliable and may exhibit inconsistent reproducibility of measurements. Factors like the uneven distribution of pressure on the sensing region, incorporation of pressure induced by sensor bending as well as the changes in human body temperature and humidity may also cause fluctuation of clothing pressure detected by the sensors. As an alternative approach to measuring clothing pressure, researchers have attempted to derive the pressure through the use of measurement or calculation of indirect parameters, such as fabric tension and curvature of body parts, etc.

7.4.1 Derivation of pressure from fabric tension and body curvature

Yoshimura *et al.* [15] derived a formula to predict the pressure on the knee by a knitted garment, which included fabric tension and the curvature of a knee surface. Based on a modified Laplace equation, the knee pressure was determined using eqn 7.1:

$$P = \frac{T_w}{r_w} + \frac{T_c}{r_c} \qquad 7.1$$

where P is the knee pressure, T is the tensile force in the fabric, r is the radius of knee curvature, (the subscript w denotes the wale direction and c represents the course direction). The stress-strain relationship in the fabric by biaxial stretching was determined from the values of tension at 48 points on the garment.

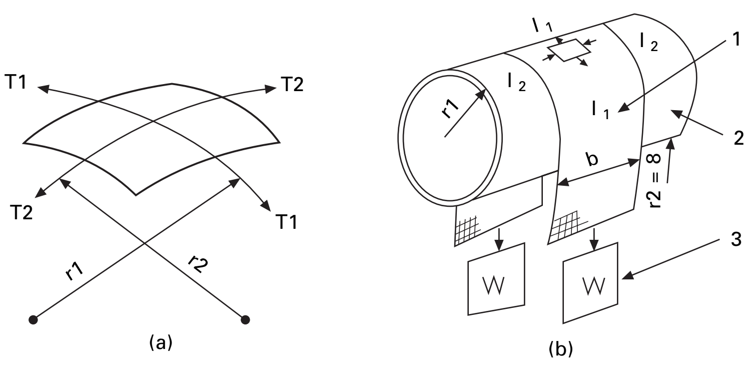
To develop a model for predicting clothing pressure, Ito *et al.* [16] verified the theoretical calculation from the uniaxial tensile deformation of fabric. In their study, cylindrical models were used to calculate the stress-strain curves in clothing materials. In order to measure the tensile deformation under clothing pressure, several cylindrical models with a variety of radii were used to simulate the circumference of the body. These cylindrical models were successively wrapped with three compression fabrics. The fabric sample was held under tension by weights to exert pressure onto the cylindrical model as shown in Fig. 7.10. The tensile deformation data for the fabrics was also measured using a tensile tester for comparison. The results revealed that the stress-strain curves for the fabrics could be used to predict the pressure on the cylinders using eqn 7.2. However, accurate prediction was found only in low compressive models which did not decrease in radius regardless of the pressure applied.

$$P = \frac{T_1}{r_1} + \frac{T_2}{r_2} \qquad 7.2$$

where P = Fabric pressure (g/cm^2)
T_1, T_2 = Tensile force (g/cm)
r_1, r_2 = Fabric radius (cm).

Morooka *et al.* [17] found that when wearing pantyhose with a crotch length of between 30 and 40 cm, the stretch was over 70% in wear. In addition, the tensile strain in the front, back, right and left parts of the band of pantyhose were influenced by the knitted structure of the panty part. The clothing pressure was derived using eqns 7.3, 7.4 and 7.5.

$$P = \frac{T\text{¢}}{r} \qquad 7.3$$



7.10 (a) Illustration of fabric tensions and curvatures; (b) testing method of fabric with different weight using a cylindrical model. Source: Ito *et al.* [16].

Where P is clothing pressure (gf/cm^2), r is the radius of waist girth.

$$T' = \frac{T}{l} \qquad 7.4$$

T is tensile strength (gf), l is the width of the pantyhose (cm), r is calculated by eqn 7.11 below.

$$r = \frac{(a/2)^2 + b^2}{2b} \qquad 7.5$$

Where a is width of the body waist, b is the thickness of body waist.

Aiming to correlate the subjective judgement of comfort, pressure sensation and shaping effect with objective pressure measurements from the human body, Yu *et al.* [18] successfully found the relationship between pressure comfort and body fat and curvature. In the experiment, human body cross-sections were assumed to be elliptical, the body curvature K was derived at the waist (w), abdomen (t) and hip (h) levels using eqns 7.6 to 7.8.

$$Kw = (\text{breath}/2)/(\text{thickness}/2)^2 \text{ at waist level} \qquad 7.6$$

$$Kt = (\text{breath}/2)/(\text{thickness}/2)^2 \text{ at abdomen level} \qquad 7.7$$

$$Kh = (\text{breath}/2)/(\text{thickness}/2)^2 \text{ at hip level} \qquad 7.8$$

Using multiple regression analysis, the pressure rating Y was derived as a function of Log pressure LnP, body curvature Kw and fat content to give eqns 7.9 to 7.11.

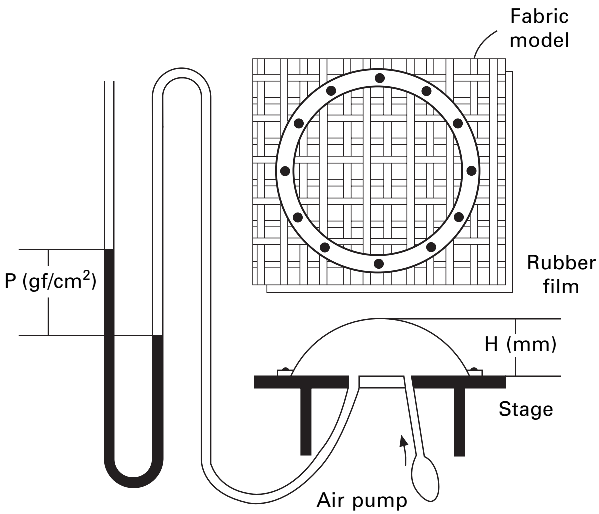
$$\text{At waist, } Y = -1.55 \text{ LnP} + 18.03 \text{ Kw} + 0.24 \text{ Fat} - 2.26 \qquad 7.9$$

$$\text{At abdomen, } Y = -1.02 \text{ LnP} - 27.76 \text{ Kt} + 12.59 \text{ Fat} + 2.37 \qquad 7.10$$

$$\text{At hip, } Y = -44.45 \text{ LnP} - 2.92 \text{ Kh} - 1.92 \text{ Fat} + 11.23 \qquad 7.11$$

7.4.2 Derivation of pressure using dome method

Kawabata *et al.* [19] estimated clothing pressure from the deformation of fabric using an experimental system. A rubber film substrate was laid under the fabric model held in a circular frame or elliptical frame as shown in Fig. 7.11. When air was pumped into the space between the rubber substrate and the stage, the substrate expanded together with the model fabric on it to form a curved surface like a dome. The air pressure was measured by a manometer when the height of the dome was 30 mm and 48 mm. Moreover, they also stated that the stresses in the threads could be estimated indirectly by measurement of the strains and transformed into tensions through their stress-strain relationships. The garment pressure was calculated using eqn 7.2.



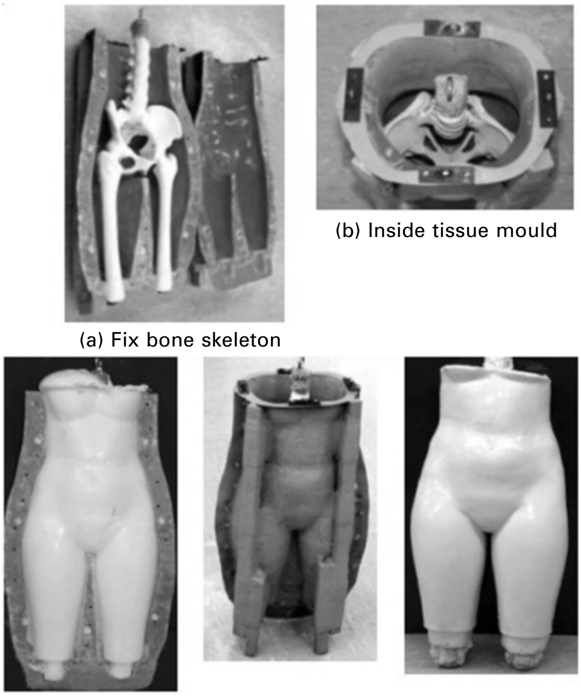
7.11 Apparatus for the dome method. Source: Kawabata *et al.* [19].

7.4.3 Prediction by numerical finite element method

Zhang [20] developed a bio-mechanical model to study the dynamic pressure distribution between bra and breast during wear. The biomechanical human model consisted of three layers of materials with different mechanical properties, i.e., the skin, soft tissue and bone. By analyzing the mechanical characteristics of the human body and garments and based on the theory of contact mechanics, a mechanical model was developed. A finite element method was used in the time domain for deriving a numerical solution for the dynamic contact model. It was able to generate a quantitative description of garment pressure distribution, human body deformation and inner stress in the skin.

7.4.4 Prediction using a soft mannequin

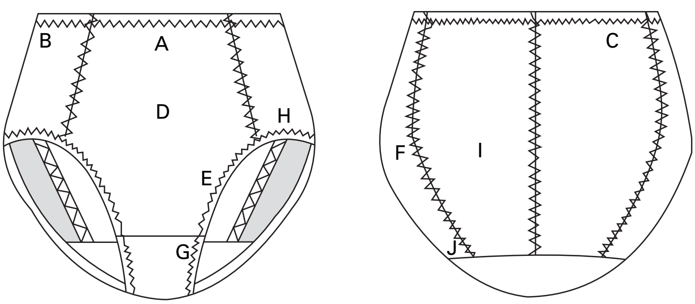
Yu *et al* [21] have attempted to replace live models in garment fitting trials to enable pressure testing of garments (Figs 7.12, 7.13 and Table 7.2). A mannequin was developed using a glass-fibre 'bone structure', polyurethane (PU) foam 'tissue' and a silicone rubber 'skin'. The overall physical characteristics, especially in appearance and surface elasticity and physical characteristics were claimed to be very similar to a human female lower body. The study enabled a comparison to be made between the measurements of pressure obtained from the mannequin with those made on a human subject by using pressure sensors. Similar pressure values were measured making it possible to predict the garment pressure based on measurements obtained from the soft mannequin.



(a) Fix bone skeleton (b) Inside tissue mould

(c) PU soft tissue (d) Skin mould (e) Skin

7.12 Structure of soft mannequin. Source: Yu *et al.* [21].



Point A: waist front
Point B: waist side
Point C: waist back
Point D: abdomen
Point E: inguinal canal
Point F: leg side
Point G: Pubis
Point H: trunk base
Point I: gluteus maximus
Point J: gluteal furrow

7.13 Pressure measuring points of girdle specimen. Source: Yu *et al.* [21].

Table 7.2 Correlations between pressure on subject (Ps) and on mannequin (Pm). Source: Yu *et al* [21]

Point A:	Ps = 0.72 Pm – 320.65,	R = 0.82
Point B:	Ps = 3.08 Pm – 1098.13,	R = 0.87
Point C:	Ps = 3.17 Pm – 397.51,	R = 0.88
Point D:	Ps = 0.18 Pm – 111.19,	R = 0.88
Point E:	Ps = 3.37 Pm – 628.55,	R = 0.94
Point F:	Ps = 2.31 Pm – 75.54,	R = 0.71
Point G:	Ps = 0.16 Pm + 13.80,	R = 0.47
Point H:	Ps = 0.98 Pm – 36.75,	R = 0.77
Point I:	Ps = 0,	
Point J:	Ps = 0.33 Pm + 81.65,	R = 0.80

7.5 Factors affecting girdle pressure absorption

7.5.1 Influence of body structure and fat content

Women of different ages may have different silhouettes and body shapes that affect the comfort and pressure sensation when wearing girdles. Katou *et al.* [22] observed that the lower half of the bodies of elderly women, especially the shapes of the abdomen and hips, change noticeably as they grow older. Hiroko *et al.* [15] found that the pressure exerted on the body by a garment was not only determined by fabric tension but was also dependent upon the curvature of the respective body part surface. This can also be inferred from the pressure eqn 7.8. The body fat percentage refers to the percentage of body fat mass in relation to body mass [7]. The human body is made up mainly of water with fat being the next largest proportion. Therefore, body fat percentage within the whole body weight may directly affect the sensory feelings from girdle pressure. The Omron Body Fat Monitor has been used [7] to detect the ratio of fat tissue to the other tissues in the body using eqn 7.12.

$$\text{Body fat percentage (\%)} = [\text{Body fat mass (kg)/Body weight (kg)}] \text{ ¥ } 100 \qquad 7.12$$

7.5.2 Influence of body soft tissue thickness and stiffness

Body soft tissue refers to tissues that connect, support, or surround other structures and organs of the body. Soft tissue includes muscles, tendons (bands of fibre that connect muscles to bones), fibrous tissues, fat, blood vessels, nerves and synovial tissues (tissues around joints) [23]. In a study in 1991, 24 subjects between the ages of 21 to 57 years were asked to wear body suits to measure the clothing pressure on 17 body parts [24]. The results showed that the subjects' tolerable pressure level was closely related to body soft tissue stiffness. Subjects felt pain if they wore body suits for long periods of time, meanwhile, subjects who had less stiffness in their soft tissue felt more pain particularly on their waist side.

Zheng *et al.* [25] believed that pressure distribution patterns depend mainly on the geometry, the bio-mechanical properties and the stress tolerance levels. A good interfacial stress distribution should facilitate effective load transfers during gait and should be well tolerated by the soft tissues. It is claimed that such tissue tolerance involves tissue damage criteria and tissue adaptation mechanisms in response to external loading.

7.5.3 Influence of fabric strain

Kirk *et al* [26] believed that the inherent desire to dress comfortably with an attractive garment appearance could be satisfied to a considerable degree by fabric stretch. To test this belief, a stress measurement was made in the warp and weft directions of some fabrics. To calculate pressure at the knee, the radius of knee curvature (horizontal and vertical) was then measured in the same bending position at which garment strain was measured. The results showed that comfort can be improved rapidly for fabric extension values up to 30–35% and then levels off.

Denton [27] stated that the object of a girdle is to flatten the abdomen, stomach and seat by stretching an elastic fabric band around the waist and hips. The tension in the band must be roughly the same all round the body so that the pressure will depend only on the surface curvature at any given point. The pressure is the highest where the curvature is the greatest. On average, the body curvature at the sides is roughly 3.5 times greater than that at the front so the unwanted pressure on the sides of the waist was 3.5 times greater than the desired figure-flattening pressure on the front.

In another study by Sato *et al.* [28], subjects were asked to adopt a series of standard postures in order to investigate the fabric strain requirement for different types of garments. The results showed that, for undergarments, subjects still felt comfortable even when the fabric elongation reached 40%, but the shaping effect was better if the fabric elongation was less than 40%.

Ito *et al.* investigated the relationship between biaxial extensions, the stress relaxation properties of six girdle fabrics and clothing pressure. The results showed that the change in clothing pressure whilst standing or moving was closely related to the biaxial extension and stress relaxation properties of the girdle's fabrics. The girdle that created the higher clothing pressure had a lower stress relaxation and low biaxial extension [29].

7.6 Range of comfortable and tolerable pressure

Ito [30] invited 25 subjects to wear six girdles with different biaxial extension and stress relaxation fabric properties. During the experiment, clothing pressure and the subjects' comfort sensation of six girdles were recorded and analyzed. For the different parts of the anatomy, the average girdle pressure range obtained from the girdles with the most comfortable compression feeling in different parts of the body is shown in Table 7.3. Based on the subjective feeling of the subjects, the comfortable girdle pressure on most parts of the body should be less than 13 gf/cm^2; the finding also showed that the side waist can tolerate higher girdle pressure, which is around 18 gf/cm^2.

In order to keep regular blood circulation, Nakahashi *et al.* claimed that clothing pressure on the groin should be no more than19.18 gf/cm^2 [31]. The experimental results also showed that subjects felt comfortable when clothing pressure on the front abdomen was 8.1 gf/cm^2, side abdomen 13.7 gf/cm^2, back abdomen 13.2 gf/cm^2 and hip 10.1gf/cm^2, if clothing pressure was lower than the aforementioned levels. Despite the fact that subjects felt more comfortable the shaping effect was worse. When the stocking pressure on the thigh was 20.4 gf/cm^2 and on the leg 23.1 gf/cm^2, blood circulation improved. However, healthy women preferred to wear stockings with a pressure on the thigh of 5 gf/cm^2 and on the leg of 7 gf/cm^2 in general.

Nakahashi *et al.* [31] conducted an experiment on the differential threshold for pressure on the front and back parts of a lower leg for 18 subjects. In addition, the compressive feeling of the trial stockings, which exerted variable clothing pressure distributions by changing the loop length in the course direction, was examined. The results showed that the pressure range on the front part of the lower leg was around 0 to 25 gf/cm^2. When the pressure was low, the back part of a lower leg was not as sensitive as that on the front part. When the pressure was more than 20 gf/cm^2, the back part was as sensitive as the front part. Since the comfort value of pressure on the front part of the lower leg was lower than that on the back part, the compressive feeling was

Table 7.3 Clothing pressure on different body parts. Source: Ito [30]

Body parts	Clothing pressure gf/cm^2
Front waist	9.07
Side waist	17.96
Back waist	4.57
Front abdomen	7.83
Side abdomen	12.21
Back abdomen	4.29
Side hip	10.88
Back hip	8.52
Front thigh	11.95
Side thigh	8.04
Back thigh	9.24

Table 7.4 Clothing pressure from the most comfortable girdle sample. Source: Makabe *et al.* [32]

Body position points	Clothing pressure gf/cm^2
2 cm off from the anterior median line at girdle waist line	13.74–15.23
On waist line and mamillary line cross	10.47–11.43
On waist line and middle axillary line cross	26.93–28.16
On waist line and scapular line cross	19.45–20.13
On 3 cm off the posterior median line at waist line	15.1–16.05
On iliospinale	16.73–17.68
On tendon of 'musculi adductor longus'	14.01–14.69
On mamillary line and inguinal canal cross	9.39–9.79

more influenced by pressure on the front part of the lower leg than that on the back part.

Makabe *et al.* [32] conducted a pressure-sensing experiment to determine the relationship between comfort and clothing pressure based on subjects' comfort sensation whilst wearing sample girdles. Subjects complained of discomfort when clothing pressure reached more than 40.8~54.41 gf/cm^2. The clothing pressure of the most comfortable girdle sample is shown in Table 7.4.

