Digital Manufacturing Technology for Sustainable Anthropometric Apparel

Edited by Norsaadah Zakaria

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Digital Manufacturing Technology for Sustainable Anthropometric Apparel

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Her main research interests include TVET education for sustainable practices in the clothing industry, traditional and 3D body scanning anthropometric surveys, data modeling for clothing sizes, shape analysis based on anthropometric data and sizing system optimization, and validation using data mining. She is also offering professional programs accredited by The Textile Institute—United Kingdom.

Preface

The technological advancements and global environmental issues in our lives today have been the inspiration behind the gist of this book taking shape in the authors' pen. The theme of the book is technology and sustainability. Currently, the apparel industry understands the importance of moving toward sustainable apparel product development with technology adoption. Globally, we have been deliberating on the impactful environmental issues that disrupt apparel product development. The distortion became worse post-Covid-19 pandemic that the apparel industry needs to find a solution in facing the competition and economics of a changed world vision pivoted on growth with knowledge of technology and well-being of all, especially that of generations to come, at its heart. Thus we need to transform the apparel industry toward technology adoption for the sustainability of the products. There is a critical need for the apparel industry to be more efficient, more effective, and more reliable in the future. In addition, this book also looks into the role of anthropometry data in designing for sustainability. Anthropometry means the study of body dimensions which is the first factor for apparel product development. Producers need to understand the variations of body sizes and shapes before determining the right clothing size to fit the end-user's body well. For this reason, we need to include anthropometric data for better apparel product development that adapt the sustainable design features. It is necessary to gather, organize, and transform the anthropometric data into a visual body image to become precise size data so that the clothing sizes can fit the individual body. The application of technology has made it possible to develop a company's size chart when going through the 3D scanning process. Having reached the objective of fitting a person well is the ultimate target of sustainable practices in the apparel industry in the future. To ensure an efficient fit for the apparel wearer, we can target to develop body patterns that fulfill the fit needs.

Digital Manufacturing Technology for Sustainable Anthropometric Apparel has comprehensive content that brings to maturity the concept of *technology and sustainability*. We begin this book by advocating *sustainable fashion education and TVET training* to make fashion communities realize the importance of pedagogy in upskilling apparel professionals. With the advent of technology, practical skills training has been the norm for a renowned system like Telestia Technology, especially for online learning that has been practiced since a few decades ago. Obtaining the anthropometric data is also much easier with the technology of 3D body scanning for the sizing developments to take root in customer thought for profitable clothing buying decisions vis-à-vis their discard in landfills so that the customers are satisfied with the garments made for them. This book highlights the importance of and opportunities for using ergonomic design principles and anthropometric sustainable sizing systems.

To summarize this book, it contains three main topics as below:

1. Sustainable Apparel Manufacturing IR 4.0
2. Technology and Application of anthropometric data
3. Anthropometric sizing and mass customization technology

Part I details sustainable apparel manufacturing with scanning technology. Chapter 1 underlines the importance of *sustainable apparel education* and technology integration for pedagogy and production. Chapters 2 and 3 give insight into 3D measurement anthropometric data for sustainable clothing size and social manufacturing. *Part II covers* the technology and application of anthropometric data. In *Part II*, Chapters 4–7 highlight the importance of anthropometric data and the management, the usage of the data for a digital dummy, and the application of data for digital fashion online. Lastly, *Part III* focuses on anthropometric sizing and mass customization technology. Within *Part III*, Chapters 8–10 discuss the sustainability concept and the application of technology in various apparel mass customization manufacturing, including apparel manufacturing sustainability.

This book will benefit a broad spectrum of readers that include the apparel academia, especially the students and researchers, the apparel industry, the apparel business, and the apparel-minded with interest in if not a passion for clothes and its men and women. Lastly, I would like to thank all the authors for contributing their valuable opinions and visions in making the chapters an ineluctable part of this book. Thanks are also due to Gabriela Capille and Howell Angelo M. De Ramos of Woodhead Publication for seeing the publication through to its logical completion.

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Part 1

Sustainable Apparel Manufacturing IR 4.0

Sustainable apparel technical and vocational education and training (TVET): integrating technology for skills training

1

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1.1 Transforming towards the new sustainable apparel industry

The word "sustainability" started to have an impact on society since its coining in 1972. After 50 years, this term has become so familiar to the community of those favoring sustainable living that there is a crucial need to educate the larger society in a manner consistent with its needs and the needs of the environment about the importance of sustainability. The issues of environmental needs were discussed in the United Nations that relate to environmental law, conversation, environmentalism, and environmental issues. The importance of lives of the generations to come fed the need to secure man's future which was already being debated, and the realization that mankind must be made to have concern for and educated on the topic of sustainability arrived on the shoulders of sustainability education to have a bigger scope which have already been suggested during that meeting.

In 2015, the United Nations (UN) launched its Sustainable Development Goals (SDG). The calling was for all nations "***to take action, to end poverty***, ***to protect the planet, and to ensure that by 2030 all people enjoy peace and prosperity***" and ***participate on the newly developed 17 SDGs*** as shown in Fig. 1.1. In the same year, *World Education Forum* was organized by UNESCO in the Republic of Korea with a gathering of 1600 important people from all over the world. This critical forum was organized for a milestone event *to sustain education* by 2030 and the main objective of the forum was to revolutionize the lives of human beings through *quality education* emphasizing the agenda of SDG 4 which was in realizing the role of education as the key driver of development and sustainability of lifelong learning.

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Figure 1.1 Sustainable development goals.

Today, the word “sustainability” has become part of our new normal in which the setting of the framework has been identified. A large number of work has been conducted throughout the world to understand the importance of sustainability. Jose and Ramakrishna (2021) stated that the research on sustainability should have the following five components: social wellbeing, resource sustainability, environmental protection, circular economy, and, most importantly, *knowledge integration*. The relevancy of knowledge integration in the context of this chapter is to state the impact of leading the future generation of apparel education towards sustainability and adoption of technology as the key economic policies introduced by the Industry 4.0. In the future, the course of events will be leading all nations to move towards adopting the new IR 5.0 manufacturing that endorses the technological implementation of products and processes embracing the sustainability elements. Synchronizing both aspects of sustainability and technology will align new opportunities for apparel industries towards innovation. According to Iannilli et al. (2019), it is evident that with the new opportunities, there is a need to guide the professions in the industry, begin the training processes, and identify skill sets required for the change in the new future apparel industry. The knowledge integration environment (KIE) was identified as the solution to foster lifelong science learning (Araneo, 2019). In accordance with that, this first chapter advocates SDG 4: *quality education* as the main factor to drive the industry forward.