Having studied all the girdle pressure data shown in Table 7.4, it can be concluded that the comfortable girdle pressure on most parts of the body should be lower than, or about, 13 gf/cm^2. The comfortable range of clothing pressure on the waist is 4.5~9 gf/cm^2, abdomen 8~12.5 gf/cm^2, hip 6~11 gf/cm^2 and thigh 6~9 gf/cm^2. For some bony regions like the side waist, the pressure level may be up to 17~28 gf/cm^2. For the sake of regular blood circulation, extra attention should be paid if the pressure exceeds 19.18 gf/cm^2. A girdle should never be made where the clothing pressure reaches more than 40.8~54.41 gf/cm^2 as it not only leads to complaints of discomfort from the wearer, but also jeopardizes the wearer's health.

7.7 Acknowledgement

We thank the Research Grant Council of Hong Kong SAR for funding the project 'Effects of Foundation Garment Pressure on Women's Health' (B-Q732).

7.8 References

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8
Intimate apparel with special functions

J YIP and W YU

8.1 Introduction

The 21st century is regarded as a high-tech era, when almost every new product is a result of combining sophisticated R&D into materials and manufacturing technology. Intimate apparel for specific applications such as sportswear, maternity wear, etc., is no exception. It always provides special functions with novel characteristics and valued-added performance. This chapter introduces several types of functional intimate apparel including sports bras, pantyhose, swimwear, mastectomy bras and maternity underwear with the focus on their product development and associated research.

8.2 Sports bra

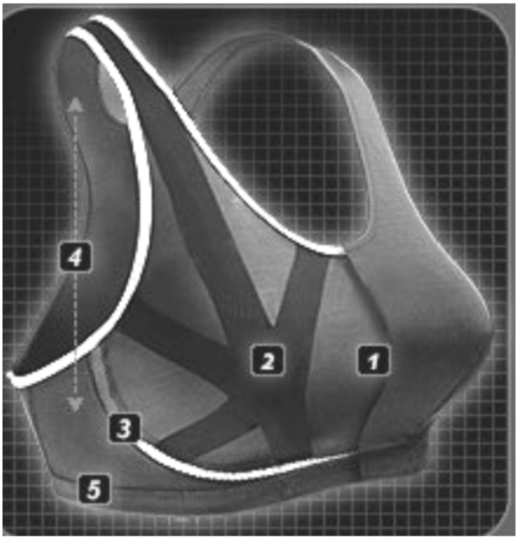
A sports bra is designed to control excessive breast motion and reduce breast pain during vigorous activities. Support and comfort are two important aspects of a sports bra especially for women in athletic activities. A good sports bra not only controls breast movement but also regulates body heat and moisture with good permeability.

8.2.1 Bra function for breast movement control

Mason *et al.* found that breast pain was common in the absence of an external supportive garment during exercise. It was suggested that wearing a well-fitted sports bra could reduce the absolute vertical movement and the maximum downward deceleration force on the breasts [1].

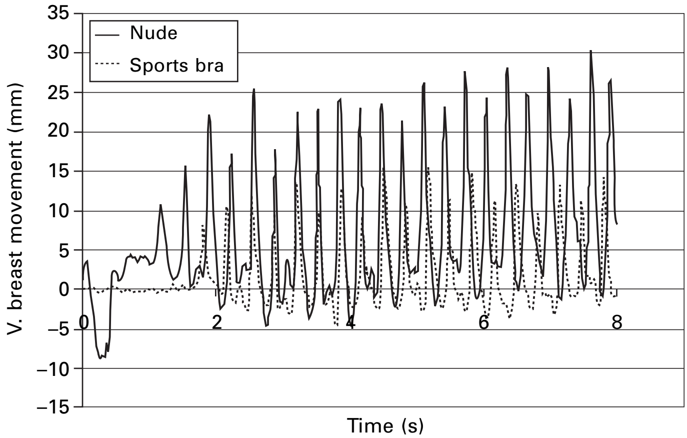
There are essentially two different types of sports bras. These are compression style bras and encapsulation style bras. Compression sports bras are designed to press the breasts tightly against the chest wall to minimize breast movement. Encapsulation sports bras are similar in appearance to regular bras, with separate straps, front closure or adjustable hook back openings, fabric panels and even underwires. However, they offer much more support by harnessing each breast individually instead of compressing them. Since every part of an encapsulated sports bra must contribute to supporting the breasts, the required fabric density and rigidity needs to be high. This leads to a trade-off between support and moisture management: the more support the wearer requires, the less effective is the moisture management. Generally, compression sports bras are designed for smaller-breasted women who pursue low-impact activities. Large-breasted women (C-Cups or larger) find more support in encapsulation bras as the designs are more similar to a regular bra [2].

Nike's pull-over style of compression sports bra has a racer-back design which is scooped out around the shoulder blades and designed to allow maximum range of motion. This racer-back design is better than the traditional straps for sports bras because it avoids deep bra strap furrows. As the breast mass increases, the bounce momentum rises which places larger pressure on the wearer's shoulders [3]. Nowadays, new designs of sport bras tend to use encapsulation to enhance support, shaping and overall fit. For example CW-X® sports bra™ (Fig. 8.1) has supportive warp knitted powernet built into the bra cups to reduce upward and downward bounce during high-impact activities [4]. Another encapsulation sports bra from Marks and Spencer has underwires. The lower cup is laminated and welded with rigid lining to



1 Four-way stretch tricot fabric
2 Inner-cup soft support web
3 Four-way stretch mesh
4 Offset flat seams
5 Elastic base strap

8.1 Encapsulation sports bra from CW-X®.



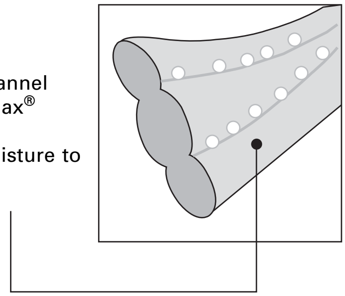
8.2 Vertical breast movement of a body with and without a sports bra.

reduce breast bouncing. The shoulder straps are wide and padded to improve the comfort level.

Tsoi and Yu used a quantitative method to measure the efficacy of the sports bra in controlling breast movement. They used a Vicon motion analysis system to measure the vertical movement of the breasts when subjects wore different types of commercial bras during five different activities (arm extension, hopping, jogging, rope skipping and sit up). Each subject performed the activities within a space surrounded by six high-resolution Vicon cameras and each camera has a ring of LED strobe lights fixed around the lens. When a subject moved, infra-red light emitted from the strobe on the light-reflective markers worn by the subject was reflected back into the camera lens and struck a light-sensitive plate producing a video signal and the real-time co-ordinates (X, Y, Z) of markers in three-dimensional space were obtained. The vertical breast movement of a body with and without a sports bra (Fig. 8.2) revealed that the extent to which the sports bra controlled the breast movement effectively. Not surprisingly, the researchers also found that small- and large-busted women had big differences of breast movement during activities [5].

8.2.2 Moisture management function

The main objectives of moisture management are to keep the surface of the skin as dry as possible and to help the whole thermal regulation process of the body. Many commercial sport bras use DuPont CoolMax® to achieve this function. The special cross-section shape of CoolMax® as shown in Fig. 8.3 has a larger surface area that allows faster evaporation. According to DuPont's



8.3 Morphology of fibre used in CoolMax® fabric [7].

moisture tests, garments made with CoolMax® dried almost completely in 30 minutes while cotton by comparison still retained 50% of wetness [6].

Dri-Fit fabrics, introduced by Nike, are also claimed to keep athletes comfortable by keeping them drier. Dri-Fit fabrics can be made of nylon, polyester, spandex or a blend of all three but mostly in the form of microfibres. The small diameter of the fibres plays a role in creating the ideal levels of surface tension and adhesion between the molecules and thus creates a capillary action. This capillary action helps to move the sweat as fast as possible along those fibres [8].

Recently, Cotton Incorporated developed the wicking windows moisture-management technology applied for cotton. The main objectives of this technology are to reduce cotton's absorbent capacity and to maintain its wicking properties. The researchers modified the cotton fabric properties which affected the cling force between the fabric and the skin, to allow the moisture to move through the fabric [9]. The company applied this technology in its new Double Dry Cotton athleticwear. It is claimed that the product delivers exceptional wicking performance while maintaining the look, feel and comfort of cotton [9].

8.2.3 Anti-bacterial function

Nowadays, women have become more aware of technical fibres and fabrics. MicroPlex, a new brand of women's activewear from Everlast contains anti-microbial fibres to eliminate odour [10]. In contrast, X-Static technology used pure silver-coated fibres to prevent static causing fabric to cling to the body and to prevent sweaty, wet bras from growing bacteria [11].

8.3 Pantyhose

Pantyhose is a woman's one-piece undergarment which, when invented in 1959, consisted of underpants and stretchable stockings. The top of the pantyhose used opaque nylon to make underpants to which the stockings were sewn. The fashion trend of the miniskirt provided further impetus to the development of pantyhose or ‘tights’. They became more commonly produced by cutting and joining two tubes to create the pant region and the legs. A crotch could, optionally, be inserted into the pant [12]. During the past 40 years, the design, machinery and manufacturing processes for making pantyhose have changed a lot with new materials. The new technology has made it possible to cut, seam and stitch the products automatically.

8.3.1 Materials used for aesthetic functions

Pantyhose can be made from 100% nylon, nylon/Spandex, microfibre like Tactel® or Meryl®. In 2000, Toray in Japan has developed ‘Super Miracosmo’ with high tenacity which had a breaking strength 30% higher than conventional nylon fabrics [13], thereby improving the product’s durability.

Many new materials have been applied in pantyhose manufacturing to enhance the beauty of women’s legs. For example, pantyhose treated with the natural essences Bio-Fresh®, can deter mosquitos and insects [14]. Sarah Borghi launched the ‘Natural LegCare®’ pantyhose with Aloe, Ginko, Ginseng, Centella and Green tea. It was claimed to moisturise and refresh the legs, and also reduce leg swelling and fatigue. If it is worn regularly, it is claimed that it may improve the health and beauty of the legs in the long term [15]. However, the efficacy of such treatments will be lost after several laundering cycles.

Nano-technology is an advanced treatment applied widely on different materials. Kanebo Spinning applied this technology on its yarns and fabrics in 2004. The materials treated with a vitamin called niacinamide can promote the synthesis of ceramido. The so-called ‘NanoFeuille’ pantyhose treated with this nano-finish could give humidity-retaining effects to body skin [16].

Matsumoto *et al.* carried out several research projects aimed particularly on improving the aesthetic appeal of pantyhose [17–19]. According to their results, the sheerness of pantyhose was one of the most important aesthetic properties for a woman’s legs [20, 21]. However, as the degree of fabric extension on each leg part is different, uneven sheerness over the entire leg will affect the overall appearance of the woman’s legs.

Normally, pantyhose are knitted from single covered yarn (SCY) with combined polyurethane core and nylon covering yarns. In the dyeing process, the nylon covering yarn can be dyed while the polyurethane core yarn remains colourless. Polyurethane yarn (PY) has higher elongation and less strength than nylon yarn (N). When the pantyhose are highly extended, the colourless polyurethane core yarn will be exposed which was regarded as ‘eye-catching’ and not looking good. Coloured polyurethane yarn improves the appearance of pantyhose that is close to the bare skin leg [17]. Hiroaki measured the transmittance of light, carried out the sensory tests and performed image analysis on the pantyhose. The results showed that coloured PY produced a reduction in lustre and was more favoured than the colourless PY.

8.3.2 Materials used for comfort improvement

Matsumoto *et al*. published several papers on the improvement of superior pantyhose with regard to thermal comfort [22–24]. The results showed that the nylon/cuprammonium blended pantyhose had a higher rating in total comfort than the traditional nylon pantyhose, particularly with regard to tacticity, stretchability and ease of putting on. The sweating simulation test indicated that the blended pantyhose had a total heat loss of 25–30%, which was higher than that of the nylon pantyhose. It had a lower frictional coefficient under wet conditions than the nylon pantyhose. This implies that the blended pantyhose had lower frictional properties between the pantyhose and the wearer's skin.

8.3.3 Machinery/technology innovation

Traditionally, circular knitting machines were used for producing pantyhose [25]. In 2002 Karl Mayer introduced the RDPJ 6/2 warp knitting machines for making seamless, jacquard patterned tights and fish-net pantyhose. Karl Mayer's MRPJ43/1 SU and MRPJ25/1 SU jacquardtronic raschel knitting machines can manufacture pantyhose with relief-like and lace patterns [26]. Other developments in machinery were aimed to increase the efficiency, productivity [27, 28] and quality of pantyhose [29].

Matsumoto *et al*. have also carried out some studies on the control of sheerness in pantyhose fabrics [18,19,30,31]. They produced an experimental hybrid knitting system composed of two experimental covering machines and a circular knitting machine. Each covering machine had two sections of single covered yarn. The pantyhose samples were knitted under a constant condition, while the single covered yarns were produced by controlling the covering levels of 1500 turns per metre (tpm) and 3000 tpm in nylon yarn with a draw ratio of 2 = 3000 tpm/1500 tpm for the core polyurethane yarn. The lower covering level produced a higher sheer in the pantyhose. Four different pantyhose samples were produced with different covering levels of tpm in different leg regions. The results showed that the aesthetics and sheerness of pantyhose fabric were greatly influenced by changing the covering level of the single covered yarn in the leg parts, and the mechanical hybrid system could improve the aesthetic properties of pantyhose fabric.

8.4 Swimwear

Major developments in fibre science and fabric technology have revolutionized the swimming game and created massive interest in what has traditionally been seen as a low-tech sport. The performance swimwear market is driven by innovation and technology. The new swimwear fabrics are engineered to exact standards of elongation, power and recovery to assure a flawless fit by the swimsuit. These fabrics must feature fast-dry, excellent chlorine resistance, minimal yellowing, and resistance to degradation due to exposure to suntan oils and perspiration.

8.4.1 Chlorine-resistant elastane fibre

The well-known problem with the use of an elastic polyurethane fibre is its degradation when exposed to chlorinated water in a swimming pool. In order to improve its chlorine resistance, many research works have been performed. In 1994, a polyester-based elastic polyurethane fibre was produced in Japan by Kuraray instead of a polyether-based one [32]. The fibre has excellent resistance to chlorine and light. Du Pont also developed a polyester-based filament [33]. The fabric made from this filament improved mildew-induced degradation, however its chlorine resistance was claimed to be insufficient.

Various metal compound additives for improving chlorine-caused deterioration of the elastic polyether-based polyurethane fibre have been developed by Bayer [34] and Asahi [35]. The fibres made by these companies showed excellent chlorine resistance even when dyed under acidic conditions. Recently, Invista™ developed polyurethane containing a combination of phenolic and inorganic additives. This polyurethane exhibited improved resistance to degradation by both chlorine and atmospheric fumes [36].

8.4.2 High-performance yarns for swimwear

In 2003, Du Pont™ Textiles & Interiors (DTI) introduced new Tactel® warp knit yarns specially developed for swimwear. The new 44 dtex 20 filament Tactel® yarns combined with Lycra® were designed for warp knit constructions in the mid-to-premium end of the market for fashion swimwear [37]. Tactel® Prisma is a unique yarn innovation combining two polymers in one single yarn for bi-tonal effects [38]. Tactel® metallic is available in gold and silver colours which impart a bright lustre to swimwear [39]. These yarns offer swimwear designers a range of innovative options to enhance touch and aesthetics.

Another new yarn, also from Du Pont™ called Sorona®, possesses unique properties such as fast drying, chlorine resistance, good colourfastness, static protection, stain resistance and easy care [40]. It is claimed that Sorona®

combines the best qualities of polyester and nylon. It maintains the excellent physical and chemical properties of polyester, but can be dyed at a lower temperature similar to dyeing nylon fabric [41]. The swimwear fabric made by Sorona® has brilliant colour and good UV and chlorine resistance.

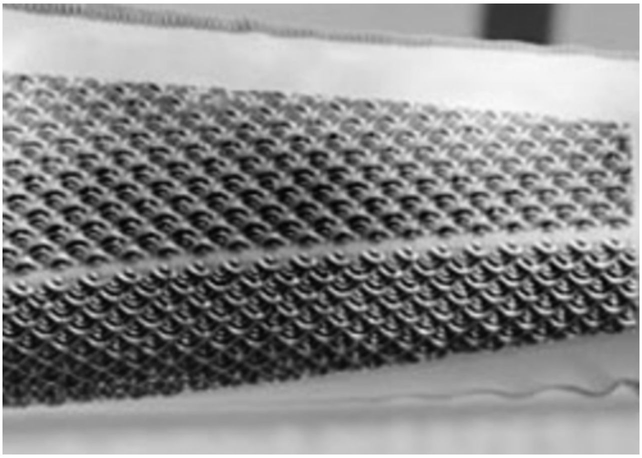
8.4.3 Performance swimwear

In recent years, manufacturers of performance swimwear have been competing to produce the world's fastest swimsuit. At least three companies – Speedo, TYR and Arena have developed some materials or special designs that allow swimmers to move faster through the water [42]. The research and development process of Speedo started with a study of the shark. They examined the shark's skin texture and movement through water. The study led to the discovery that the shape and feel of the shark's denticles varies across its body to manage the water flow. Speedo took these findings and created a full bodyskin with different fabrics on different parts of the body. This design which, they claimed, could optimize the flow around an athlete was named FASTSKIN®FSII™ [43].

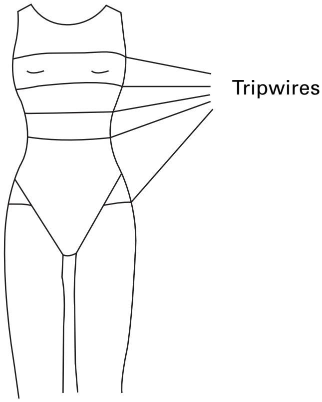
There are several technologies applied by FASTSKIN®FSII™. The fabric's surface characteristics imitated the rough shark denticles to reduce drag along key areas of the body. The fabric compressed the body to stop skin vibration and muscle oscillation to save energy. They applied a 'Turbulence Management System' (TMS) in certain locations in order to reduce drag caused by the human form as it travels through water. Speedo also developed three-dimensional titanium silicon scales in the inner forearm panel (Fig. 8.4). This scale could help the swimwear to 'grip' the water.

Aqua Shift™ from TYR applied a latitudinal wire (tripwire) on different points of a swimsuit to re-direct the laminar boundary flow around the athlete's body. Figure 8.5 shows the Aqua Shift™ suit with several tripwires located in different positions. The mechanism of TYR's design was to improve the swimming speed based on the reduction of drag coefficient. When the athlete hit the water, the wave drag was created. The bigger the wave drag the greater was the energy loss. By using the latitudinal wires, Aqua Shift™ literally 'shifted' the laminar flow, to provide a significant reduction in wave and pressure drag [44].

On the other hand, Arena's swimwear used an ultra-lightweight fabric (146 gm/m^2) called X-Flat. It had micro-grooves in the warp direction and a sleek fabric finish for a smoother, faster surface. Figure 8.6 shows how the micro-grooves of the X-Flat fabric and sleek finishing reduce water resistance. It was claimed to provide 4.8% less friction than human skin, 50% less drag than normal swimwear fabric, absorb 40% of its weight in water and dry rapidly [45].



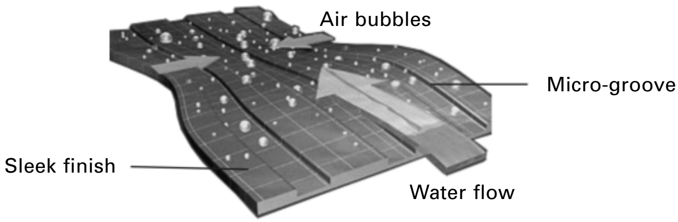
8.4 Inner forearm neutralizer panel with 3D silicon scales on Speedo's FASTSKIN®FSII™ swimwear from www.speedo.com [43].



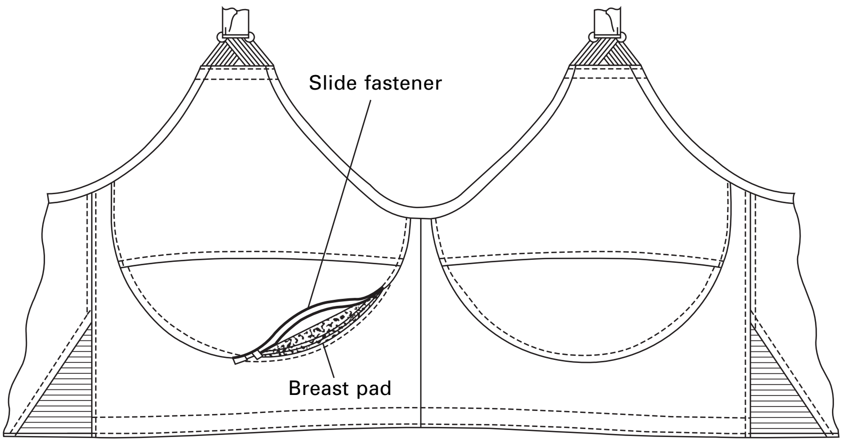
8.5 The Aqua Shift™ suit from TYR with tripwires located in different positions [44].

8.5 Mastectomy bras

Mastectomy is the surgical removal of all or part of a breast, usually performed as a treatment for breast cancer. The physical and psychological changes resulting from mastectomy require weeks or months of recovery time. The patient must overcome not only pain, limited mobility in the arms, but also a feeling of flatness and imbalance resulting from the loss of the weight of the breast [46]. A mastectomy bra is therefore designed with an inside liner to form a pocket for the breast pad or prosthesis, in order to provide the wearer with an appearance of having a pair of natural breasts. In this section, different types of mastectomy bras will be reviewed.



8.6 The design of X-Flat fabric from Arena [45].

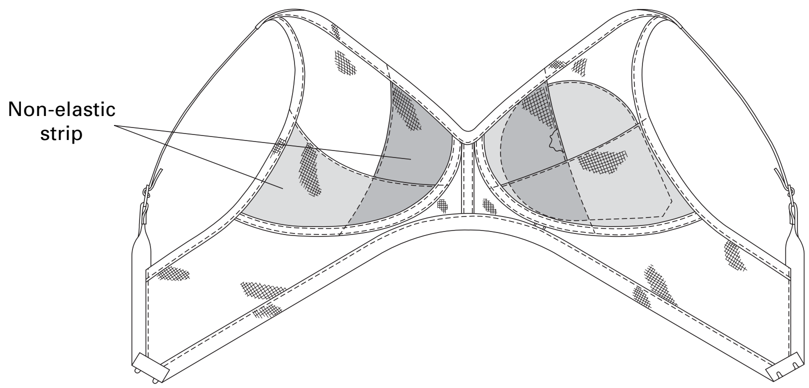


8.7 The breast pad holding bra with a slide fastener [47].

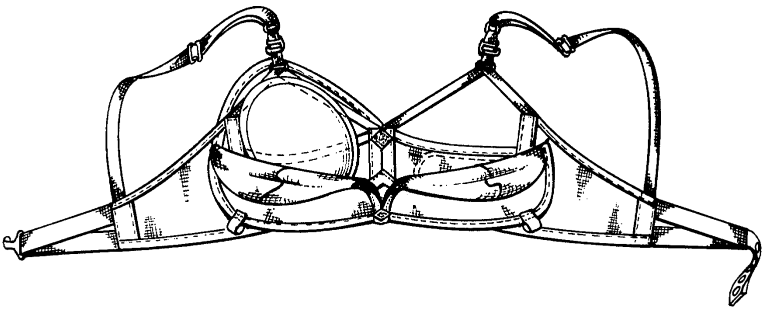
8.5.1 Breast-pad holding style

In the days when mastectomy bras were not available, the patient normally bought a standard bra and then sewed a pocket into one bra cup for the insertion of a pad. In 1953, Day invented the 'breast-pad holding bras/garments' that contained a simplified pocket with a zipper which was concealed along the cup for inserting the pad [47] as shown in Fig. 8.7. Since mastectomy operations vary from one to another, this design which held the standard size pad in one fixed position, was not satisfactory for all patients.

Farino in 1976 designed a mastectomy bra including two cups. Each accommodated either a natural breast or a mastectomy form pad as shown in Fig. 8.8 [48]. Each of the cups had two upward non-elastic strips, an outer non-elastic fabric cover and two separate stretchable flaps for the insertion of a mastectomy form pad. Farino suggested that with this design, the mastectomy form pad could be inserted into the cup in any desired orientation to compensate and correct individual types of surgery. However, if the prosthesis is too heavy the bra would be pulled down or shifted. Later, Penrock invented a prosthetic bra that contained U-shaped springs to maintain the back panel



8.8 Breast pad holding bra with two separate stretchable flaps [48].



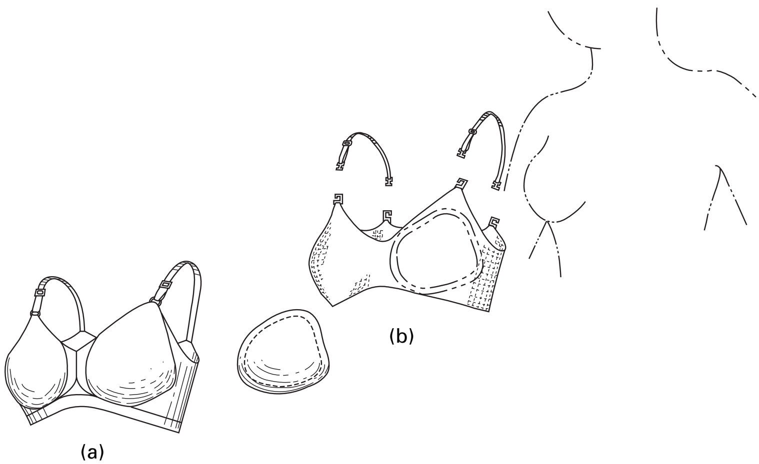
8.9 Front view of prosthetic bra with U-shaped springs [49].

that ensured a uniform and comfortable distribution of forces on the wearer's body without displacement of the prosthesis [49] (see Fig. 8.9).

8.5.2 Two-piece style

In the 1980s, as the need for mastectomies increased rapidly, post-mastectomy foundations and breast forms became important items in the lingerie market. The requirements of mastectomy bras were not only to provide functional support, but also to satisfy the aesthetic aspects. Sherwood pointed out several problems of the previous mastectomy bras, for example, the breast prosthesis often extends visually beyond the edges or border of the bra. Because of the high cost incurred in constructing such prosthetic bras, they were not readily adaptable to the changing bra styles.

To address this issue, Sherwood designed two different mastectomy bras as shown in Fig. 8.10. The mastectomy garment included an underbra, breast prosthesis and an outerbra. The underbra was used to provide the prosthesis fixation and the outerbra was styled normally. The inventor claimed that the



8.10 Mastectomy bra containing an underbra, breast prosthesis and an outerbra [50]. (a) Frontview of fold-down mastertomy bra; (b) Exploded view of fold-down cup.

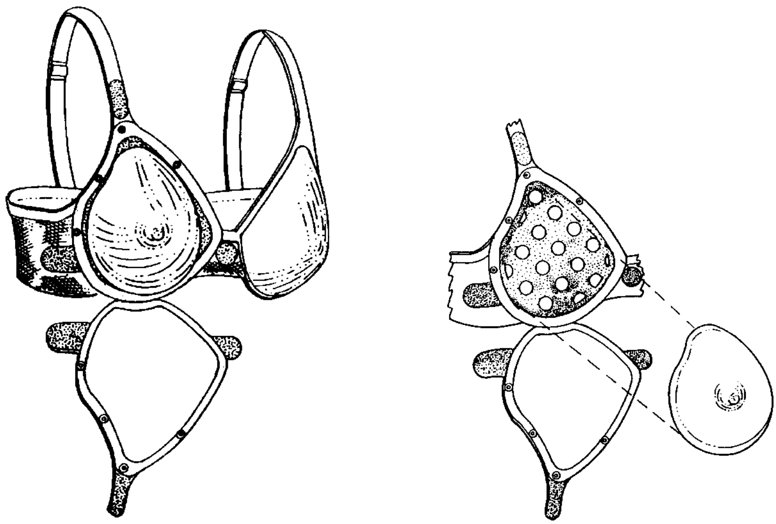
products could provide women with a large range of fashion bra shapes and styles. It allowed the mastectomy prosthesis to fit both comfortably and accurately, but would not shift in position from the chest [50].

8.5.3 Prosthesis holding style

In the 21st century, product development of the mastectomy bra has been focused on 'comfort', 'natural' and 'aesthetic' aspects to the users. Many patients have complained that the prosthesis readily shifts on the chest wall, and is never securely placed in the correct position like a natural breast. In order to solve the problems, Eaton developed a mastectomy garment to retain the breast prosthesis in place on the anterior chest wall of a patient [51]. The design included a normal bra cup and a fold-down cup for the prosthesis (Fig. 8.11(a)). Beneath the fold-down cup, there were loop fasteners for the attachment of the breast prosthesis. The rim of the prosthesis was provided with hook fasteners that engaged with loops on the cup (see the exploded view of fold-down cup in Fig. 8.11(b)).

8.5.4 Built-in prosthetic device style

The mastectomy bra designed by Fanelli in 2001 was constructed with a built-in prosthetic device of varying weight (Fig. 8.12). The invention could be used in different fashionable garments to enable the wearer to merely dress with the garment without having to go through a process of inserting the prosthesis, affixing and adjusting the prosthesis [52].



(a) (b)

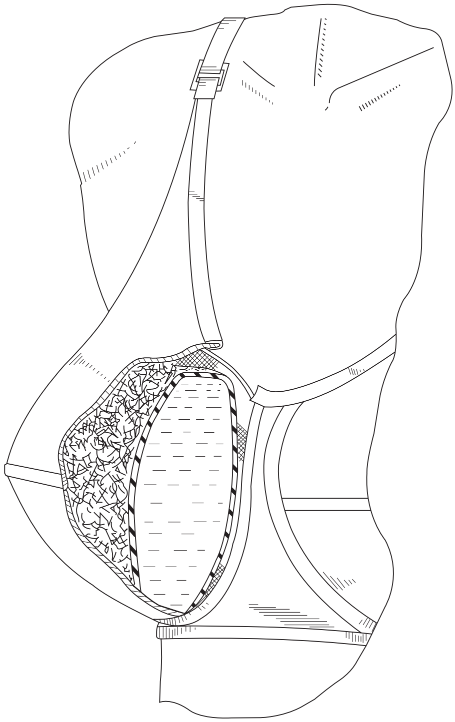
8.11 Design of mastectomy bra – prosthesis holding style [51]. (a) Front view of fold-down mastectomy bra, (b) Exploded view of fold-down cup.

8.5.5 Recent research

Recently, Tsang *et al*. has carried out research to evaluate mastectomy bras for Hong Kong women. In-depth interviews with mastectomy patients have revealed the physical and psychological needs of the patients and their expectations for the mastectomy bra. It was found that the expectations of the patients could be divided into three categories: style design, pattern design and fabric combinations within the mastectomy bra. For the style design, most of the patients preferred a padded cup with a horizontal cut seam, a straight around cup and inside pocket with two openings rather than the lace or wired style. The ideal or preferred mastectomy bra pattern had a high top cup with short bottom cup, narrow top bridge, high wing, long back curve of the wing, wide shoulder strap and underband. The patients were also concerned about the fabric's durability, elastic recovery, moisture absorbency and breathability. The study was helpful for the development of a mastectomy bra for the Hong Kong mastectomy patients [53].

8.6 Maternity underwear

During the last trimester of pregnancy, most women experience substantial pressure and discomfort, including lower back pain, pelvic aches and strain of the anterior abdominal muscle wall. Breast enlargement in the antenatal



8.12 Mastectomy bra with a built-in prosthetic device [52].

and postnatal stage may cause breast soreness [54]. Different maternity undergarments are designed to alleviate such discomfort by providing support to the breasts, the lower back and the abdomen of pregnant woman. A selection of maternity garments, such as maternity bra, belt, girdle, briefs, cradle and bodysuit are widely commercially available. As many women nowadays remain active during their pregnancy, product development with the emphasis on comfort in these maternity undergarments has become very important.

8.6.1 Maternity bras

Breast changes are one of the earliest signs of pregnancy. Stimulus by pregnancy hormones results in further development of the nipple and growth of the lactiferous tubules and ducts. This produces a sensation of heaviness, or even pain for a pregnant woman [54]. The increment of the breast size is not in direct proportion and usually is concentrated in the lower part of the breast. It is recommended not to wear a larger cup size or a loose-fitting bra for the enlarged breast.

A good maternity bra is essential to provide support and comfort for the pregnant woman. However, there are few choices of maternity bra offered in the market other than that of the nursing bra. The common maternity bra is made of elastic fabrics like Cotton Lycra® or Nylon Lycra® which provide flexibility for expansion. Very often the maternity bra will provide four-row hooks and eyes for better adjustment. Wire is necessary to provide enough support to the enlarged breasts and prevent breast sagging. The maternity bras provided by Wacoal® used 'soft flat wire' or 'maternity wire' which could provide enough support without affecting comfort.

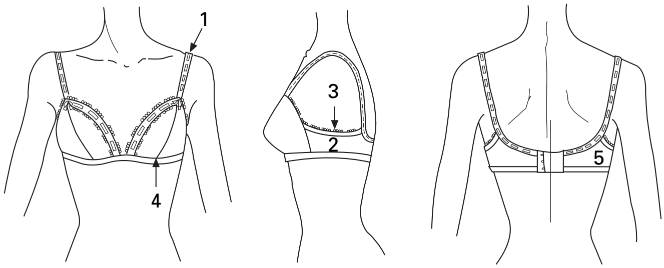
As there is a lack of literature related to the maternity bra, Lee conducted market research on the maternity products found in Hong Kong [55]. The results showed that very few maternity bras could be found on the market. Most consumers focused only on the nursing bra and neglected the importance of the maternity bra. The fabrication and garment details were compared between the maternity and the nursing bra. The nursing bra was designed mainly for convenience of breastfeeding while the maternity bra was usually designed to provide good support for the enlarging breasts. Moreover, the maternity bra was usually designed without a cradle so as not to increase the pressure on the stomach [55]. It was commented that further development and wide promotion of maternity bras is necessary to increase consumer awareness on preventing breast soreness and breast sagging.

8.6.2 Nursing bra

The weight of the enlarged breasts of a pregnant woman tends to pull the breasts down so that the tissues attaching the breasts to the chest wall and the skin over the upper part of the breasts are stretched. The excessive stretching of the skin, which caused the breasts sagging, can be partially prevented during pregnancy by wearing a good supporting bra [56].

Anastasia *et al*. have conducted pressure analysis to determine the design criteria for increasing the comfort of a nursing bra. The objectives of their study were to determine whether localized pressure on the areas of breasts, shoulders, and back of nursing mothers could be decreased by varying specific design features of the nursing bra and whether objectively measured changes in pressure were related to noticeable changes in subjective perception of bra comfort. The researchers measured the pressure readings in five locations (as shown in Fig. 8.13). The results indicated that there was a relationship between the pressure a garment exerted on the body and the wearer's comfort. The design features could be developed to distribute pressure more evenly on the body. For example, an increase in the width of the shoulder strap of a basic bra from 5/8 to one inch could significantly reduce the pressure at point 1 (the shoulder) and 5 (the back) [57].

Traditionally, the nursing bra was constructed with buckles, hooks [58], clasps [59] or snaps [60] for the detachable bra cup. Instead of using two hands to fasten or unfasten the bra, the wearer can open and close the cup



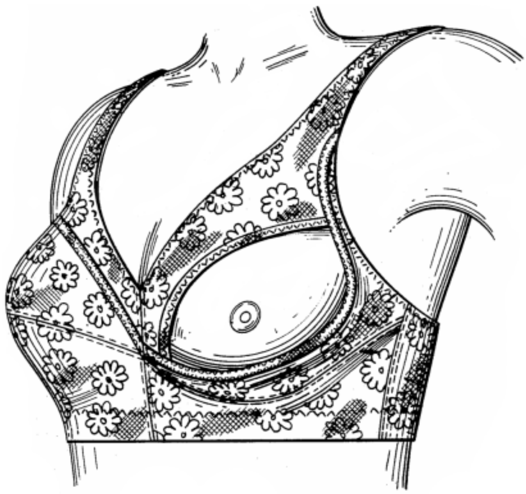
Body area
1. At the top of the shoulder on the trapezius muscle under the bra strap.
2. Directly inferior to the centre of the armpit, in the middle of each side panel.
3. Under the top elastic of each panel, directly inferior to the centre of the armpit.
4. Under the elastic band at the base of the bra, directly inferior to the nipple.
5. One and one-half to two inches from each side of the centre back clasp, directly inferior to the crest of each shoulder blade.

8.13 Locations of pressure reading for various bra designs.

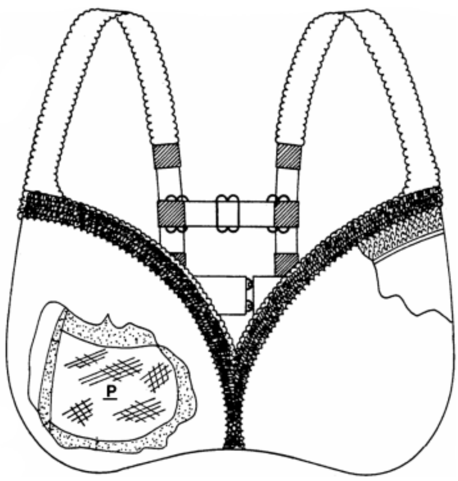
components easily using one hand. Most nursing bras are designed with detachable means either at the front of the shoulder straps [61] or in the upper portion of the cup [62]. Mothers always find that these products fail to provide an expedient, discreet manner to open and close cups for breast feeding. In the light of these problems, new designs without fasteners were proposed. Porco designed a bra with an upper cup portion and a 'fold-over' portion that allowed easy opening for nursing [63]. However, the overlapping materials created a 'bulky' look and was easily pulled away from the body. An improved design suggested by Scullin used 'freely folding' construction [64] that could solve this problem and provide aesthetically pleasing effects. Figure 8.14 shows the nursing bra designed by Scullin.