1.2 Sustainable apparel education

The apparel industry has significant changes especially post covid-19 in the direction of customers needs whom desire for low cost and flexibility in design, quality and speed to market. These changes have created a great challenge and strain to the apparel market. In the education industry, the players as stakeholders of educational change must face the challenge well by continuously attuning the curricula to the current needs of the industry and transforming the curricula of apparel education accordingly (Abu Bedor et al., 2021). The change is necessary for future fashion graduates to gain today's demand for sustainable knowledge, skills, and technological competencies. Sustainable apparel is also known as *eco-fashion, ethical fashion, re-fashion, or slow fashion.* Sustainable fashion is "*clothing, shoes, and accessories manufactured, marketed and used in the most sustainable manner possible.*" The objective for sustainable apparel is to gain a solid business model which considers the safety of the global natural environment. Many apparel industries in the world today are aggressively converting their processes and policies towards sustainable concepts to benefit the global environment and people (Franco et al., 2019). There are only eight more years to achieve the global SDG goals targeted by 2030. In addition, the strength of this goal is towards the United Nations Industrial Development Organization's (UNIDO) vision which is to channel the industry's full potential to achieving lasting prosperity for all: *people and environment* in total.

According to Alves (2021), in her latest article "*What exactly is sustainable fashion and why is it so important*" encapsulated eight major areas that can be adopted by apparel companies who believe in the sustainable concept as below:

i. Conscious fashion.
ii. Eco-friendly and green.
iii. Circular fashion.
iv. Upcycled and recyclable.
v. Slow fashion.
vi. Thrifting swapping and renting.
vii. Ethical fashion.
viii. Vegan and cruelty-free.

The main element of a sustainable industry is its becoming more innovative and highly adaptive technologies to enhance productivity and lending efficiencies (Kennedy & Terpstra, 2017). The apparel industry is one of the world's eminent industries that churn out trillions of businesses in monetary worth. Clothing is accepted as a basic human need and involves continuous manufacturing. This implies that the industry needs to consider the impact of industrial manufacturing on the global environment as the apparel industry is a significant contributor to environmental and human habitat damage (Parsons et al., 2017). The apparel sector is responsible for carbon dioxide emissions, chemical emissions, greenhouse emissions, waste generated, and high water consumption. Hence, by 2030, the apparel industry's contribution to all these issues is slated to rise and increase global warming and many other harmful environmental impacts. Up to this date, there has been numerous research conducted on the learning and training of sustainable practice in higher education. The integration of sustainability into teaching and learning is seen as the paradigm shift in education at all levels today to achieve the goal of quality education.

The apparel sustainability education and training are the combination of knowledge, TVET skills, and technology as shown in Fig. 1.2—*the sustainable fashion education model*. The three elements of the responsible apparel sustainability strategy are based on the apparel education model which will have the apparel sector moving towards the new sustainable apparel industry. Finding the right balance between the needs of the stakeholders and the needs of the environment in a sustainable fashion education model is very challenging and more so in the coming years since the crucial elements need to be implemented well at the level of the institution, the industry, and the consumer. Thus, in this first chapter of the book, the importance of TVET sustainable fashion education will be highlighted as a significant aspect of education to be taken up for implementation in the future. Fig. 1.3 itemizes the apparel education elements that require training integrating the sustainability concept. The advocacy is towards including new curricula in the apparel education system for the future apparel industry and fashion students thereby marking the commitments of three major groups: academia, industry, and students.

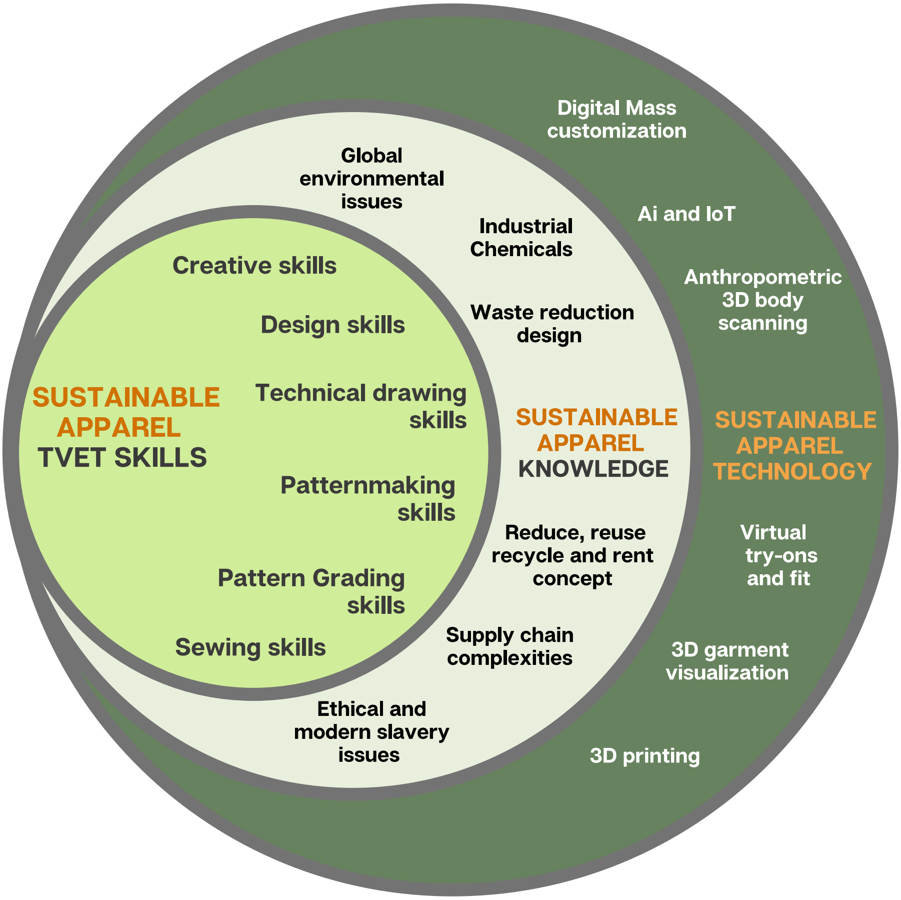

Figure 1.2 Sustainable apparel education model.

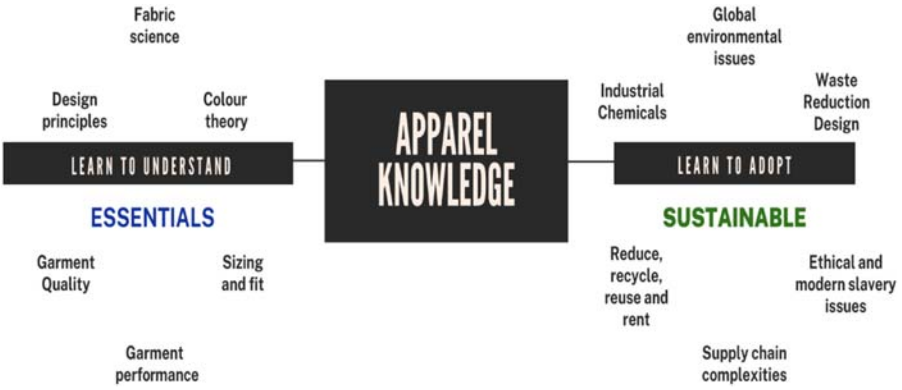

Figure 1.3 Sustainable apparel knowledge model.

1.2.1 Apparel sustainable knowledge

Apparel sustainable knowledge and skill are different and, yet, are related in conceptual aim. In Fig. 1.2, the model shows three elements for sustainable apparel education. Of these, sustainable knowledge is the core element to ensure that learners are alert about the importance of sustainable practices and achieve the targeted SDGs promoted by the UN. Sustainable knowledge is the theoretical aspects covering topics like global environmental issues, waste reduction design, the concept of 4Rs, the ecosystem of the supply chain, ethical fashion issues, and industrial chemistry. This knowledge is crucial to be embedded in the apparel education curriculum today as it educates about the impacts of the environment and the surroundings on society's wellbeing (Leerberg et al., 2020).

The sustainable knowledge in the syllabus will drive the concept of a process, actions, and resourceful participation towards the social, environmental, and economic benefits. In addition, the knowledge will enhance the facts about sustainable apparel and transmit the importance of that knowledge for change to form the mindset when dealing with environmental issues. A combined sustainable knowledge curriculum with an essential knowledge curriculum is shown in Fig. 1.3 which is highly suggested in future fashion education as it will enhance the students' understanding of sustainable practices. Students must gain critical thinking and interpret information in a meaningful way when they are aware of the sustainability impact on the apparel industry, understand the sustainable practices, and make the right ethical decisions for the benefit of workers and society (Shephard, 2015). Apparel education's role is to propel towards an ethical and sustainable fashion future (Kennedy & Terpstra, 2017; Murzyn-Kupisz, and Holuj, 2021). The core of fashion education lies in the knowledge acquisition achievement that opens the minds towards sustainability adoption in every design and production field of the apparel industry.

1.2.2 Apparel sustainable technical and vocational education and training skills

The highlight of this chapter is on the apparel education model (Fig. 1.2) that showed the first element on the chart: the TVET skills. Many research work today has concluded that the TVET skill competencies are the core necessities to implement sustainable apparel approaches in professional practices and to act as the essential tool for creating an ethical fashion system and generating social change (Yunus et al., 2021; Leerberg et al., 2020; Murzyn-Kupisz & Hołuj, 2021).

Sustainable apparel skills, subsequently, are the teaching of the practical art of apparel making and applying the knowledge learned to specific situations. The TVET skills for apparel education, specifically, are emphasized in many research works conducted as it proves the lacunae of this need for skilled mastery to produce better sustainable apparel products (Mair, 2020). We advocate the upgrading of sustainable skill practices in the TVET institution to match the skill sets needed in the industry. We also support the sustainable knowledge that includes the curriculum of fashion education.

According to James (2021), "fashion students lack the engagement of design and production processes". We need to change fashion education towards more practical based tasks so that industry professionals should be in the system to integrate the knowledge and skills as an immediate reflection (James, 2021). As shown from Fig. 1.4, the technical skill competencies identified in apparel education are creative, design, technical drawing, pattern making, pattern grading, and sewing skills. The technical skills required are the understanding of sustainable apparel knowledge that correlates the impact of the environment to the way the apparel is being produced based on the competencies. If competent in practical skills, the apparel industry will be efficient and this will benefit the consumers and contribute to the environment and society's wellness. In addition, Ryder-Caddy and Vouyouka

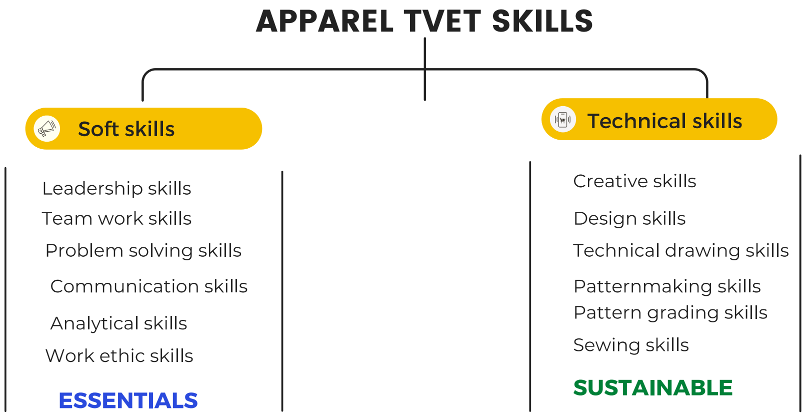

Figure 1.4 Sustainable apparel TVET skills model. *TVET*, technical and vocational education and training.

(2016) stated that it is critical to have design skills to understand the importance of the sustainable definition of apparel products. These skills include having pattern cutting and technical skills like sewing, technical drawing, and pattern grading. She emphasized that fashion technical skill is crucial to serving both industry and fashion consumers.