Many nursing bras have sought to allow a measure of convenience to mothers. For example, a maternity and nursing bra designed by Sanchez provided a one-handed fastening and unfastening operation for discreet nursing (see Fig. 8.15). The design allowed a stronger cup support and variable adjustment of cup size. It was accomplished by affixing hooks of Velcro on an inner cup and loops to an inner band [65]. Other nursing bras were emphasized as having 'hands-free' breast pump support which allowed simple and effective breast milk expression [66–68].

There have been numerous nursing bras that have attempted to provide a sanitary environment for breast feeding newborn children. Basically, these products used replaceable absorbent pads to prevent milk leakage from seeping into and through clothing. For instance, Turner *et al.* described the use of a moisture absorbing pad placed within a removable section of the bra. The pad must be detached from the main body of the bra during breast feeding



8.14 Nursing bra with 'freely folding' construction [64].



8.15 Nursing bra providing one-handed fastening and unfastening operation for discreet nursing [65].

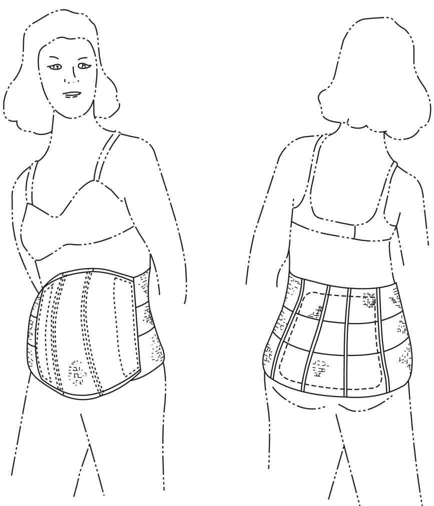
[69]. The nursing bra is a necessary item of maternity underwear, especially as breast feeding has become increasingly popular in recent years. It is suggested that product development on nursing bras should cover the mother's concerns of support, convenience, comfort, fit and hygiene.

8.6.3 Maternity supportive undergarments

The purpose of a maternity supportive undergarment is to support the abdomen and lower back of pregnant woman without restricting the growth of the developing baby. As the womb becomes larger and heavier, it puts strains on the lower abdomen, lower back and groin area. Pregnant women naturally clasp their hands under their abdomen and distribute the weight burden between their elbows and shoulders. The supportive undergarment holds the abdomen in the same manner to provide symptomatic relief from pain. The supportive undergarment can be categorized into four main groups: belts, girdles, cradles and bodysuits. The product development of each group will be briefly described with emphasis on their merits and limitations.

Maternity support belt

A maternity support belt is an elastic panel wrapped around the body under the abdomen. An early design by Castiglia was a fully adjustable lower torso support appliance which included an elastic portion extending around the back of a wearer (see Fig. 8.16) [70]. Similar designs can be easily found on the market and most styles used Velcro tabs or buckles as fasteners. However, the simple belt design was not structured to provide optimum comfort. Walker later improved this by providing a non-padded, expandable front panel made of soft material to allow fullness across the abdomen with room to accommodate abdominal expansion [71]. Alberts designed a maternity brace which could provide more support to the abdomen of the wearer and distribute forces in the abdominal region to other portions of the body [72]. Maternity belts are popular and widely used by pregnant women as they are easy to wear, adjust and take off. However, some consumers may complain that the belt is stiff, has not enough support and restricts their body movement [73].



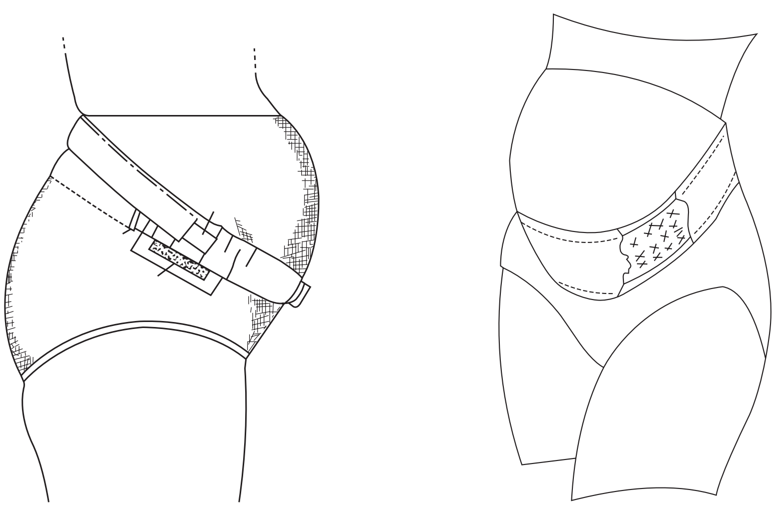
8.16 Maternity support belt [70].

Maternity girdle

A girdle is a controlled brief with supportive panel at the abdomen. Typical designs could be found in the US Patents [74–75], as shown in Figs 8.17(a) and (b) respectively. The girdle usually looks simple and can provide well distributed pressure to the abdominal region. However, it is difficult to put on and take off. Sometimes, too much pressure will cause discomfort and influence blood circulation. A side-leg opening girdle invented by Jackson permitted direct placement of the front panel against the torso without the need to pull the front panel upwards against, around and over the protruding abdomen [76].

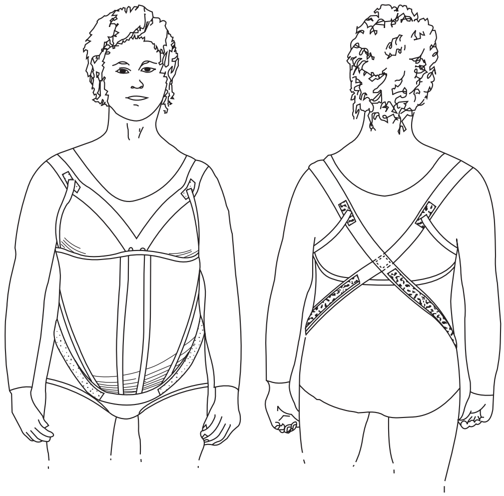
Maternity cradle

A maternity cradle is made of suspenders with different shapes of belts. BabyHugger®[17], as shown in Fig. 8.18 (US Pat. No. 4,789,372), is one type of this cradle. The inventor claimed that the design could lift the abdomen, and transfer the weight of the abdomen to the wearer's shoulders. It is claimed that the product helped to reduce the chance of getting varicosities or stretch marks [77]. Other cradle designs by Ford [78], Seering [79] and Wicks [80] could also assist in carrying and distributing the weight of the extended abdomen, improve the posture and eliminate the acute abdominal and lower back pain. However, the products look quite odd to certain consumers [73].



(a) (b)

8.17 Maternity girdle designs. (a) Maddux's design [74]; (b) Unger's design [75].



8.18 Maternity cradle – BabyHugger® [77].

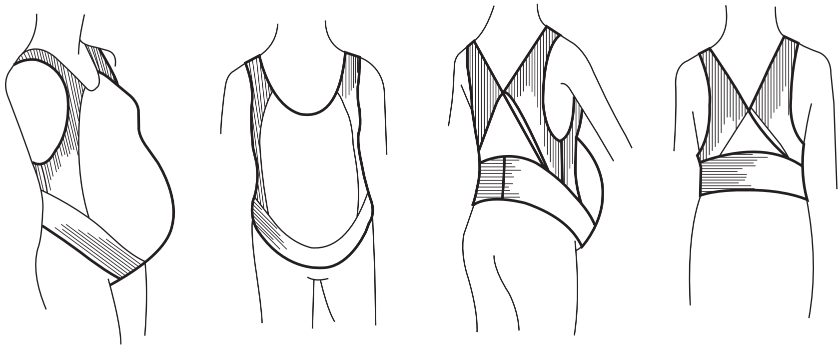
Maternity bodysuit

A maternity bodysuit, also used for athletic activities, looks like a one-piece bathing suit, to be worn during pregnancy in order to ease discomfort and permit the pregnant woman to engage in relatively vigorous physical activity. Steiman's maternity bathing suit [81], Moyer's maternity exercise garment [82] and Hilpert's exercise undergarment [83] are some of the examples in this category.

Yu *et. al.* evaluated different designs of maternity undergarments and developed a new fashion prototype for optimum physical support and protection. They made several garment prototypes, performed fitting trials and moiré topographic shape analysis. The final prototype (shown in Fig. 8.19) was found to be optimal in providing the required support, having simple and nice styling with perfect fit and comfort. Further research conducted by Yu *et al*. aimed to study the problems of low back pain during pregnancy in a wider perspective. It was a multi-disciplinary research into the effects of the wearer's 3D anthropometry, psychology, skin sensation, biomechanics and motion analysis and their pain perception and pregnancy outcome. A new design principle has been developed to make medical garments to relieve or prevent the low back pain symptoms [84]. This could also help to alert people to health concerns in designing garments for special needs.

8.7 Conclusions

This chapter has described five special categories of intimate apparel including sports bra, pantyhose, swimwear, mastectomy bra and maternity underwear.



8.19 Maternity supportive undergarment designed by Yu *et al.* [73].

The important requirements of these products are support, comfort and aesthetic appeal. The sports bra is designed to reduce breast motion. It helps to control excessive breast motion and reduce breast pain during vigorous activities. With moisture management technology, a sports bra can provide good air permeability and optimum heat regulation. Other specific features, like anti-bacteria or odour elimination can also be achieved by the application of pure silver coating on the fabrics. Pantyhose provide a shape-up effect and are worn principally to enhance the beauty of legs, a result of their optical properties of transparency, lustre, and colour. New materials developed are not only used to improve aesthetic effect, but also to add special properties, like ease in putting on, good stretchability and good hand feel.

The 21st century has marked a new era in swimwear for women. Swimwear is now becoming more fashionable and functional. The new swimwear fabrics are engineered to exact standards of elongation, power and recovery to assure a flawless fit of the swimsuit. These fabrics must feature fast-dry, excellent chlorine resistance, minimal yellowing, and resistance to degradation due to exposure to suntan oils and perspiration.

Mastectomy is a surgical removal of all or part of a breast. A mastectomy bra is specially designed to enable the patients suffering from a mastectomy to overcome the mental and physical shock. A well designed mastectomy bra should provide enough support to the excessive weight of the prosthesis and give the appearance of having a pair of complete natural breasts.

Maternity undergarments including maternity bra, maternity support belt, girdle, cradle and bodysuit are designed to alleviate discomfort caused by pregnancy. They are used to provide support to the breasts, the lower back and the abdomen of pregnant woman. A nursing bra is a necessary maternity undergarment used for breast feeding. Product development on maternity undergarments should consider the mother's concerns of support, convenience, comfort, fit and hygiene.

8.8 Acknowledgement

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9
Performance evaluation of knitted underwear

J KAR, J FAN and W YU

9.1 Introduction

Underwear is a type of apparel worn next to the skin for reasons of hygiene and comfort [1]. It should provide comfort for the wearer, possess good sewability, retain its appearance during wear, be durable and have easy-care properties [2, 3]. This chapter considers the functional requirements of knitted underwear fabrics, describes the relevant standards and test methods for the performance evaluation of such fabrics, and reviews the recent developments in fabric engineering and product innovation. It serves to provide a reference for the product development and evaluation of knitted underwear fabrics.

9.2 Functional requirements of knitted underwear

9.2.1 Comfort

Comfort is a primary requirement of clothing, which can be categorized into aesthetic comfort, thermal comfort, moisture comfort, tactile comfort and pressure comfort [4]. Aesthetic comfort is the subjective perception of clothing by visual sensation [5] which is influenced by colour, style, garment fitting, fashion compatibility, fabric construction and finish [6, 7].

Thermal comfort is primarily related to the efficiency of heat dissipation from a clothed human body [6] and is viewed as the 'neither too hot nor too cold' feeling of the wearer [8]. The body is in a state of comfort when the core temperature of the body is maintained at 37 °C and the average skin temperature is approximately 33 °C without the presence of sweat. One of the primary functions of underwear is to act as a buffer against environmental changes to maintain a thermal balance between the heat generated by the body and the heat lost to the environment while allowing the skin to remain free of liquid water [6].

Moisture comfort is dependent on the dampness sensations which are recommended as a sensitive tool to evaluate the thermal function of garments according to the subjective sensations of wetness of skin and clothing [9]. Although humans have no humidity receptors, in some way the wetness of the skin is also sensed, and can be related to the evaluation of comfort and discomfort [10]. This has been confirmed by Hollies [11] who found that the sensation of loss in comfort occurred if there was sweating. When more than 50–65% of the body surface is wet, discomfort is experienced [12].

Tactile comfort is related to the frictional interaction between clothing material and the human body [6], where physical/mechanical properties (surface structure, weight per unit area, thickness, bulk, compressibility, flexure, shear, elongation and frictional properties) of the fabric worn next to skin are thought to influence an individual's assessment of tactile comfort [13, 14]. Some of the terms that have been used to describe the tactile sensations are clingy, sticky, scratchy, prickly, soft, stiff, heavy, light and hard [6]. Tactile discomfort may be derived from allergy, clinging to the skin, tickling, prickling, abrasion of the skin and coolness [7]. The finishes, dyes, softening agents, washing powder used in laundering, the structure and construction of the fibres and fabrics are contributing factors that can cause tactile discomfort. For example, if a fabric is hairy and rough to the touch, and tends to shed fibres, it may cause tickling and irritation, especially when the skin is damp with perspiration [15]. Ruckman and Green [16] also confirmed that skin irritation could be caused by breakage of the fibres and the fabric remaining wet during perspiration. Fabric hand is a generic term for the tactile sensations associated with fabrics that influence consumer preferences [17]. To specify the fabric hand of underwear, Chen [18] reported that the best hand for use in undershirts was rated as being the softest, slickest, smoothest, thinnest, lightest and coolest.

Pressure comfort has already been discussed in detail in Chapter 7. Ishtiaque [19] suggested the comfort requirements for general clothing, which are also relevant to the comfort requirements of underwear. These are listed in Table 9.1.

Table 9.1 Functional requirements of clothing [19]

- Maintains a comfortable microclimate in terms of temperature and humidity in the skin sensory zone.
- Good moisture absorption and water vapour transmission.
- Absence of unpleasant odour such as perspiration.
- Compatibility with the skin.
- Good extensibility without restricting mobility.
- Good fit stability.
- Low intrinsic weight (not impairing physical performance).
- Fabric substantially water-repellent and dirt-repellent.

9.2.2 Sewability

Underwear should be manufactured to a consistent quality free from defects. One of the major potential sewability problems of knitted underwear fabrics is sewing damage (needle holes). This is particularly a problem for tighter, denser and lightweight knitted underwear fabrics. There are generally two types of sewing damage derived from frictional forces in the fabrics, mechanical damage and needle heating damage. Mechanical damage is the cutting or breakage of yarns in the fabric caused by the penetration of the needle during sewing. Needle heating damage is the fusing and melting of synthetic yarns in the fabric caused by the high needle temperature arising from the friction between the needle and the fabric. The faults may be noticed only during wear or after laundering when the damaged holes are enlarged as a result of yarn laddering owing to the stresses during wear and laundering [20].

Sewing damage is related to the choice of sewing needle (in terms of size, needle length and point shape) and sewing speed. Needle size determines the extent of the deformation of the knitted loops within the fabric, and directly influences the stresses and strains imposed on the yarns. Moreover, short-point needles interact with the fabrics more violently than long-point needles, and tend to produce more yarn breakages. The use of bulged-eye needles, in which the diameter of the needle at the eye is enlarged with respect to the diameter of the shaft, can assist to reduce the sewing temperature effectively (about 15–30 °C). Furthermore, lower sewing speeds are effective in controlling the overheating problems of needles. At the same time, the number of yarn breakages is relatively reduced [20]. Therefore, finer needle size [21], bulged-eye needle [20] and reduced sewing speed [22] can reduce sewing damage.

On the other hand, the ease of deflection depends not only on the needle, but also on the ease of yarn movement which is related to yarn friction. With increasing yarn friction, the level of each penetration force value will be greater, since the increased yarn friction will lead to a higher value of tension in the yarn around the needle as it is pulled from the adjacent loops [23].

It is also known that the condition under which sewing takes place can also affect sewing damage. It was reported that the lower moisture content in winter of about 8% in cotton fabrics make them brittle and thus susceptible to sewing damage [24]. Therefore knitted fabrics should not be sewn in an over-dry state. Application of appropriate lubricants to the fabric can lower the frictional forces in the fabric to allow needle penetration easily. Heat generation and mechanical strains also can become relatively lower [20]. This can significantly improve sewing performance by reducing the number of yarn breakages. Cooling attachments can also reduce needle heating. A cooling air jet can be used to increase the convective heat losses from the needle and reduce its temperature. With the vapour spray, a coolant of light oil or similar material is atomized and sprayed over the needle and onto the fabric so that the coolant can absorb heat [20].

9.2.3 Appearance and appearance retention

The presence of pilling and discoloration are major problems related to cotton underwear. Ukponmwan [25] defined pilling as a fabric-surface fault in which pills of entangled fibres cling to the cloth surface, giving an unsightly appearance to the garment and reducing its serviceable life [26]. The broken loose fibres develop into fluffy agglomerations anchored to the fabric surface and are called pills. Generally, the pills are produced by attrition with different parts of the garment, by rubbing against the same fabric or other objects, or by other mechanical actions such as several cycles of laundering and drying, during wear and cleaning [26–28]. As a result, it causes negative performance in appearance, fell, texture and service life of the garment with pills [27]. Pilling is a serious problem for knitted underwear. Because of their knitted loop construction, a greater yarn surface area is exposed, making such fabrics more susceptible to abrasive wear [25].

Colourfastness is also an important requirement for underwear. Colourfastness is defined as the resistance of a fabric to change in any of its colour characteristics and to the transfer of its colourant(s) to adjacent materials during end-use [29]. According to ASTM D4154 [30] and ASTM D4156 [31], the colourfastness requirements of underwear under different end-use conditions are listed in Table 9.2.

9.2.4 Durability

The durability of knitted underwear is commonly characterized by bursting strength and abrasion resistance [32, 33], which are important attributes for the aesthetics and functional performance of underwear during use [32]. ASTM D4154 [30] and ASTM D4156 [31] state that the bursting strength of knitted underwear should exceed 222 N (50 lbf) for a durable garment based on the ball-burst testing method of ASTM D3786, where the test sample is cut into 375 mm (15 in.) along the selvedge.