1.2.3 Apparel sustainable technology

The apparel sustainable technology shows the adoption of technology for an innovative design which has the potential to increase the demand of productivity of the apparel products. The competitiveness of the industry relies on the efficiency and agility of the product development cycles and lead time. Furthermore, the business models of a company adopting sustainable technology must be well-considered because heavy investments are needed for sustainable production processes to be accomplished. In addition, future fashion designers must be trained to have the right technical skills and the mind's predilection to exploit the new textile and apparel digital technologies as part of the creative design process (Pisani & Augier, 2021). Sustainable technology as seen in Fig. 1.5 shows the technology digitalization adoption for apparel product development in the production processes.

On the other hand, technology is also being adopted in the TVET apparel pedagogic training and learning. The importance of technical pedagogic training using technology will be discussed in the next chapter. This section will be looking into the implementation of technology for digitization and digitalization. Digitization is defined as converting something into a digital format while digitalization means converting processes using digital technologies. In summary, digitization refers to information, while digitalization refers to processes. Learning to digitize the technical process into digital information has been adopted by many big apparel industries

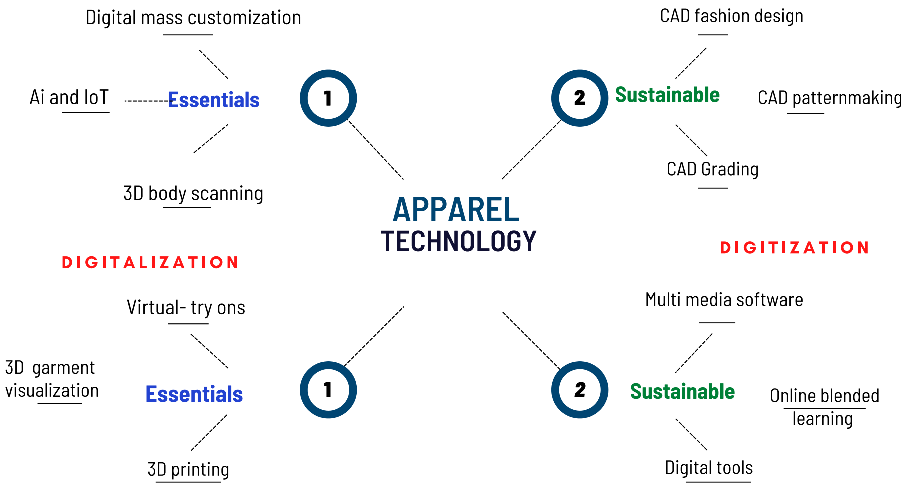

Figure 1.5 Sustainable apparel technology model.

worldwide (Zeike et al., 2019). Digitization advantages are yet to be penetrated by apparel home hobbyist, micro, and SMEs apparel companies in the future. The major objective of applying the digitization process is to adopt the sustainability concept in totality. On the other hand, the adoption of digitalization is also seen as another important sustainability factor to be considered in the future for competitive business. The goal of digitalization in the apparel industry is to increase the efficiencies, effectiveness, quality, and timely deliveries. According to Tareque and Islam (2021), digitalization in apparel manufacturing gives huge sustainability and transparency benefits.

The apparel sustainable technology consists of two elements based on Fig. 1.5:

- The technology adoption for technical training adopting digitization;
- The technology adoption for apparel product development adopting digitalization.

The digitization can be implemented for the process of design which happens at the stage of product development. The conversion towards digitization will result in better efficiency and will be more effective for the business since paper usage is less and since it reduces the redundancy of repeating the same work process. For example, drawing on the digital platform will permit the designer to just delete the information or alter the drawing on the digital platform without having to take new papers to draw on and repeat the same drawing with some alteration or corrections (Quang et al., 2020).

On the other hand, the adoption of digitalization in apparel product development can be seen in the usage of 3D body scanning replacing the body measurements procedure. The usage of this technology will give the advantage of the body visualization converting from 2D format to 3D anthropometric data. The accuracy of 3D as a tool for anthropometric data acquisition will enhance the development of the 2D garment pattern from where garment geometry originates and which garment pattern from this format can be corrected. The application of digitization format for apparel product development is the application of a virtual format, and this 2D pattern will become the medium between design concept and garment product. Using the technology of digital format, the 2D garment pattern can be altered and digitally cut to finish the garment production and in this format, the accuracy of fit is determined (Quang et al., 2020). The accuracy of good fit is the most crucial part of garment development at this early design stage which is the main driver for sustainable apparel manufacture practices. Thus, again, the emphasis of the 3D technology application for digital clothing development is to exclude redundant physical sampling and waste generated by pattern cutting or fittings. The other main factor is to make sure that the TVET skills are conducted efficiently for the process of apparel product development in the areas of technical drawing and pattern making which are the most important elements to ensure good garment fit and accurate size garments matching with the different types of body size and shapes (Obinnim, 2018). To conclude, apparel sustainable technology is recommended for the integration of innovation. From the view of other research conducted, the usage of advanced tools and technology is focusing on not only the adoption of the technology itself but also the enriching of the students' experience and learning process

(Shafie et al., 2021). E.g., using technology to learn pattern-making skills is easier as it gives you the space to complete it at your own pace and time.

1.3 Changes in sustainable apparel technical and vocational education and training education

The twenty-first century is different as there is a movement towards adopting the sustainability perspectives. Though the most devastating COVID-19 pandemic struck millions of people who went through a disruptive time including the global economy been hit by the catastrophe, still, there were a few world meets to decide on world agenda for tackling matters of world concern, like, recently, many countries came forward to discuss on and reach an agreement to tackle climate change and make a change while helping protect lives and livelihoods at the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow, UK. The Covid-19 pandemic and global climate change in the 21st century have forced us to think of the best way to move forward (Mair, 2020) without losing focus on matters of national and international importance. We need to change the way we handle apparel education, transiting from the traditional apparel skills over to the typical sustainability education in the TVET technological education to ensure competent skills for future fashion designers (Syed Azman et al., 2019). The turmoil in the sustainable environment of the future will evoke the awakening to the importance of TVET skills education in apparel education. The aim behind sustainable TVET education is for each fashion graduate to be well-equipped by possessing the proper technical skills to bring the designs alive. They thus gain skills to match the skill-sets needed in the industry.