Table 9.2 Colourfastness requirements of knitted underwear fabrics

Colourfastness characteristic	Requirements
Laundering, shade change	Class 4^{A} min
Dry cleaning, shade change	Class 4^{A} min
Perspiration, shade change	Class 4^{A} min
Light (40 AATCC FU) (xenon-arc)	Class 4^{A} min

Source: [A]AATCC *Gray Scale for Colour Change*.

9.2.5 Aftercare

For repeated laundering of knitted underwear, shrinkage is potentially the most serious problem. Shrinkage is more likely to be present in the course direction compared to the wale direction in weft knitted fabrics following several laundering cycles, as fabrics tend to be stretched more in the course direction during manufacture. Laundering causes the release of these internal strains such that there may be a large increase in the course density and with less change in wale density as reported in previous research [26, 34].

Abrasion damage is another problem during daily use. It was reported that as much as 50% of the abrasion damage in some fabrics could be attributed to laundering [35]. Much of the laundry abrasion damage is in the form of extensive peeling of the cuticle, primary and secondary wall of the cotton fibre, in the form of fibrils, fibril bundles and sheaths. Fibre encrustation is caused by laundering with sodium carbonate-based detergent used with different degrees of water hardness and phosphate-based detergent used with very hard water (284 ppm) [34].

In addition to laundering, drying underwear with a household tumble dryer is another factor that causes severe fibre damage, especially for wet fabric dried at high temperature. For cotton, dried at high temperature for five cycles, serious abrasion damage, changes in fibre morphology and fibre breakage under the microscope have been observed. Although the damage was reduced when the wet fabric was tumbled without heat after five cycles, there was also substantial damage to the fibre walls. Buisson [36] recommended that the fabric should be placed in the dryer after the set temperature was reached to reduce abrasion damage. Moreover, reducing the time to reach the set temperature by controlling heat energy or airflow may also potentially minimize tumble drying damage.

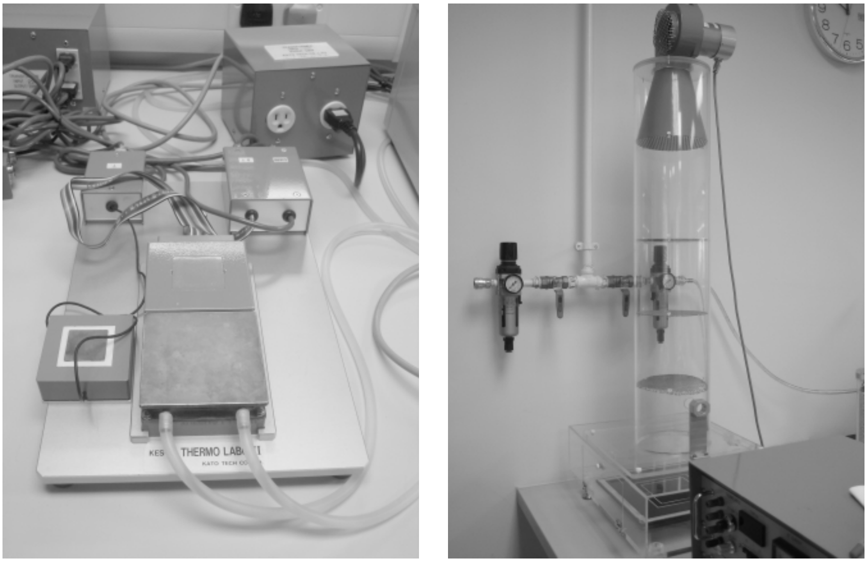
9.3 Performance evaluation of knitted underwear

9.3.1 Thermal properties

There are many different testing methods and apparatuses used for measuring the thermal conductivity, thermal transmittance, thermal resistance or insulation and warm/cool feeling of fabrics. BS 4745 and KES-FB7 are two commonly used testing methods for measuring thermal properties of the fabrics.

Thermo Labo II KES-FB7

This instrument (as shown in Fig. 9.1) is used to evaluate thermal conductivity and insulation in dry and wet conditions (simulating sweating or no sweating) of fabrics, and the warm/cool feeling when the fabric is in contact with the skin precisely and quickly. For thermal conductivity measurement, water at



(a) (b)

9.1 (a) and (b) apparatus of Thermal Labo II.

20 °C circulates inside the water box, and the BT-plate and the guard plate in the BT-Box is pre-set to 30 °C and 30.3 °C. The heat loss from the BT-box through the test specimen to the water box in watts is recorded by digital panel meter. The thermal conductivity in watts/cm·°C can be calculated by

$$k = (W \cdot D)/\mathrm{A} \cdot \Delta T_o \qquad 9.1$$

where D = the thickness of samples;
A = area of heat plate of BT-box (25 cm^2);
ΔT_o = temperature difference between BT-box and water box (10 °C);
W = the reading on the digital panel meter, which is the heat consumption of the BT-box.

On the other hand, the warm/cool feeling test is used to determine the initial contact feeling of fabric. The T-box and water box are used in this measurement where the BT-box at 30 °C supplies heat to the T-box until they have the same temperature with the water box temperature set to 20 °C. The warm/cool feeling is represented by a q-max value which is the heat current required per unit area to maintain the condition of a 10 °C temperature difference recorded on the digital panel meter.

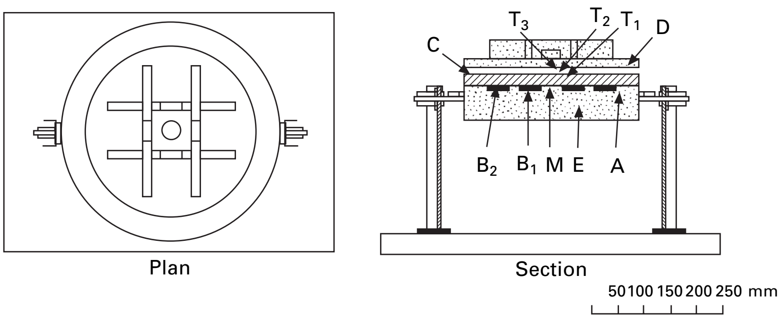
For measuring thermal insulation, there are four methods as below:

1. Dry contact method – the thermal insulation of the fabric is measured with the fabric directly in contact with the BT-plate;

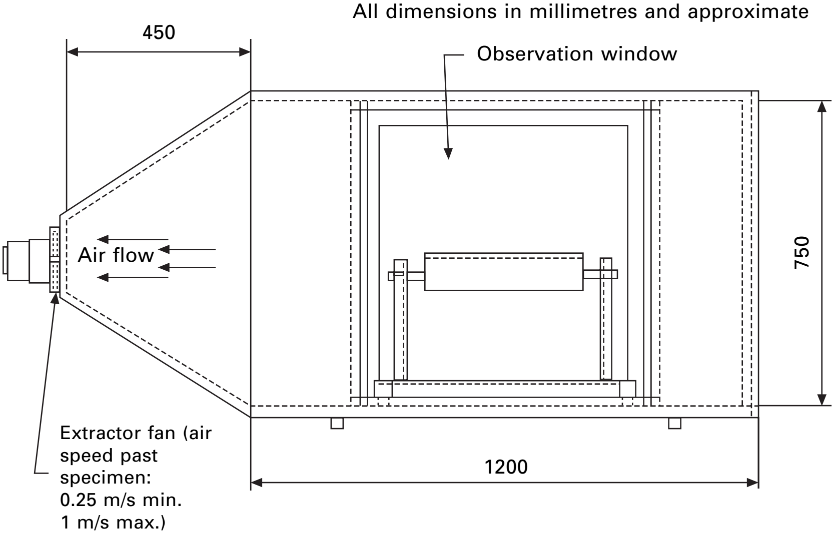
2. Dry space method – the thermal insulation of the fabric is measured under the condition that there is a constant distance between the fabric and the BT-plate;
3. Wet contact method – the thermal insulation of the fabric is measured under the condition that the fabric is in direct contact with a wet filter paper on the BT-plate;
4. Wet space method – the thermal insulation of the fabric is measured under the condition that there exists a constant distance between the fabric and wet filter paper on the BT-plate.

BS 4745:1990 / ISO 5085-1:1989 Method for Determination of Thermal Resistance of Textiles

This testing standard (BS 4745:1990/ISO 5085-1:1989) [37] specifies a method for 'the determination of the resistance of fabrics, fabric assemblies or fibre aggregates in sheet form to the transmission of heat through them in the "steady state" condition.' The apparatus is shown diagrammatically in Figs 9.2 and 9.3. This standard includes two testing methods, a two-plate method and a single-plate method. The two-plate method is used to measure the thermal resistance of the material with the test specimen between a hot plate and a cold plate. This is similar to the thermal conductivity testing method used in the KES-FB7 apparatus. For the single-plate method, the test specimen is just laid on the hot plate and the outer side is exposed to the ambient air. The single-plate method is more suitable for measuring the thermal properties of underwear because it allows more air circulation so that it simulates the wearing condition. The thermal conductivity of the fabric is calculated by the thickness divided by its thermal resistance which is the ratio of the temperature difference between the two faces of the fabric to the heat flow rate per unit area normal to the faces.



9.2 Diagram of apparatus [37].



9.3 Diagram of cabinet [37].

9.3.2 Moisture permeability

Two testing methods, the desiccant method and the water method, are specified in ASTM E96-90 [38] to determine the water vapour transmission of sheet materials of thickness not exceeding 32 mm. According to the wearing conditions of underwear, the moisture properties of fabrics may be evaluated by the water method. A test specimen is attached to cover the dish/cup and wax is used to seal the fabric to prevent edge leakage, which is shown in Fig. 9.4. The change in mass of water is used to calculate the water transmission rate.

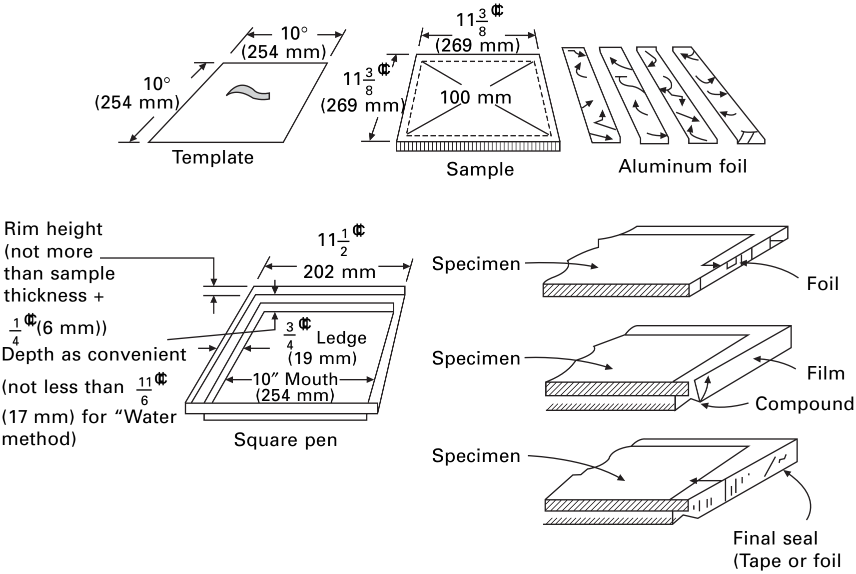
9.3.3 Liquid transport properties

Wetting

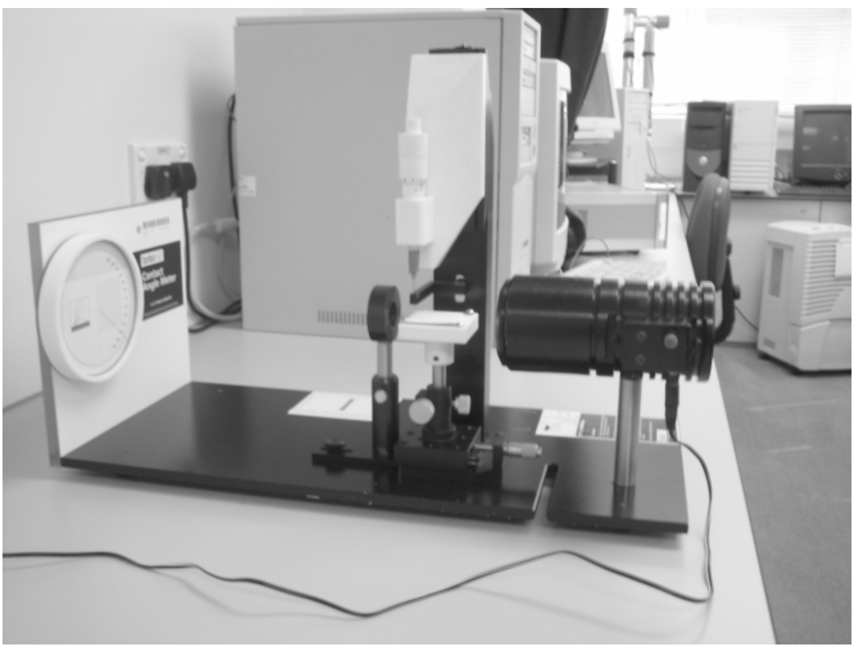
ASTM D5725 [39] defines a test method to measure the contact angle of water in contact with a flat specimen of a fabric under specific test conditions (Fig. 9.5). A drop of a specified volume of water is applied to a fabric surface using a liquid delivery system. The rate of change of the contact angle is recorded by a video camera and is used to determine the water absorbency of the fabric.

Wicking

Harnett and Mehta [40] have described two methods to measure the wicking properties of fabrics. They are the longitudinal wicking strip test and the



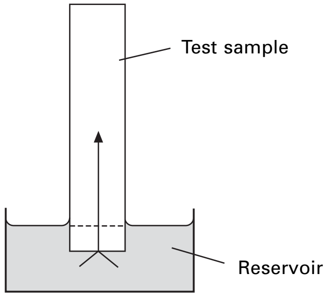
9.4 Water vapour transmission tester [38].



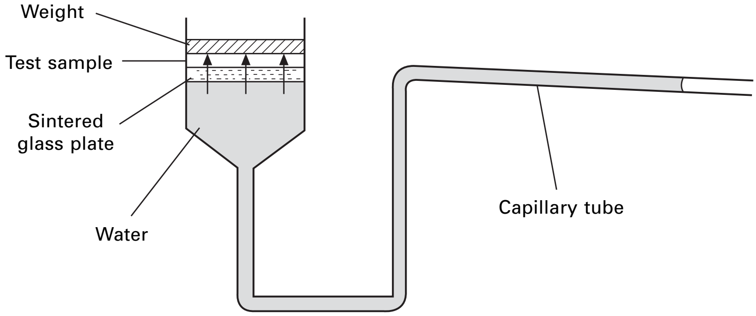
9.5 Contact angle tester.

transverse wicking plate test. For the longitudinal wicking strip test, a strip of fabric is suspended vertically with its lower edge immersed in a reservoir of distilled water as shown in Fig. 9.6. It is recommended to add a dye to the water in order to track the movement of the water more easily. The measured height of rise in a given time is used to indicate the wickability of the test fabric. The water wicking performance is highly dependent on the fabric structure and thickness and it is difficult to compare the wicking performance of fabrics with extreme thicknesses or structures.

The transverse wicking plate test is used to determine water transmission according to fabric thickness, that is, perpendicular to the plane of the fabric. It simulates the mechanism of liquid perspiration moving from the skin through the fabric. The test fabric is placed between a weight and sintered glass plate as shown in Fig. 9.7. The horizontal sintered glass plated is kept moist by a water supply whose height can be adjusted so as to keep the water level precisely at the upper surface of the plate. The fabric will draw water from the glass plate at a rate which is dependent on its wickability. Given the diameter of the capillary tube, the recorded data is used to calculate the mass transfer rate of water into the fabric.



9.6 Longitudinal wicking strip test.



9.7 Transverse wicking plate test.

9.3.4 Fabric low-stress mechanical properties

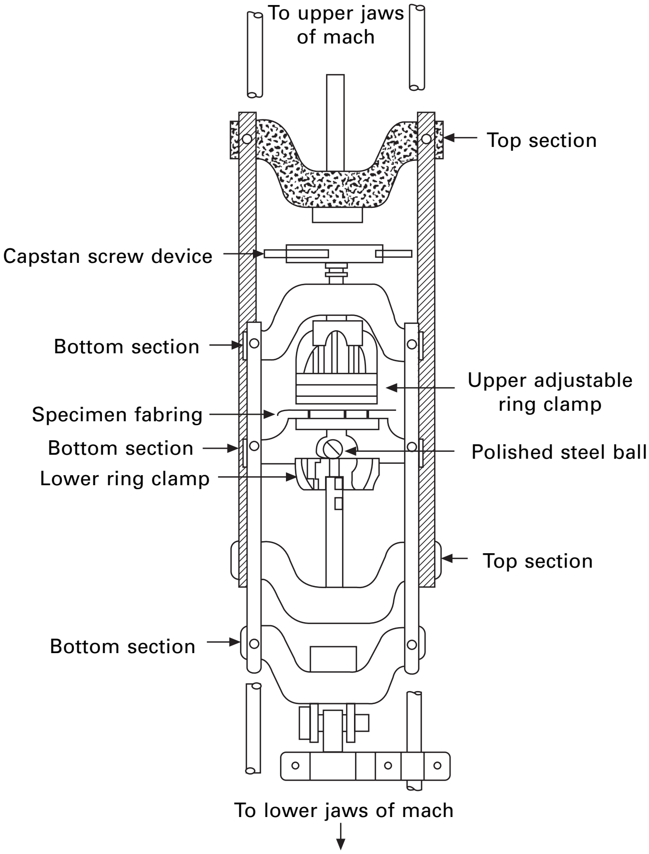
The handle and tactile comfort of knitted underwear are strongly related to the fabric low stress mechanical properties. The Kawabata evaluation system (KES-F) is a set of sophisticated instruments for characterizing the fabric low-stress mechanical properties, which include tensile, shear, bending, compressional, and surface properties [41]. The specimens are cut into 20 ¥ 20 cm^2 samples and conditioned at 21 °C and 65% R.H. for at least 24 hours before taking the measurements. The instruments comprising the KES-F system are shown in Figs 9.8–11.

9.8 KES-F1 shear and tensile tester.

9.9 KES-F2 bending tester.

9.10 KES-F3 surface tester.

9.11 KES-F4 compression tester.



9.12 Ball burst attachment [42].

9.3.5 Fabric bursting strength

As has been previously mentioned, the durability of underwear fabrics is very much related to their bursting strength. ASTM D3787 [42] defines a method that may be used to measure the bursting strength of knitted fabrics using a ball-burst strength tester (Fig. 9.12). The instrument consists of a polished steel ball which has a diameter of 25.4 ± 0.005 mm. The conditioned fabric specimen is placed tension-free in the ring clamp of the device. The polished steel ball is then pushed through the specimen until it ruptures. The bursting strength is determined as the force applied to the ball at the instant of fabric rupture.

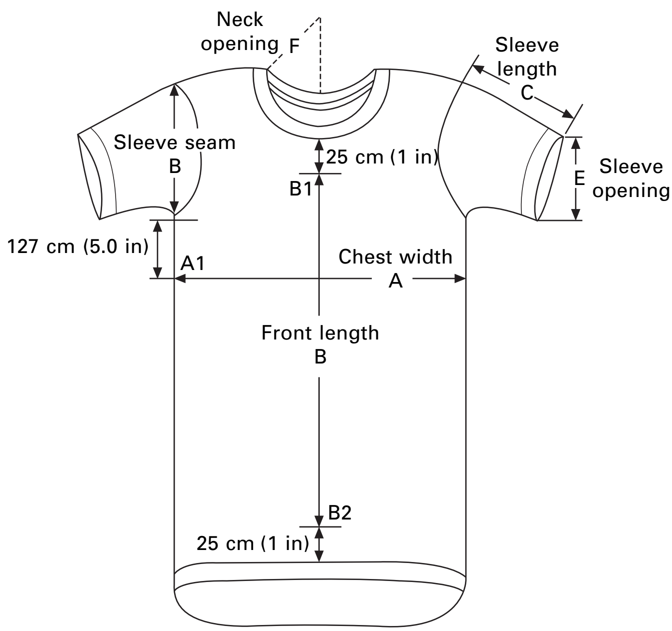
9.3.6 L&M sewability test

This test measures the needle penetration force to predict the sewability of the fabric. The apparatus is called the L & M Sewability Tester. The fabric is fed forward by rollers beneath a needle that penetrates it. It can operate at a speed of 20 penetrations per minute, which means a test of 100 penetrations takes no longer than five minutes. The peak force of penetration is indicated on the meter and registered on a pen recorder. Penetration values that exceed a critical threshold value can be registered on the ‘high reading’ counter [23].

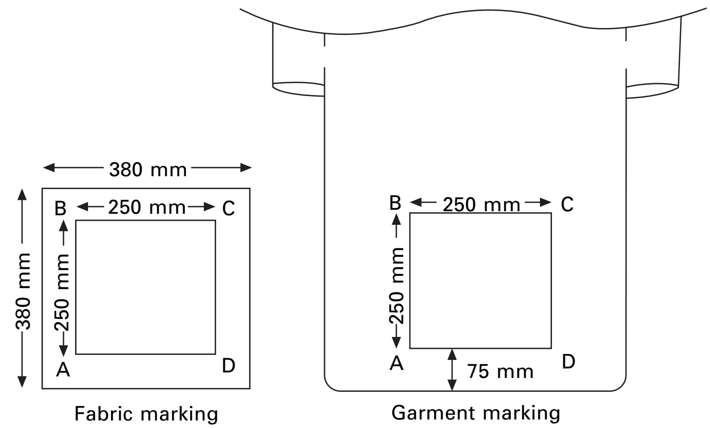
9.3.7 Dimensional stability and skewness stability

AATCC TM 150 [43] describes a method to measure the dimensional change after laundering. Locations are marked as shown in Fig. 9.13 using a plastic or metal tape graduated in millimetres after laundering. This testing method can be used to measure the shrinkage or extensibility at different positions of undershirts after laundering.

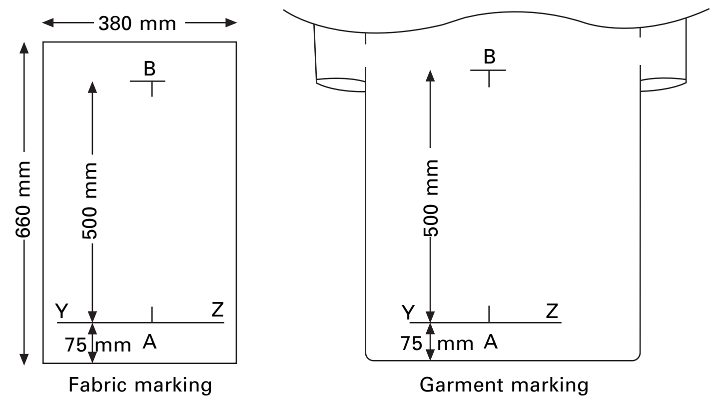
For measuring the skewing stability of under-shirt fabrics, AATCC TM 179 [45] provides two methods to mark the positions on the garment or fabrics before laundering, as shown in Figs 9.14 and 9.15. There are three options to calculate the skewness changes in undershirt fabrics. For method 1, the percentage change in skewness to the nearest 0.1% can be calculated by the following two options: Option 1, (Fig. 9.16) percentage change in skewness = 100 ¥ [2 (AC – BD)/(AC + BD)].
Option 2, (Fig. 9.17) percentage change in skewness = 100 ¥ [(AA¢+ DD¢)/ (AB + CD)].



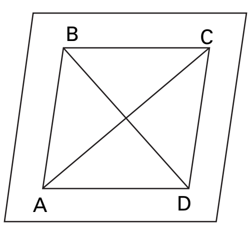
9.13 Dimensional change marking location [44].



9.14 Method 1 of AATCC TM179 skewness stability testing method: square marking [45].

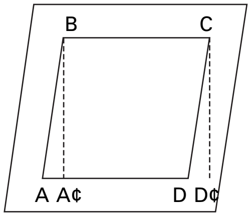


9.15 Method 2 of AATCC TM179 skewness stability testing method: inverted marking [45].

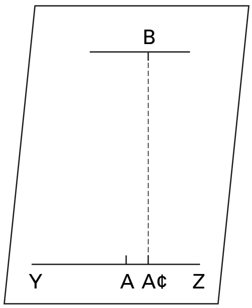


9.16 Diagonal lines for option 1.

For method 2, change in skewness can be measured by calculating option 3. Option 3, (Fig. 9.18) percentage change in skewness = 100 ¥ (AA¢AB). Tables 9.3, 9.4 and 9.5 summarize alternative washing and drying conditions and settings for the dimensional stability and skewness stability measurements.



9.17 Offset marks for option 2.



9.18 Offset marks for option 3.

Table 9.3 Alternative washing and drying conditions [45]

Machine cycle	Washing temperatures	Drying procedures
1. Normal/Cotton Sturdy	(ii) 27 ± 3 °C (80 ± 5 °F)	(a) Tumble:
2. Delicate	(iii) 41 ± 3 °C (105 ± 5 °F)	(i) Cotton Sturdy
3. Permanent Press	(iv) 49 ± 3 °C (120 ± 5 °F)	(ii) Delicate
	(v) 60 ± 3 °C (140 ± 5 °F)	(iii) Permanent Press
		(b) Line
		(c) Drip
		(d) Screen

Table 9.4 Washing machine setting conditions without load [45]

Cycle[1]	X	Y	Z
Water level	18 ± 1 gal	18 ± 1 gal	18 ± 1 gal
Agitator speed	179 ± 2 spm[2]	119 ± 2 spm	119 ± 2 spm
Washing time	12 min	8 min	10 min
Spin speed	645 ± 15 rpm[3]	645 ± 15 rpm	430 ± 15 rpm
Final spin cycle	6 min	6 min	4 min

[1]Cycle names vary with machine model, 'X' generally corresponds to 'heavy duty', 'Y' generally corresponds to 'delicate', 'Z' generally corresponds to 'permanent press'.
[2]spm = strokes per minute.
[3]rpm = revolutions per minute.

Table 9.5 Tumble dry conditions [45]

Designation	Cycle	Maximum exhaust stack temperature with loaded dryer
a	Normal or permanent press	67 ± 6 °C (154 ± 10 °F) after 1983 (65 ± 6 °C (150 ± 10 °F) before 1983]
b	Delicate, synthetic, low	< 62 °C (144 °F) after 1983 (< 60 °C (140 °F) before 1983)
Cool down time	Normal and Delicate	5 min
	Permanent Press	10 min
	All	10 min after 1983

9.3.8 Colorfastness to water

In the AATCC TM 107 method [29] for measuring the colorfastness of knitted underwear materials, 60 ¥ 60 mm ± 2 mm specimens are immersed in freshly boiled distilled water or de-ionized water from an ion-exchange device at room temperature with occasional agitation to ensure thorough wetting out (approximately 15 minutes is generally required for average fabrics). Then, the test specimen is removed from the solution and passed between squeeze rolls to remove excess liquor when the wet weight of the test specimen is more than 3 times its dry weight. The test specimen is then placed between glass or plastic plates and pressed under a perspiration tester with 4.5 kg pressure. After heating in an oven at 38 ± 1 °C for 18 hours, the specimen is dried by hanging in air at room temperature. The colour change of the undershirt fabric is rated subjectively for colour change using a grey scale.

9.3.9 Wearer trials

Wearer trials are the ultimate test for the performance of knitted underwear, although the process tends to be expensive, time consuming and the results tend to be less reproducible and consistent [15]. Wearer trials are especially necessary for assessing the subject sensations of the wearers, for example, comfort sensations. Wearers are often asked to judge the comfort of the garments after carrying out a series of instructed activities. This method has been used for evaluating moisture, thermal, tactile and aesthetic comfort [11, 15, 16, 46–48]. Wearer trials can also be designed to obtain some objective sensory measurements under different wearing conditions [48], which are relevant to the behaviour of the knitted underwear. For example, sensors such as copper-constantan thermocouples may be attached to the wearers to measure skin temperature during a wearer trial [9, 49].

9.4 Engineering of knitted underwear fabrics

Knitted underwear fabrics can be better engineered with improved understanding of the effects of fabric composition, yarn properties and fabric structure. Nevertheless, since such effects are far from fully understood, the following discussion serves only to contribute towards the knowledge base for the engineering of knitted underwear fabrics.

9.4.1 Fabric composition

Cotton is the most common material used to make underwear. It was found that cotton was associated with both physical and psychological comfort, and was viewed as youthful, honest, pure and dependable [50]. From the Australian perspective, cotton is seen to be close to the ideal material for making sportshirts – the only disadvantage of cotton is that it is crushable [51]. Boslet [50] has also stated that it was difficult to find any fibre matching the advantages of cotton. However, cotton exhibited more broken fibres after abrasion and greater flexural rigidity. Furthermore, cotton could be more likely to cause skin irritation. On the other hand, other knitted underwear materials, conventional nylon and polyester were regarded as artificial, insincere, low quality, unfashionable, clammy, sweaty, clingy, synthetic and itchy [50, 51]. In recent years, the scene has totally changed. A number of studies have shown that by using appropriate yarn and fabric structures, clothes made from synthetic fibres can be as comfortable to wear as those made by natural fibres, especially the newly developed polyester fabrics [16, 52–56].

Many researchers [7, 16, 57, 58] stated that 100% cotton, or cotton-rich blends were more comfortable underwear materials as these were more effective to absorb water vapour and perspiration from skin than synthetic fibres. According to ASTM D1909 [59], the moisture regain values for specified fibres are shown in Table 9.6. Cotton is a vegetable fibre which consists mainly of natural cellulose with a thin coating of wax. During finishing, this wax coating will be removed, so the cotton fibre can absorb moisture effectively and allow it to evaporate easily. However, fibres with a higher absorption of sweat can increase the weight of the garment, especially when wearing this

Table 9.6 Moisture regain of different kinds of fibre

Fibre	Regain, %
Cotton, dyed yarn	8.0
Cotton, mercerized yarn	8.5
Nylon	4.5
Polyester	0.4

kind of underwear to exercise, and results in undesirable evaporative cooling after exercising [58].

On the other hand, composition is a contributory factor to fabric shrinkage. Quaynor *et al*. [60] conducted research to investigate the shrinkage of different knitted fabrics including polyester and cotton. It was found that cotton knitted fabric seems to have some progressive shrinkage. Polyester, another common fabric type used for making underwear, has better performance in preventing shrinkage. It can be explained by its low moisture regain property which is about 0.4%. Also polyester knitted fabrics do not swell in water and therefore have a high resistance to deformation. It has also been found that fabrics knitted from blended yarns (50% cotton/50% polyester) had a better dimensional stability compared to the fabrics from 100% cotton ring and open-end yarns [26].

In addition, fabric composition is directly related to its appearance after laundering. Bresee *et al*. [61] conducted research to evaluate the pilling problems of six different kinds of single knitted underwear fabrics made from 100% cotton, 50/50 polyester-cotton and 60/40 polyester-cotton. Three samples were bleached and the rest were both bleached and treated with a durable press finish. The unworn, unabraded and unlaundered fabrics were pill free and laundering caused pilling and affected pill grades of 100% cotton fabrics more than the polyester blended fabrics. They found that the pills formed on the cotton fabrics were more easily removed during laundering than the pills anchored by the higher tenacity polyester fibres. Fabric composition is also very much related to durability. It was reported that cotton/polyester fabrics possess greater strength than the all-cotton fabrics [62].

9.4.2 Effect of yarn characteristics

Yarn type and structure affect the durability of underwear fabric. McKinney and Broome [62] found that fabrics made from open-end spun yarns were less resistant to both abrasion and bursting than those of the comparable ring-spun yarns. Conversely, ring-spun yarn is more resistant to pilling than open-end spun yarn [28]. Other research showed that fabric constructed from air-jet-spun yarn was the most pill-resistant and a fabric constructed from rotor-spun yarn was the least pill-resistant [25]. Those spinning methods which control the fibres such that the finer fibres tend to stay in the centre of the yarn and the coarser fibres remain at the outside produce yarns with a lower tendency to pill. Conversely, spinning systems that produce yarns in which the longer fibres tend to stay in the centre of the yarn and the shorter fibres at the outside, produce yarns with a higher pilling tendency [63].

The propensity for pilling is also related to the yarn twist. The higher the twist in the yarn, the less is the tendency to pill because the twist compacts the yarn and reduces the number of protruding fibres that cause pilling. Consequently, double yarn gives less pilling than single yarn [25].

9.4.3 Fabric thickness

Fabric thickness is one of the most important factors determining its thermal comfort [6]. It was found that fabric thickness had a direct effect on thermal transmittance, where the thicker the material, the lower the thermal transmittance [64]. Dorkin and Beever [8] also stated that the thermal resistance through individual layers of dry fabrics was primarily dependent upon their thickness and was approximately two togs per 1 cm thickness varying from about 0.05 for cotton poplin to about one tog for a heavy overcoat. This value would be lower if the wind was present to cause more air penetration and higher natural convective heat loss.

9.4.4 Fabric structure

Fabric handle is highly related to fabric structure. Chen *et al*. [18] compared four different structures of weft knit fabrics, and found that single jersey fabric was softer, lighter and had richer hand than the other single knit fabrics. Using the Kawabata evaluation system (KES-F), they found that single jersey fabric was physically lighter and thinner and required less energy to bend, compress and shear than the others.

Knitted structure also affects some degree of dimensional deformation [60]. Slackly knitted fabrics have a higher tendency to shrink more, attaining complete relaxation at raised temperatures, than tight knits. Comparing weft knitted fabrics with different combinations of knit, tuck and miss stitches, Anand *et al*. [32] found that fabrics containing miss stitches pull the wales closer together, so they had higher relaxation shrinkage in the width direction than the plain single-jersey structure. Fabrics containing 50% miss stitches had higher relaxation shrinkage than a fabric with only 25% miss stitches.

With respect to cotton knitted fabrics, The International Cotton Technology Institute in Manchester developed a software program, Starfish, to predict the dimensional behaviour of the fabric based on the knitting parameters (the size and type of the yarn, the stitch length, the size of the knitting machine), the finishing process and the nominal finished dimensions. The name Starfish is derived from Start as you Mean to Finish. The Starfish program can be used to predict the shrinkage of cotton rib, single jersey, interlock and pique fabrics.

Starfish predicts shrinkage mathematically and is based on the following three logical foundations:

1. Determining a particular state of relaxation for cotton knits which is

stable and reproducible; the reference state on which all measurements will be made and all calculations based.

2. Developing a comprehensive database of measurements made on systematic series of cotton fabrics that have been manufactured and processed under close quality control but nevertheless on a commercial scale and under commercially realistic conditions.
3. Developing suitable mathematical models for the reference states that link the knitting and finishing parameters to the dimensions of the relaxed, finished fabrics in a simple and reliable way [65, 66].

Fabric structure also affects durability. It was reported [32] that plain knitted fabric, one of the popular knitted structures used for making underwear, had the worst abrasion resistance. It may be improved by knitting the structure to high area densities. Anand *et al*. [32] found that there was a linear relationship between the stitch density and the bursting strength. The higher the stitch density, the higher was the bursting strength of the fabric. In the fully relaxed state, knitted fabrics with miss stitches in their structure had higher stitch densities which, again, were linearly related to its abrasion resistance. Single jersey fabric containing tuck stitches had lower bursting strengths than fabrics with miss stitches. The construction of a fabric also directly determines its susceptibility to pilling. Pilling problems are often associated with a loosely knitted fabric when continually worn or cleaned as there are more fibres anchored loosely on the fabric surface than on a tightly knitted fabric [25].

Fabric structure is also an important factor affecting the comfort properties. Fabrics with more pores or bigger sizes of pore, potentially allow more air movement through the fabric which results in a cooler feeling for the wearer [6]. Conversely, the tighter the fabrics, the smaller the spaces that are available and thus the lower is the air permeability. So the tightness and area density of fabrics are important considerations when designing underwear.

9.5 Recent developments in knitted underwear fabrics

Underwear is traditionally made from cotton in single jersey or interlock knitted structures. However, in recent years, new fabrics have been developed using engineered fibres and special constructions to achieve improved wicking properties, quick drying, lighter weights, improved durability and easy care.

9.5.1 Akwatek® polyester fabric

Akwatek® polyester fabric is one of the performance fabrics that, it is claimed, can transport moisture and assist thermoregulation using an electrochemical principle. Furthermore, it is also claimed that the chemicals cannot be removed by repeat laundering. The Akwatek® technology modifies the polyester fibre surface at the nano-particle level. With chemical treatment, Akwatek® modifies the chemistry of PET and releases hydrophilic groups at the molecular level. The modified polyester has an active surface layer with anionic end groups that transport water molecules and release them to the atmosphere before they can form into liquid water. Consequently, it is claimed that Akwatek® polyester fabric can enhance wearing comfort properties [67, 68].

9.5.2 Coolmax® fabric

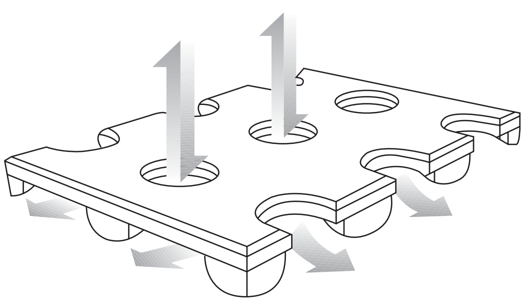
Coolmax® is another functional fabric that, it is claimed, can keep the wearer cool and comfortable in any situation. Four channel fibres in Coolmax® fabric can transport moisture and heat to the outer surface rapidly which makes it a quick drying and breathable fabric [69, 70].