The future is dictating to us to change the education system for the apparel industry. At last, TVET skills shall be embedded in the curricula to make fashion education more conducive towards apprenticeship programs. In the past, fashion designers developed garments by thinking abstractly, cognitively, and creatively. Today, the scenario has changed to match the demand and competitive employability market of the apparel industry. The education stakeholders are thriving towards imparting the extensive practical requirements of garment development and bringing in direct industrial involvement where both practitioners and apprentices can work together in the industry and gain benefits. Fashion students are looking at the possibilities of getting information, skills, and aptitudes to be competitive and to be prepared to gain sustainable apparel literacies.

The change will involve three different entities: the TVET institution as the skill education provider, the industry as the skill set advisor, and the learner as the recipient of the skill education. Sustainable TVET education ensures the right skills are acquired by the learners to align with the industry's needs. The skill gives better opportunities for them to be employed. The success of this change can only be seen in the loop when the practices include every skill for product development to the retail. The skill sets required for the apparel industry are the design and technical drawing skills, the ability at enhancing the visual appeal of the final apparel products, the details of the construction, and finishing. The practical aspects of TVET education are for completing the student's educational process. The ideal approach of TVET apparel education includes sustainable apparel knowledge and technical skills combined to produce a motivated specialist in the apparel industry.

1.3.1 Adoption of pedagogical teaching using technology

The outlook of TVET fashion education today shall be geared at moving towards pedagogical teaching using technology. The advent of technology-based teaching in apparel TVET education is not something new. The technology to be applied has been introduced since the late 20th century and early 21st century in many of the First World countries. During that time, the pedagogy of apparel TVET education started with the concept of blended learning. Blended learning principles adopted some usage of multimedia software in the teaching besides face-to-face interactions. Students have the opportunity to use technology to understand and learn the materials that are needed in fashion education. However, applying technology-based teaching for TVET fashion practical classes still seems impossible for many TVET institutions as the traditional workshops or labs use methods like hands and needle and thread instead of technology to know dressmaking. Students are used to practicing their fashion skills like drawing, pattern making, pattern grading, and sewing in the workshops (Mohd Ramly & Shaar, 2020). The advantages of using technology in the TVET apparel education are in the ease for learning as the population of youth now belong to the online society, and learning can happen at any time, at their own pace, and by a mode they are familiar with, i.e., it is accessible online. The criteria of pedagogical skills using technology for TVET education must meet standards in terms of sustainability and fashion skill-based learning and education. Sustainable fashion skills education signifies that the process of learning must be easy to adapt, efficient, repeatable, and meet the purpose of practicality. Using technology in learning will enhance the capability of students to meet the criteria above and cater to the advancement of education. Adopting full blended learning using technology is highly beneficial to the learners as they adapt to the full program independently. Practical learning becomes very adaptable with the time factor, helps gain self-discipline, and increases self-motivational tendencies.

The most relevant factor in the application of technology in apparel TVET education is to ensure that learners gain the correct skillsets matching the industrial needs so that the outcome of the products is delivered most sustainably. The right skill sets can be obtained efficiently using the technology, wherein it is anticipated that the apparel products are produced better with a good fit, good quality, long-lasting, and adhering to performance norms, accordingly and maintaining the expected clothing lifespans. Enhancing the technical capabilities when using technology will also drive a greater rate of innovation as more time can be spent on the creative aspects that are time-consuming while devoting less time for each other skill set needed. The skill set gained from using the technology-based training will ensure proper clothing fit and proper fit simulated alteration before the pieces are to be cut (Syed Azman et al., 2019). This is a sustainable practice as only the right size and fit of clothing shall be produced and the pattern-making blocks can be simulated for trial on the avatar, for try-on virtual. Additionally, according to Wai Yee et al. (2016), sustainable garments should minimize wastage and damage to nature. Sustainable garments also do not negatively affect the environment and the clothing designs can be used for a long time (Shafie et al., 2021). According to Klepp et al. (2020) "*the average lifespan of clothing is about 5.4 years. It was also mentioned that some of the garments being disposed are because of unstable size and unfunctional clothing*". This is proof that there is a need to cater to proper TVET training for apparel product development, and in the next section, there is one institution being discussed that takes TVET apparel education seriously for many decades.

Telestia Fashion School, Greece, is the only established fashion institution offering internationally accredited TVET education in fashion design programs using multimedia and also able to offer practical classes online. Telestia is an established learning institute whose apparel design technology and system is also applicable to the industry and recognized by the only world professional body, the Textile Institute, UK. The system was established in the 1970s by Ms. Anastasia Vouyouka, who understands the importance of TVET fashion education for the industrial application which ensures the production of sustainable clothing products. The apparel designing system has been utilizing the pedagogies for TVET fashion education for the last 40 years and was transformed into advanced multimedia-based learning system using state-of-the-art technology at the beginning of the 21st. century.

The Telestia technology is a TVET fashion education program that is very practical and comprehensive starting from the introductory level and going up to the advanced level with its method covering all the technical aspects of product development such as fashion design skills, pattern making, pattern grading, and sewing skills. The system also includes the computer-aided design (CAD) technology-based pedagogy for the learning of fashion design, pattern making, and pattern grading. The beauty of this system is that it is 100% technology-based training where students can access the technical practical tasks on multimedia software consisting of text, multimedia video, pictures, and interactive animation of the classroom-based training. In addition, this learning can further be adapted to use the e-learning mode, where the software can be accessed from online platforms, for participants to practice at any convenient space, in their preferred time. The flexibility of time and technology usage will enhance the learning of Generation Z and Generation Alpha, especially; the Glass Generation of the future. The system also uses sophisticated tools with embedded calculated formulas to avoid mental or manual calculation and to expedite the process of learning the skill of pattern making. In addition, the process of learning is made easy using step-by-step instructions to reach the final output. The Telestia fashion designing program consists of comprehensive modules of fashion design, pattern making, sewing, and grading technology in both modes: manual and CAD. The competency skills obtained from the disciplines taught using the system is the most complete syllabus anybody can go through as it covers the whole spectrum of apparel product development.

In general, the practical lessons are very systematic and have a structured learning methodology incorporated with comprehensive learning in a step-by-step manner making the learning very enjoyable and realistic. If the outcome of the learning skills applied to fashion design is to ensure the production of a well-fitted bodice block and style to fit each different individual and that has been tested on thousands of fashion students from all over the world, then the application of technological pedagogy makes the TVET fashion education a niche factor as it gives participants the feeling of empowerment when learning, as it is a self-explanatory education software to train self-studying, independent learners who can benefit from the modern concept of learning.

In a nutshell, the technology-based Telestia fashion designing system has provided visual media adoption and a conducive learning environment. The system also lends experiential learning through real-time practical observation when using multimedia software. While the learning becomes more flexible with different teaching practices and facilitation, still TVET students become attuned to an education that is more learner-centric and become active participants in a collaborative student-teacher interaction environment. Furthermore, the integration of innovation into their work in the fashion design course is applicable when there is the pairing of the right technology with innovative tools. The apparel TVET skill education is regarded as sustainable when it provides the right skill-adjusted work in the early stages of the product development, namely at the design and pattern-making stage. Manufacturing the right quality apparel products at the early production stage will avoid the dumping of the apparel at the landfills at the post-purchase stage. The waste and reduction of clothing in use due to non-conformance can also be avoided as user requirements are taken care of at the early stage of design and pattern.

1.3.2 Internship collaborations between industry and academia

Another major change that the sustainable fashion design industry is looking forward to in TVET education will be the alliance between the industry and academia. With these much-awaited collaborations, both the industry and the academia can look forward to the combined thinking synergy leading to more realistic and futuristic educational programs and the growth of students' practical learning skills for future fashion students. The strategies for internship collaboration that can be implemented are listed as below:

- Industry and academia shall build a good networking base to ensure the continuous intake of interns at the industry provided by the academia.
- Industry and academia shall have consistent discussions to understand the changes that occur both in knowledge and skills.
- The duration of practical training or internship shall be longer than traditional workshops, where lengthening the time will introduce more realistic skill sets needed in the industry.
- Interns should be working closely with the industry exchanging their knowledge and skills with the industry and that too interchangeably.

- Involvement from academia is crucial in imparting current knowledge of the industry to students, and the same goes to the industry as the input about the products and the demand from the consumers' viewpoint must be communicated to academia.

In summary, one of the main challenges faced by the interns is the readiness to be in the market place which should be the responsibility of sustainable TVET education and industry. While both entities shall work very closely with interns to identify the technology skills gap and curricula profile, still it's the responsibility of academia and industry to expose the interns to the sustainable fashion products specifications and the impact factor of this phenomenon. Both academia and industry must understand the importance of collaborations within the circle to make the students work with real-life situations of the industry and have the right skillsets needed (Syed Azman et al., 2019).

1.4 Industry changes towards ensuring the right skill set for workers

The future of the apparel industry in the post Covid-19 foresees challenges. This situation is not new to the industry as they have faced many challenges in the last few decades. Pisani and Augier (2021) reported on the apparel industry and said that "the industry had come under intensifying scrutiny for being exploitative, environmentally damaging, and unsustainable." In addition, given, post Covid-19, the industry is still dealing with the ongoing sustainability issues accelerating towards the anticipated adverse impact, if not properly managed, it follows that there must be plans and strategies for the industry to move forward, post Covid-19, and adopt and adapt the circular sustainable technology as fast as possible. The change in the industry is towards making the worker's skillsets match the production demand so that they can face competitiveness in the post Covid-19 situation. It is highly recommended to practice collaboration between academia and TVET institutions which can ensure practical training adoption interchangeably. The industry also needs competent STEAM-based designers who have all the necessary education background such as scientific knowledge, technical skills, and esthetics with creative skills while adapting to the innovative approach. The challenge is also in adopting technology and the sustainability concept.

1.4.1 *Innovation challenge 1: digital technology with sustainable process integrated*

The first innovation challenge is to adapt to digital manufacturing practices using technology. This challenge is to enhance the sustainable process targeting the aspects of delivering creatively using the technology approach. This method for products with a shorter lead time adapts to circular economies and will harness innovative projects to reduce waste and create a sustainability impact.

Based on some projects that have been conducted, there are two other adoptions that we can utilize as below:

- Design and manufacture: using digital technologies to design and produce designer-led, small volume, customized products, and cutting lead times.
- Design tools for maximizing materials utilization: developing new processes for recycling high-value textile waste.

1.4.2 Innovation challenge 2: digital communication and data analytics inclusivity

The second innovation challenge is towards utilizing digital communication abilities to improve the design process. Some of the digital tools are: digital esthetics design system and artificial intelligence (AI) integrated digital drawing toolbox. The digital tools will deliver efficient communication for the work, with a better speed to develop luxury fashion products or mass customized products. Some of the sample projects are these two works below:

- Communication of esthetics: communicating the physical sensation of touching and feeling fabric – entirely online.
- *Color meaning and international customer preferences: making better use of AI and big data analytics to forecast and interpret consumer trends around the world.*

1.5 Design, technology, and fit in relation to skills

Why it is difficult to use technology for successful design? The problem of the industry is deep vis-à-vis time, and also in substance. Covid-19 is not the cause of the current array of difficulties in the fashion design scenario but it has proven the social trigger to tip the balance of survival for retail and market methods. The problem is systemic and has mainly been related to "Big Retail" calling the shots of the industrial practices. It affects the overall design, while the homogenization of style leads to confusion and chaos of sizing and shape. This has led to a design that appeals to the senses, but not to all the other functions that shape our demand for a suitable outfit. Covid-19, and the environmental issues, finally triggered the big retail image of the no-choice situation that we find ourselves in. The causes of this though stemming deep from the 90 s when simplification and standardization of processes led to the homogenization of styles and collections, still the fact remains that this gradually resulted in the loss of the special skills needed to achieve good fitting garments. Design being completely misunderstood has not been applied properly, and exploitation of technology to serve this purpose was neglected. While the processes of design, sampling, and manufacturing for the mass and the fast fashion of the styles they market do not serve the technical details needed, still they serve the simplicity of work required, to lower the cost. Technology that could be groundbreaking for sizing, and many other stages of the process serve the cause of oversimplification, and not of *fit quality*. The process in relation to *design* is disoriented.