9.5.3 Nike® Sphere Cool fabric

Nike® has developed many different functional materials for making undershirts and sportswears. Nike® Sphere Cool [71] is one of their innovative technologies to increase the heat loss to enhance the air circulation. It is claimed that the mesh structure accelerates the evaporation of sweat, so that the wearer becomes cooler and more comfortable. Good moisture absorbency by the inner layer is also claimed to improve the thermal comfort of the wearer (Fig. 9.19).

9.5.4 Nike® Dri-Fit

Nike® Dri-Fit [71] is a popular inner layer fabric as it is claimed to carry the sweat from the skin to the outside of a T-shirt rapidly where it then evaporates. It is proposed that it should be worn next to the skin to keep the body dry.



9.19 Nike® Sphere Cool fabric structure [71].

Table 9.7 Reference values of the properties of single jersey knitted fabrics

Percentile	Thickness (mm)	Mass per unit area (g/m^2)	Air permeability	Thermal conductivity	q-max	Contact angle	WVTR
90% percentile	0.780475	259.8803	160.3983	0.697562	0.127604	123.9107	0.055963
70% percentile	0.713567	228.7349	117.0496	0.64433	0.119713	88.63974	0.052057
50% percentile	0.667314	207.2043	87.08286	0.60753	0.114257	64.25714	0.049358
30% percentile	0.621061	185.6737	57.11616	0.570731	0.108802	39.87455	0.046658
10% percentile	0.554153	154.5283	13.76738	0.517498	0.10091	4.603544	0.042753

Note: air permeability was measured according to ASTM D737-96.
Thermal conductivity and Q-max were measured by Thermal Labo II KES-FB7, mentioned in section 9.3.1.
Contact angle was measured by ASTM D5727, mentioned in section 9.3.3.
Water vapour transmission rate (WVTR) was measured by ASTM E96-90, mentioned in section 9.3.2.

Table 9.8 Reference values of the properties of interlock knitted fabrics

Percentile	Thickness (mm)	Mass per unit area (g/m^2)	Air permeability	Thermal conductivity	q-max	Contact angle	WVTR
90% percentile	1.085118	239.0271	228.332	0.712801	0.120217	119.2669	0.055893
70% percentile	0.926454	203.6248	192.5585	0.64456	0.111862	80.62629	0.052128
50% percentile	0.816771	179.1514	167.8286	0.597386	0.106086	53.91429	0.049524
30% percentile	0.707088	154.6781	143.0986	0.550211	0.10031	27.20229	0.046921
10% percentile	0.548425	119.2758	107.3252	0.481971	0.091954	-11.4384	0.043155

Note: air permeability was measured according to ASTM D737-96.
Thermal conductivity and Q-max were measured by Thermal Labo II KES-FB7 mentioned in section 9.3.1.
Contact angle was measured by ASTM D5727, mentioned in section 9.3.3.
Water vapour transmission rate (WVTR) was measured by ASTM E96-90, mentioned in section 9.3.2.

9.6 Properties of commercial knitted underwear fabrics

For the comparison of commercial knitted underwear fabrics, it is useful to establish reference values of the different properties of the knitted underwear fabrics. In our present study, we have tested nine different types of commercial single jersey knitted fabrics and eight different types of commercial interlock knitted fabrics have been tested in terms of thickness, mass per unit area, air permeability, thermal conductivity, q-max (warm/cool contact feeling), contact angle and time to full water absorption. The 10%, 20%, 50%, 70% and 90% percentile values are listed in Tables 9.7 and 9.8, respectively.

9.7 Acknowledgement

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10
Process innovations of seamless intimate apparel

W YU, S-P NG, R ZHENG and J YIP

10.1 Introduction

The design and manufacture of intimate apparel has readily adopted the new developments in seamless manufacturing technology. Innovative Bemis' tapes are now widely used for laminating stretchable fabric. These tapes have made the elastic bands traditionally used on the under bust for bras, or the waist and legs for underpants redundant. Multiple proprietary technologies of moulding, laser cutting and ultrasonic bonding are common methods that replace the conventional assembly line [1]. New Tactel and Lycra yarns are popular for seamless knitting in the manufacture of whole garments.

Whether garments are constructed using adhesive bonds or seamless knitting, it has been postulated that traditional underwear may be phased out in future [2]. If the trend in seamless fashion continues, sewing machines and operators may become things of the past. This chapter is devoted to the key developments in lamination and moulding as well as seamless circular knitting and warp knitting technologies that provide detailed understanding of the process innovations of seamless intimate apparel.

10.2 Lamination

Lamination is a common process used in apparel manufacture. The lamination systems used in intimate apparel manufacture in particular must satisfy health and safety specifications to ensure, for example, that no vaporized adhesive evolves to harm the wearer. Ideally, they should be environmentally friendly, and ensure that the functional requirements of underwear materials can be maintained after wear and laundering. These requirements include breathability, moisture management, stretch ability and shape retention.

When a piece of foam is laminated to a fabric, the bonding quality may deteriorate during subsequent moulding processes if the high temperature of the mould exceeds the setting temperature of the adhesive used in the lamination. This weakened bond often results in an uneven finish in the bra cup surface, poor washability and delamination [3]. Lamination methods and materials have evolved to minimize these problems. In the following sub-sections, the evolution of these methods is discussed.

10.2.1 Solvent-based adhesive

The solvent-based adhesives used in lamination involve dissolving solid adhesive components such as resin, fillers, antifoaming agents, surfactants, and other performance-enhancing ingredients in a solvent liquid [4]. These solvent-based adhesives using polyurethane, polychloroprene or rubber-based polymers offer solutions for bonding a wide variety of substrates. They are particularly suitable for lightweight and ultra-soft fabrics [5]. Solvent-based adhesives can be applied to the laminates using smooth rollers, engraved rollers and spraying-nozzles.

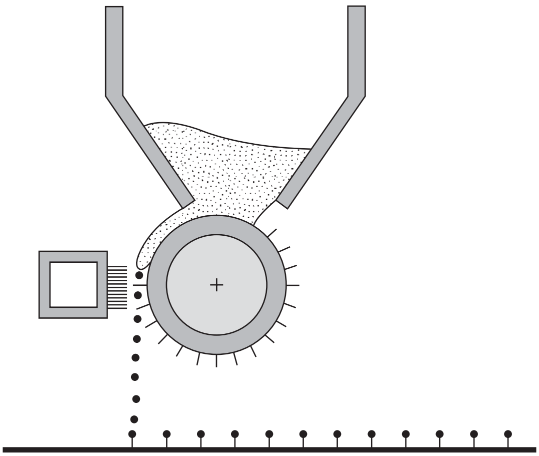
Coating the laminate with solvent using a smooth roller is the most commonly used method in the intimate apparel industry but it significantly reduces the breathability of the laminate. The use of an engraved roller can improve the breathability but there is a trade-off with bond strength. Spraying is a very common contact-less technology used for the application of solvent-based adhesives. In practice, the molecular structure of the adhesives has to be adapted to the specific spraying heads and hence their rheological properties must be well investigated before mass production [6]. Although solvent-based adhesives still prevail in the intimate apparel industry, growing environmental and health legislation is leading to a significant decline in their use.

10.2.2 Water-based adhesive

The water-based adhesive system uses water as the liquid portion. For laminate constructions, various polymer types including PVA, acrylic, polychloroprene and polyurethane polymers are used in this adhesive system. Processing the textile laminate is expensive because large drying ovens or high cost stenters are required to evoke polymerization. Cleaning of the application machines at the end of each production shift is another indispensable process. Consequently, the use of this method is declining as manufacturers prefer more cost-effective alternatives.

10.2.3 Dry adhesives

Dry adhesives are relatively new inventions and they include 100% solid polyesters, polyamides, EVAs, polyethylene and thermoplastic urethane adhesives which are applied to a substrate at ambient temperature and activated at elevated temperature [7]. To facilitate accurate application, dry adhesives



10.1 Powdered adhesive application system. (Source: Gillessen, 2000)

are required to first undergo a converting operation which modifies their raw, physical form (pellets or granules) to powders, films, nets or webs.

The powdered adhesive is transferred to the substrate by a powder applicator. This machine consists of a roller covered with short-needle wires that are positioned over the conveyor with the foam proceeding underneath (Fig. 10.1) [8]. Both the fabric and substrate are bonded by melting the adhesive in between and adhesive re-solidification is accomplished after sufficient cooling time. A recently developed curing trigger system allows the thermoplastic powder to be incorporated into this adhesive system. When the polymerization reaction of the powder is triggered at a specific temperature, the physical properties of the adhesive are changed from thermoplastic to thermoset and hence the laundering and dry cleaning resistance of the laminate is increased significantly. Furthermore, powder adhesive is considered to be environmentally friendly since there are no solvents or water vapour to be evaporated. It will also benefit the environment in that the materials may be recycled.

Films, nets and webs are non-woven structures produced by extrusion, melt blowing or gravure methods. These forms of adhesives are usually melted between laminated materials at relatively low temperatures. Various structures of the adhesive confer differences in stiffness in the laminated products. Despite this, laminated products with good handle and drape characteristics can be achieved.

10.2.4 Hot melt adhesive

The use of hot melt adhesives for laminating textiles is relatively new compared with all the other aforementioned adhesives. The concept of a hot melt adhesive is to manufacture a breathable material using a membrane and adhesive. Under elevated temperature, the adhesive is melted and applied to the substrate via a rotogravure, spray or dot coating system. The adhesive is then cured and adhesion occurs in a very short time. After that, curing continues to occur due to the humidity of the air, and the structure of the adhesive becomes mesh-like. The strength of adhesion varies with the melting viscosity. The permeability of the adhesive located between the film and the base fabric can be increased easily [9]. It is important to maintain the laundering and dry-cleaning resistance of the laminate and to maximize the effect of a breathable adhesive in the laminate.

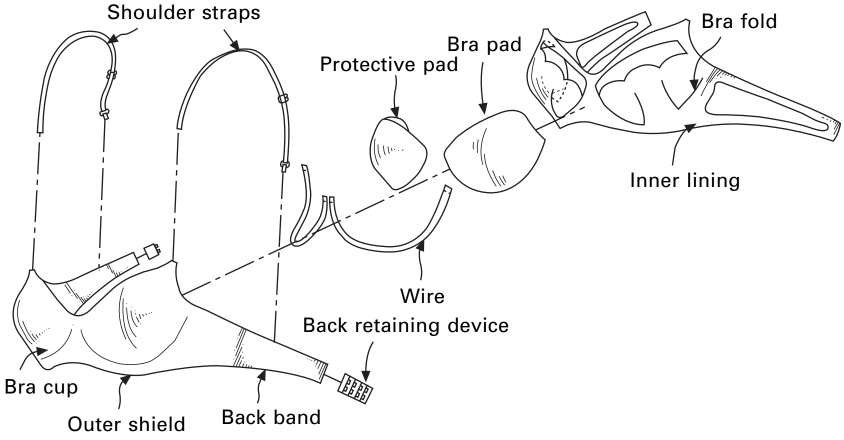
10.2.5 PUR adhesive

The most recently developed adhesive is the reactive hot melt moisture cured polyurethane adhesive (PUR). It is produced from a combination of different polyester and/or polyether polyols which react with an excess of di-isocyanate to form pre-polymers with terminated isocyanate groups [10]. These pre-polymers are thermoplastic and can be processed with gravure rollers, in the screen printing process or with slot nozzles. Typically, when this adhesive is applied at a temperature around 110~130 °C, there is approximately one gram of water being absorbed by 100 grams of PUR in the curing process in order to achieve full cure. The adhesion attains its maximum capacity after complete cross-linking of the reactive isocyanate groups with moisture from the environment or substrates. These PUR adhesives are revolutionizing both textile and laminating processes so that many of problems of the aforementioned systems are overcome. Features include low cost, small batch size, ease of use and cleanliness, short start-up times, high-speed processing, versatility in terms of changeover, and ease of control of films and tensions, and coating add-on [11].

10.3 Moulding

For today's seamless bra cup construction, fabrics are normally laminated with a polyurethane foam sheet before undergoing the moulding procedures. Moulding is a thermoforming process that compresses a material into a desired shape under high temperature for a predetermined time. This technique was first used for garment moulding at the end of the 1960s when good quality polyester and elastane fibres became available [12].

Moulded bras have become well received probably because they are much easier to fit, producing fewer bulges or wrinkles. The elimination of irritating seams [13] is also an advantage. Seamless bras intrinsically guarantee a smooth configuration under the outer garments and reduce the risk of chafing on nipples.



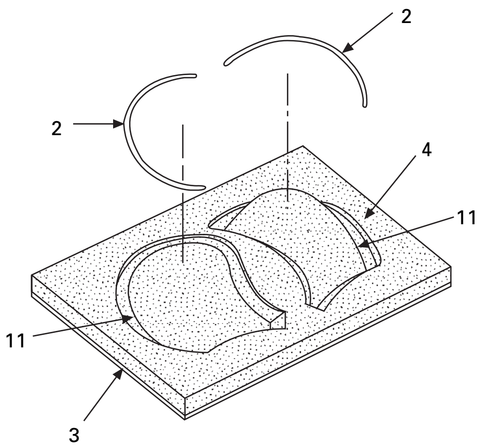
10.2 Seamless bra moulding. (Source: US patent US6,425,800).

10.3.1 Integral moulded bra

The original concept of moulding an integral piece of a seamless bra was patented [14] in 2002. As shown in Fig. 10.2, the moulded bra comprises an outer shield, an inner lining, a support pad and a back retaining device (i.e. hooks and eyes). The outer shield, bra cups and the two back bands (i.e. wings) are cut from the same piece of fabric. Moreover, shape and size of the inner lining and outer shield should match each other. Some regions of the inner lining can have openings in order to enhance air permeability. Each individual bra cup on the inner lining is pre-formed to a desired shape. The outer shield, the inner lining and the support pad are adhered together by a moulding machine to form an integral component – the forming process can be performed by hot pressing. Bra pads or sealed bags with fluids or semi-fluids can be incorporated in the bra. In the case of the sealed bags, they can be enclosed by two protective pads made of foam.

10.3.2 Placing of wires

For the accurate location of wires at the bottom rim of a bra cup, a patent [15] was granted in 2004. The patent claims to initially mould the cup shape on a laminated foam sheet by using a die casting machine. Then, two steel wires are placed onto grooved channels (Fig. 10.3) in the foam breast cups before superimposing another piece of foam. The entire bra cup is finished after moulding for a second time. This not only saves manufacturing time, but also enables the steel wire to be entirely and closely affixed to the breast cup to more completely support the breast shape.



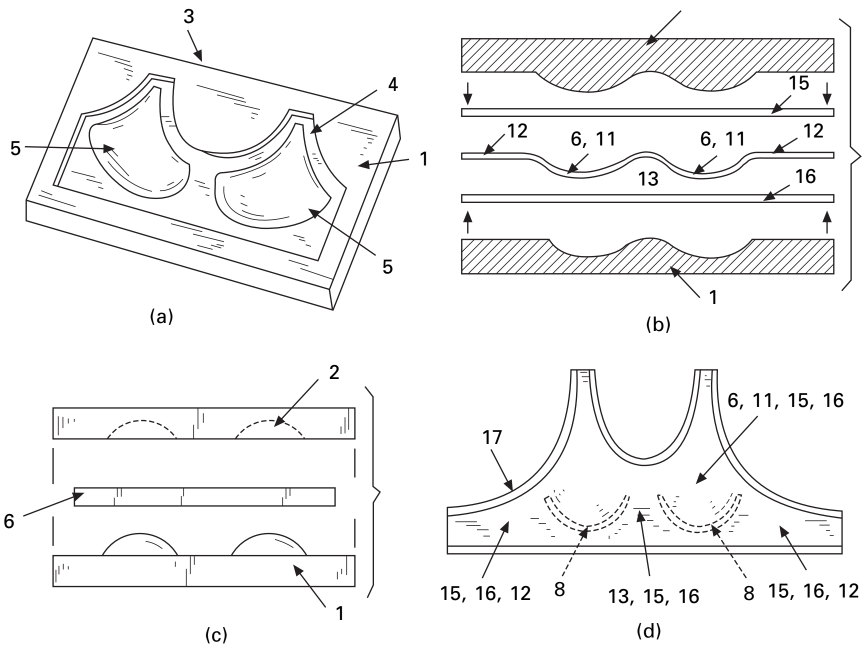
10.3 Groove channels for placing wires. (Source: Bra structure, United States Patent 6695677).

10.3.3 One-piece bra

Currently Regina Miracle International Limited (HK) dominates the supply of moulded bra cups by manufacturing new products with the emphasis on technological innovation. In October 2004, Luk of Regina Miracle patented a moulding method for a 'one-piece bra' sold by Triumph International which attracted large interest from the market (Fig. 10.4) [16]. The patent describes a bra core comprised of two bra cups attached to a chest band extending to the end fasteners. A sheet of fabric is laminated to each side of the bra core, which is moulded to a 3D shape with a wire situated between the two fabric layers. The first sheet is an open cell foam material having a thickness of 1 mm to 5 mm. The second sheet is a skived foam material cut to a predefined cup shape. The underwire is either plastic or metal. The casing, a tubular sock within which the underwire is located, is adhered to the facing surfaces of each foam sheet. The wire casing is preferably a fabric material such as polyester-based cotton, spandex or nylon fabric material.

For the cup construction, the first foam sheet is moulded at a temperature of approximately 200 to 210 °C for 150 seconds. Then the second foam sheets are placed onto the convex side of each cup shape formed in the previous step. These second sheets are substantially the same or larger than the cup shapes defined in the first sheet. They are preferably pre-shaped and skived into a 3D curvature, or alternatively made from a flat foam sheet and formed either prior to or during its engagement with the first foam sheet. Again a temperature of 200 to 210 °C and dwell time of 150 seconds are used to laminate both sheets together.

If the cup construction includes an underwire, then an underwire assembly can be sandwiched between the first and second sheets before moulding. The



10.4 One-piece bra moulding. (Source: United States Patent 6805610).

underwire is first formed to its 3D shape and then adhered to the first sheet by sprayed glue. Once the second sheets are placed on top of the first sheet, the underwire becomes trapped between the two sheets. Using an ultrasonic bonding machine with a 3 mm setting, the ultrasonic cutting and fusing step removes the excess margins from the bra and simultaneously seals the perimeter of the bra to prevent any fraying of the material. Thereafter straps and hook pads can also be added by ultrasonic bonding. This innovative bra is made of at least two sheets of foam material without any visible stitching, so it is more durable. It eliminates problems of broken seams or stitches caused by repeated washing and wearing. It also avoids skin allergies or abrasions from wires which would have penetrated through the bra. The positioning of the wire assembly between the cups ensures its secured position and prevents sliding. This leads to stronger support and a more conformed fitting of the bra against the body.

10.4 Seamless knitting technology

10.4.1 Development of seamless knitting

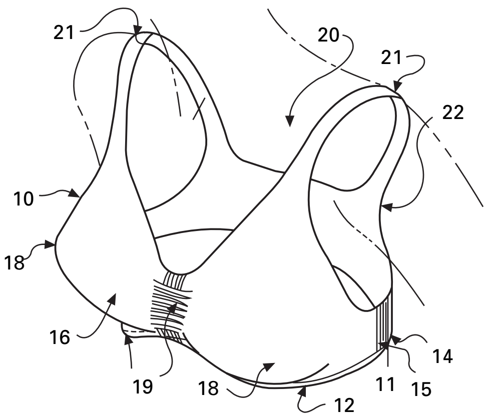
Seamless knitting technology is not a new concept [17]. It has been used in the past for hosiery production [18] and it has been well known throughout the industry since the 1980s. The advent of electronics and computer aided design and control systems have enabled the principles used in sock manufacture to be applied to knit seam-free body panels, integral waistbands and shoulder straps to create body-size seamless garments although the market did not take up the challenge until Santoni of Italy offered machines capable of producing body size articles. Body size garments aim to envelop the body in a comfortable seam-free second skin. The finished garment is actually normally only free from side seams, but does not guarantee the elimination of seams at other parts such as gusset seams for the underpants or fastening seams for bras.

With the emphasis on the natural look and comfort in fashion, many brands have been using the 'body-size' circular knitting machines to develop their distinctive seamless underwear. They include Jockey, Victoria's Secret, Wolford, Nike, Reebok, Adidas, Dior, Banana Republic, Donna Karen, Calvin Klein and many others [19]. Their seamless products are mainly panties rather than bras. The tension at the bra cup region constricts or squeezes the wearer's breasts due to the limited range of yarn linear densities. A seamless bra having a pair of breast-receiving cups knitted on a circular knitting machine was invented as long ago as 1970 [20]. Manufacturers have applied seamless technology to create various styles and patterns of garments. It can also utilize special yarns or finishing processes for particular functions. It is claimed that seamless technology shortens the manufacturing process and reduces material wastage, offering greater comfort and better fit to the wearers [21].

Santoni and Sangiacomo are the major manufacturers of body-size circular knitting machines. They have developed a series of electronic seamless knitting machines for both men's and women's hosiery products. They have also advanced their machines' capabilities and created new opportunities for seamless fashion [22]. Seamless knitting machines are produced in single cylinder or double cylinders, normally fine gauge for producing bodywear models. All include electronic needle selection plus striping to give versatile patterning for both openwork and coloured patterns. The ability to knit a single or double elastic waist makes them especially suitable for underwear [23]. Double needle bar warp knitting machines have been available for many years for the production of sacks and tubular products. These have been adapted by Karl Mayer to produce seamless garments and this innovative knitting method is further elaborated in section 10.4.3.

10.4.2 Structural design of seamless circular knitting garments

The following examples are presented to illustrate the concept of producing bras using seamless knitting technology. Some of the bras required some



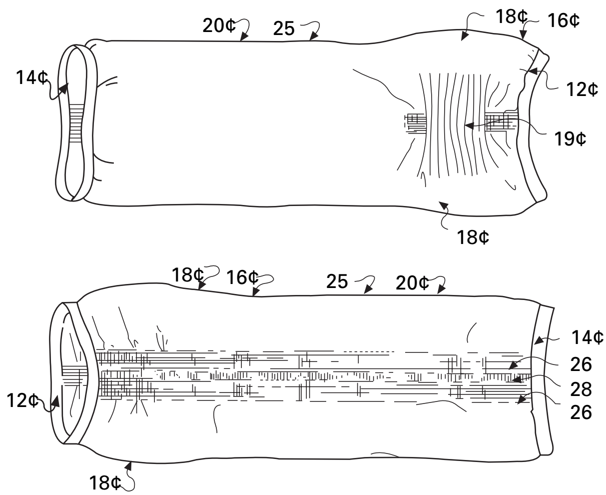
10.5 Seamless knitted bra. (Source: US patent 4,531,525).

cutting and sewing, but this is substantially less than that used in the manufacture of a conventional cut and sewn bra. In 1985, the invention of a knitted bra produced from a cylindrical tube knitted on a circular weft knitting machine was invented [24]. As shown in Fig. 10.5, the knitting structure used for the centre panel of the bra was constructed using combinations of plain stitches and float stitches. An alternative construction was proposed, whereby every fourth needle knitted a plain stitch and the intervening needles produced float stitches. The yarn was held in either a float or missing stitch for a multiplicity of courses ranging from three to 22 courses in order to generate different sizes of the garment. Side gathered panels were constructed using a similar method. The bra cups were thus defined between the centre panel and the two side panels.

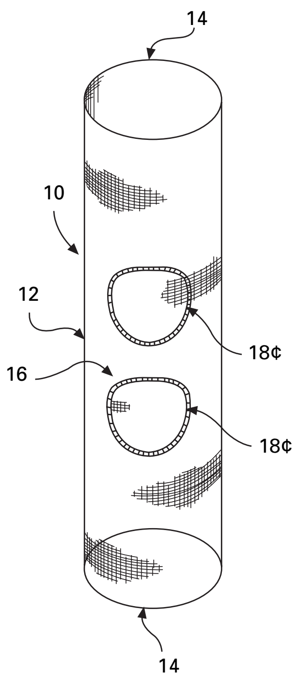
The knitting bra made from the cylindrical blank is shown in Fig. 10.5. The cylindrical blank is then cut and sewn to produce a garment having straps knitted integrally with bra cups and a torso portion that formed a welt band. The different portions labelled in Fig. 10.5 correspond to those in Fig. 10.6.

In 1999, the Russell Group Ltd. patented a knitted bra blank which had integral seamless elasticized contours that defined the bra cup borders [25]. A circular knitting machine equipped with a computerized electronic needle selection system was used to design a sports bra without cutting and sewing operations. The blank shown in Fig. 10.7 was cut into two to produce two separate bras.

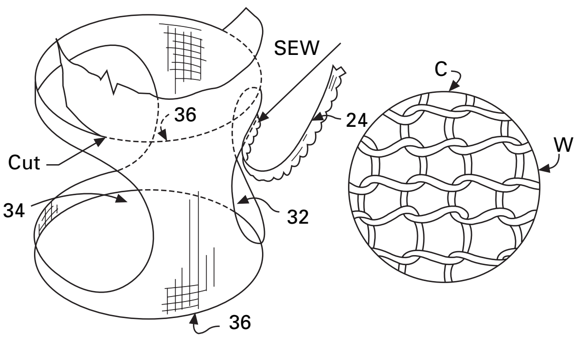
Another patented seamless bra produced using circular seamless knit technology is shown in Fig. 10.8. A tubular blank knitted on a circular knitting machine, comprised walewise extending longitudinal openings to form the torso and neck openings of the bra along opposite sides of the blank. It was claimed that this ‘knit-in-one’ bra could support the breasts and



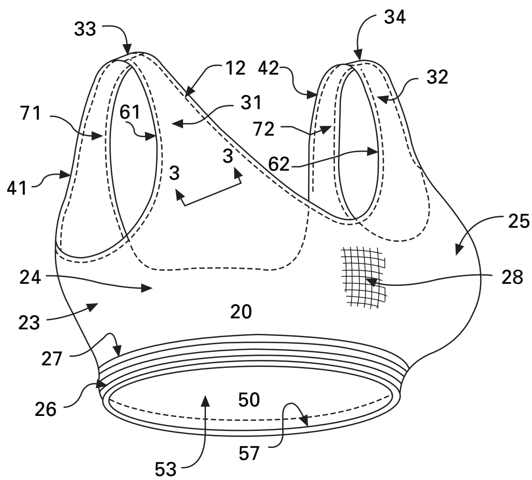
10.6 Front and rear elevation views of the cylindrical blank. (Source: US patent 4,531,525).



10.7 Perspective view of the bra blank. (Source: US patent US5,850,745).



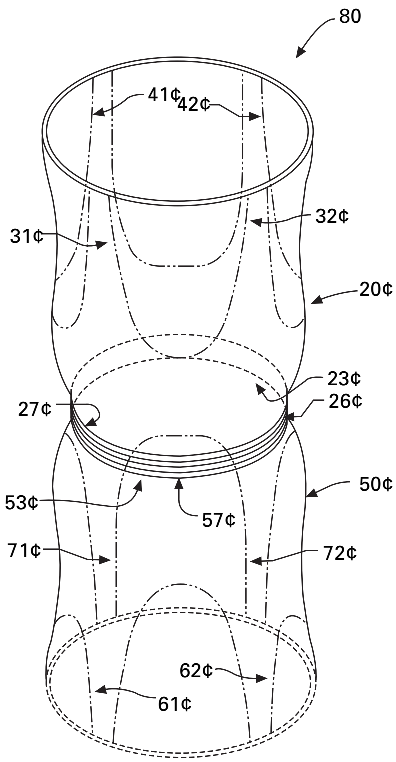
10.8 Front elevation view of the blank with enlarged sectional view in accordance with the US patent 5,946,944.



10.9 Perspective view of the bra. (Source: US patent 6,125,664).

offer a figure-flattering look, similar to that achieved by wearing a wired bra but without discomfort and inconvenience of pads, wires, hooks and snaps [26].

Browder [27] invented a circular knit bra formed of an inner fabric and an outer fabric that connected to each other (Fig. 10.9). The patent proposed that the outer fabric should preferably be knitted from flat nylon ground yarn, or combinations of nylon and cotton, to provide strength, support, or aesthetic properties in specific areas and the inner fabric should be knitted with yarns selected for their softness, comfort, and moisture wicking properties. The blank comprised a series of circular knitting courses with the courses for the turned welt preferably being constructed from structures containing knit and miss stitches (Fig. 10.10). Different parts of the knitted bra are cut from the blank according to the portions labelled in both Fig. 10.9 and Fig. 10.10.

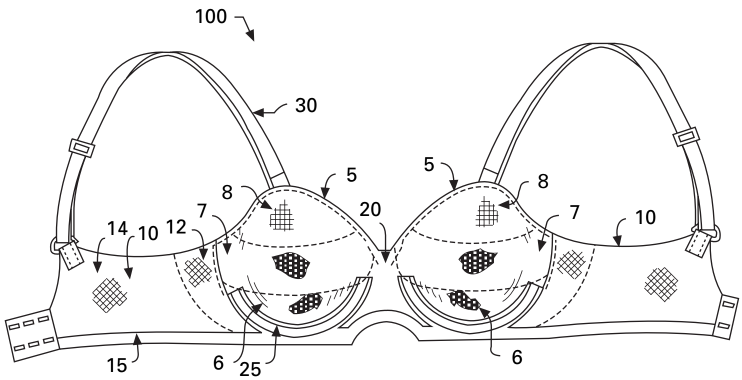


10.10 Perspective view of the cylindrical blank. (Source: US patent 6,125,664).

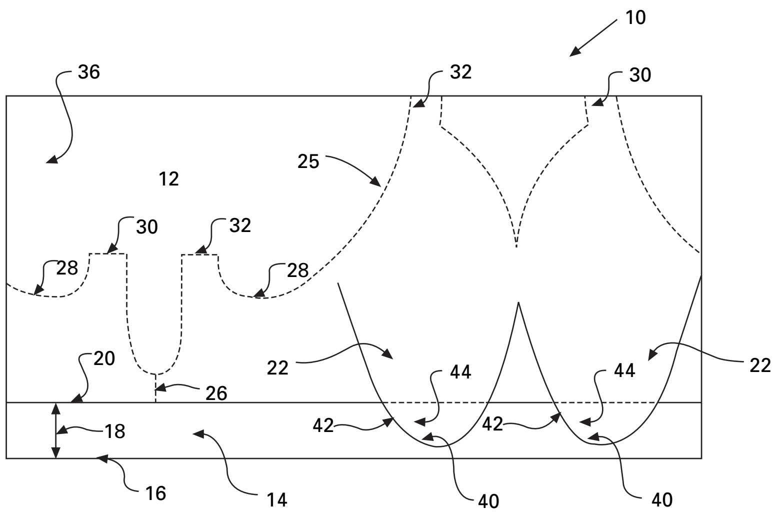
The bra is completed by sewing up the straps and tacking the outer and inner fabrics together.

Most recently, an invention of a seamless circular knitted bra [28] was developed that comprised breast cups with varying degrees of stretchability in different areas to enhance the supporting and shaping effect for the wearer's breasts (Fig. 10.11). The method of making this bra uses specific yarn tension control devices which can regulate the stitch construction configuration throughout the bra. The graduation stretch throughout the bra cups is achieved by varying the stitch lengths and hence the stitch density. The stitch density should be most dense at the bottom of the cup and gradually decreased towards the top of the cup. Each bra cup is formed using a plain jersey stitch. Software used to program the circular knitting machine controlled stepper motors to regulate the yarn tension to vary the stitch length. Each bra cup has three distinct areas of stitch density as shown in Fig. 10.11.

A similar patent to US patent 6,899,591 B2, filed by Mitchell and Waitz [29] also focuses on changing the extensibility of different areas of the bra. Compared with the core region, tighter stitches with shorter stitch lengths



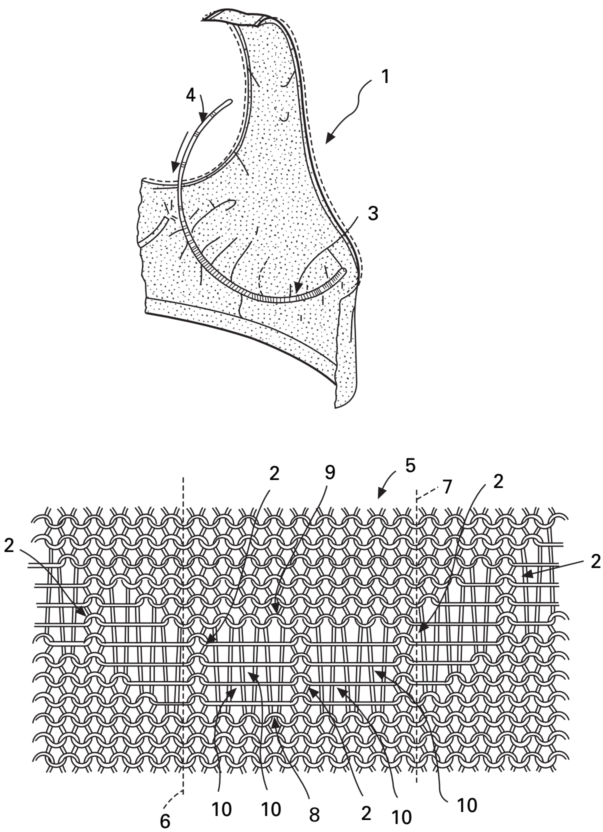
10.11 Top view of the bra. (Source: US patent 6,899,591 B2).



10.12 Front view of the bra. (Source: US patent US 6,685,534 B2).

are used in the cup areas for supporting the weight of the breasts. Conversely, looser stitches with longer stitch lengths are used in each side wing to provide more comfort and flexibility.

Seamless tubular garment blanks with an integral complete band or welt have been widely used to produce bras, underwear and other apparel items. This integral knitted band can provide better comfort to the wearer than cut-and-sewn bras. However, they have an 'unshaped' appearance when compared with those bras with preformed cup shapes. Mitchell *et al.* [30] invented seamless shaped bands to improve the benefits of normal complete bands. As shown in Fig. 10.12, the breast cup areas are designed to extend to the underband regions. Therefore, the seamless interface of the underband and



10.13 (a) Back view of the bra according to the invention (top); (b) knitting structure of the invention (bottom). (Source: US patent US 6,082,145).

body portion is defined between the main body regions and the shaped band. This technique creates a shaped band having a variable dimension from the lower edge upwards towards the interface along with the dimension of the cups.

After the manufacture of circular knitted bras, fabric tapes are usually sewn on to construct pockets or passages for inserting wires to improve the support of the bras. For the purposes of reducing the production costs and improving the wearing comfort, Lonati *et al.* [31] invented a knitted structure that created tunnel-shaped passages for the insertion of wires (see Fig. 10.13(a)). The passages are created by knitting a series of courses containing knit and miss stitches as shown in Fig. 10.13(b). They form after the fabric is removed from the knitting machine when the held knitted loops that are stretched whilst under tension on the machine, relax and contract when the tension is removed.

10.4.3 Seamless warp knitting technology

Seamless warp knitting technology has enabled manufacturers to develop a niche market and enabled the innovation and quality of products to be taken to a new level. As opposed to circular seamless weft knitting machines which normally have a body-size cylinder, warp knitting requires double needle bars to produce seamless garments. The double needle bar Raschel machine RDPJ 6/2 developed by Karl Mayer is specially designed for the production of jacquard seamless fabrics [32, 33]. The built-in piezo-jacquard system is capable of joining the thick sectional fabric structure smoothly and seamlessly. Application of this technology can produce cylindrical products almost completely, in many cases without the need for subsequent sewing [34].

The machine operates in a gauge of E16 or E24 with a working width of 138 inches. It has four ground guide bars and two piezo-jacquard guide bars. Unlike other electronic jacquard systems, the piezo-jacquard system uses the piezoelectric elements to control individual jacquard guides independently, and thus the pattern area in the width direction is unrestricted [3].

10.4.4 Seamless finishing routes

After the garment panels have been knitted, they need to pass through additional different finishing processes [35]. These include cleaning (scouring), garment washing (for those knitted with dyed yarn), heat setting, making up, dyeing (for those knitted with ecru yarn), pressing and finally packing. For garments with a high content of elastomeric fibre, the finishing processes [36] involve pre-shrinkage, pre-boarding (heat setting), cleaning (scouring), making up, dyeing, pressing and packing.

10.5 Conclusions

Traditionally, manufacturing of intimate apparel has been considered to be labour intensive. It requires a high level of operator skill in handling tiny pattern pieces and stretchy materials. The measurements must be precise to achieve a perfect matching of components, a smooth and symmetric appearance and a comfortable stretch fit. With the advances in seamless technologies, the cut and sewn operations may be substantially reduced. Fitting is somewhat easier using stretchy moulded foam cups and elastic laminated panels. No seams, no elastic bands and minimum trims have become the new fashion, and, in doing so, have created new business opportunities for the intimate apparel industry. This final chapter has presented a summary of the major process innovations particularly in the use seamless technologies such as lamination, moulding and whole garment knitting. These have shown how technological invention working with creative design can produce new, innovative products with enhanced performance, appearance and comfort for the future development of intimate apparel.

10.6 Acknowledgement

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