In this process, size tables became blurred, and *shape and fit* was lost to the convenient design. The style was repeated with minor variations, leading to complete distortion of Fit and misrepresentation of Design. Solutions, like measurement data collection and customization efforts based on unspecified fit needs, have even more blurred the idea of what is needed for a good fit. All this turned technology use, and application into an example of wrong practice and one to avoid in the future. To apply all the suggestions and solutions of sustainability, for the environment and fashion *per se*, it is necessary to focus on not only materials, and every kind of technology suggested, but also their knowledgeable use in an inclusive holistic design process. It is necessary to make sure that there is cooperation at all the stages needed for design and its realization. If the target is to make the wanted/saleable garment from the first stage, (with no waste!!) then, to take advantage of every advance, and have them serve the purpose of product quality, it is necessary to get back and identify the basic skills of size, shape, and fit for the design. This cooperation is vital for a holistic design approach. However, the special skills needed to achieve this, namely, the technical skills of design, clothing, and realization need to be respected and learned. This need is repeatedly stressed at every possible conference or meeting for the last ten years and beyond. It is now the time for the industry and society to decide to invest in the young and in improving their technical skills. To manage this with success, both social and learning cultures need to change. We should not be afraid of a disruption in the *status quo*, which is necessary. An example of a useful technology that can dramatically fail if not served well. Why it is important to understand body scanner data use in Clothing Technology!

Data use is one of the important factors that may determine outcomes in today's impersonal dealing with the personalized clothing design process. The reason is that in the last few decades the industry has been designing in a chaotic application of its size tables, which were based on past experiences. These experiences were acquired when there was a clearer and closer contact, understanding, and appreciation of body measurements and their role in the good fitting of any size or shape, and, eventually, in the garment styling. They served their purpose well during their time, but they can be confusing in today's approaches.

Then, there was a closer involvement and application of skills in garment fit, both in size but also in styling and grading which are greatly influenced by size data. This was overwhelmingly proved in all our years of research and experimentation of relevant applications, and most recently and specifically in the study below: "An exploratory study of participants' fit perceptions of customized garments" (details below). The current industry trend has alienated both designers and students of design from this relationship. It has been proved and is clear that when designing and using this valuable data, you should always use them by understanding their relation to their individual use and application in the clothing technology, and pattern-making process.

1.6 Conclusion and future direction for technical and vocational education and training apparel apprenticeship

With the comprehensive deliberation taking place over the TVET education as the way forward, the apprenticeship programs seem to be the best chance of a REAL future for the apparel industry. This apprenticeship program is highly recommended for the future as it is a unique combination of training and career-specific work experience in gauging both the competency and knowledge-based qualification for the apparel industry's skill sets. Global institutions have been delivering TVET through apprenticeships collaborating on the schemes with the partner industry. TVET apprenticeship is the workforce establishment leading to sustainable practices. Sustainable practices are possible because the apprenticeship is on the competency-based pedagogy that increases the prospect of training on the right skillsets to match the industry needs. Proper skillsets can be implemented at the workplace for apprenticeship training for the future apparel industry. In addition, the TVET apprenticeship is the best solution in gaining skills, applying learning methodology, and gaining work experience. TVET apprenticeship is acknowledged as the solution for future employment. The suggested application is seen below.

1.6.1 Competency work-based syllabus for apparel apprenticeship

- Centered on the expertise and specialization of the industry coach for better assimilation of knowledge and skills at the industry.
- Curriculum that is updated based on the needs and current trends of the industry.
- Flexible syllabus based on the competency level of the interns, alongside progressive training.
- Training that is within the distance reach of the institution and industry.
- Far more engaged and more able to build better relationships among industry and institution.

1.6.2 Apparel apprenticeship training integrating the sustainability concept

- Strategic visibility upstream to downstream: from supplier to retail.
- Proximity leading to collaboration and partnership that guides the curricular requirements.
- Inclusive of workable collaboration, green talks, environmental education, and exchange of students and industry staff.
- Experiential exchange in the different global apparel industries worldwide.
- New ecological ways for consumers in the context of design, production, and retaining clothes.
- Re-educating fashions students towards inventing more functioning and performing clothes that last longer and fit better.

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The role of 3D measurement technology and anthropometric data for improved garment fit and sustainable manufacturing

2

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2.1 Introduction

Twenty-first century technologies have radicalized the apparel trade. The human form can be digitally rendered, garments virtually fitted, supply chains streamlined, and time optimized with cyber workflows. However, the full benefits of 3D apparel technologies remain untapped for varied reasons such as: virtual fitting platforms struggle to define garment fit for optimal size selection; made-to-measure protocols continue to have difficulty fitting outlier body types; and, sampling continues to require both a physical and digital sample.

"Fit," defining the body-to-garment relationship, is the driving force behind all stages of apparel production. From measuring human form to apparel production, and all the nuanced steps in between, fit remains critical to all decision-making processes. Apparel sustainability initiatives are therefore intrinsically linked to 3D measurement technology and anthropometric data acquisition. The relationship between human form and garment, however, is so complex that only now, thirty-plus years past first body mapping considerations (Heisey et al., 1988) came to the fore, years after photogrammetry discussions (Gazzuolo et al., 1992) were first heard, and years after early ease and fit preference discussions (Ashdown & DeLong, 1995; DeLong et al., 1993) became known, can issues affecting garment fit begin to be addressed.

Whether achieved in a physical or virtual-to-physical environment, the garment design process remains mainly heuristic. To sufficiently break down intuitive processes into detailed steps requires exhaustive detail which can seem quite unnecessary; it is far more intuitive to show someone how to put on a shirt than it is to write detailed instructions for that task. The same is true with almost all aspects of fit. Consequently, an abundance of data remains hidden within heuristic practice waiting to be unpacked, with the widespread adoption of 3D technologies stalled as a result. As will be discussed, 3D measurement technology will continue to play a vital role in tracking the vast quantities of data required to mathematically define, and track through time, the body-to-garment relationship.

Digital Manufacturing Technology for Sustainable Anthropometric Apparel.
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This chapter will initiate a discussion concerning the 2D application of 3D acquired anthropometric data. Since the accuracy of 3D as a tool for anthropometric data acquisition or visualization is indisputable, examples of 3D fit will not be provided. The focus will instead be on the 2D garment pattern from where garment geometry originates and from where it must also be corrected. Whether discussing a physical (paper pattern) or virtual environment (virtual pattern), the 2D pattern is the conduit between the design concept and garment product. It is the vital link in the garment fitting value chain driving decisions toward sustainable apparel manufacturing practice.

2.2 Background

"Fit" encompasses a breadth of detail in stark contrast to its deceptively simple three-letter name. At its core, fit describes how garment dimensions vary from body dimensions. The term, however, is used both to consider a single body-to-pattern relationship (how does this garment fit this person) and to broadly reference a spectrum of body-to-garment relationships across a garment size range (this jean has been designed to have a relaxed fit while the other one has a slim fit). Fit, therefore, encompasses a breadth of objective and subjective points of view defining numerous body-to-garment relationships. It is, therefore, more precise to say *fit defines how garment dimensions vary from body dimensions within an acceptable fit intent error range*.

Scope of fit intent is best understood by contemplating three common fit subgroups as a spectrum of results with varying degrees of acceptable fit error: bespoke, ready-to-wear (RTW), and made-to-measure (MTM), explained here:

- Bespoke fit takes a body-to-garment perspective on fit. Pattern geometry is directed by the concerns of a single individual's fixed body-shape and fit perfection is expected.
- RTW fit takes a garment-to-body perspective on fit. Initial pattern geometry is directed for a bespoke fit and then further adapted (fit error away from bespoke fit) to have tolerance for other body shapes within a set dimensional size category. Fit is concerned with how product geometry (e.g., t-shirt, skirt, trouser) interacts with a range of body morphologies (body shapes). For example, a slightly looser fit over the tummy on one individual may permit the size to accommodate a fuller abdomen body-shape with a snugger fit. A range of flat to full tummy shapes can thus be accommodated within the same garment size. Fit imperfections are expected.
- MTM garment fit rests somewhere between RTW (garment-to-body) and bespoke (body-to-garment). In general, MTM garments reflect the degree to which a brand is willing to adapt RTW pattern geometry to suit a degree of bespoke fit. MTM fit moderately improves a garment-to-body perspective on fit. The expectation here is that the garment-to-body relationship will be improved (pant length corrected), not that it will be perfected (crotch curve matched to unique morphology).

Fit is strongly directed by personal preference and interpretation. Therefore, any available guidleins for critiquing good fit may be negated by personal preference and indeed made irrelevant if a design is created for “shock intent.” The dilemma then is: how to objectively quantify that which is subjective?

2.2.1 The body as a 3D object

Just as garments are offered with a range of fit intents (bespoke to RTW) so too are avatars (the virtual customer or fit mannequin). This is partially related to scan device adequacy and partially related to avatar intent. Standards to define avatar “intent” remain undefined, but it is highly likely digital presentation of human form will be presented as a scope of intent like garments, ranging from RTW to bespoke. For the purpose of discussion here, we will assume there is a high degree of relevance between the “digital space avatar” to “physical space” person; where the digital avatar is a reasonable representation of an individual’s physical body-shape in static virtual form and reflecting fixed body dimensions.

Avatars are offered in a range of qualities. Work toward standards to make this quality transparent to consumers is ongoing and in-depth discussion of avatar quality is outside the scope here. The following is offered as a baseline for further discussion:

- Synthetic or statistical avatars are the result of statistical data from demographic studies. These are the digital equivalent of physical fit models and mannequins. In many regards, these models are superior to physical models in that they reflect the averaged body-shape dimensions for a particular size range. In contrast, a physical fit model reflects only one of several body-shape variations the size was intended to accommodate. *Synthetic avatars can be resized (parametrized) for an approximation of unique morphology but degree of accuracy is not always suitable for critical fit assessment.*
- Twin avatars are the result of processed scanned body data (point clouds). Subject to unstandardized processing methods, discussions regarding precision and accuracy are ongoing; with need to know posture variability, landmarking discrepancy, etc. While the accuracy of traditional booth scanners is undeniable, discussion regarding “which moment in time” reflects the best baseline for a ground zero representation of human form remain in discussion. Methods of averaging the body at “moments in time” have proven very successful and the application of these methods will further our understanding of changes to human morphology through a dynamic range of movement. *Twin avatars are suitable for critical fit assessment.*

2.2.2 The garment as a 2D object

When considering garment fit, it is natural to focus on the garment as a 3D object and not the 2D pattern that directed its production. This focus on the 3D result (garment-to-body) rather than 2D process (body-to-garment) may, however, have inhibited a quantification of artisanal tailoring and fitting practice. Most garments are morphable objects capable of near-infinite shape variation. Laying on a table a garment may appear as nothing more than heaped fabric. Hanging from a hanger the fabric begins to take the form of familiar garment shapes. Wrapped on a body the morphing continues as the fabric drapes from individual bumps and curves or lack thereof. It is therefore more correct to describe a garment with reference to its origin: 2D pattern geometry cut out from a given material. From this perspective, a garment is 2D origami capable of morphing to the 3D object it is wrapped around. Geometrically modeling fit from an origami perspective adds an element of clarity. From the perspective of origami, the connection between 2D points on a flat surface (patterns and fabric) to 2D points in 3D space is better established and an understanding of fit may begin.

Heisey summarized garment fitting as a process by which "fitting devices" are used to control the wrinkling and buckling that occurs as fabric is wrapped and draped around human form (Heisey et al., 1988; Heisey et al., 1990). Their explanation of fitting as a process of either removing (darting and pleating) or adding (flare, gathers, and/or pleats) material relevant to fabric grain remains true to the workings of modern-day pattern-making practice.

Describing the garment as a 3D object can therefore be misleading as it encourages one to focus on the 3D end result with little consideration for the 2D shaping and buckling causing that result.

The process of translating 1D measures to 2D pattern geometry for subsequent manipulation into a 3D shape is deceptively complicated. Fig 2.1 illustrates where the nature of non-developable surfaces adds complexity to body-to-garment understanding. Just as a sphere cannot be flattened to a singular precise 2D shape, neither can it be done for the human form; nor the garments wrapped around that form. To gain a better understanding of the relationship between origami-like shaping, buckling, and the heuristic skill of a master pattern-maker, understanding the connection between the 3D garment and the 2D pattern is critical.

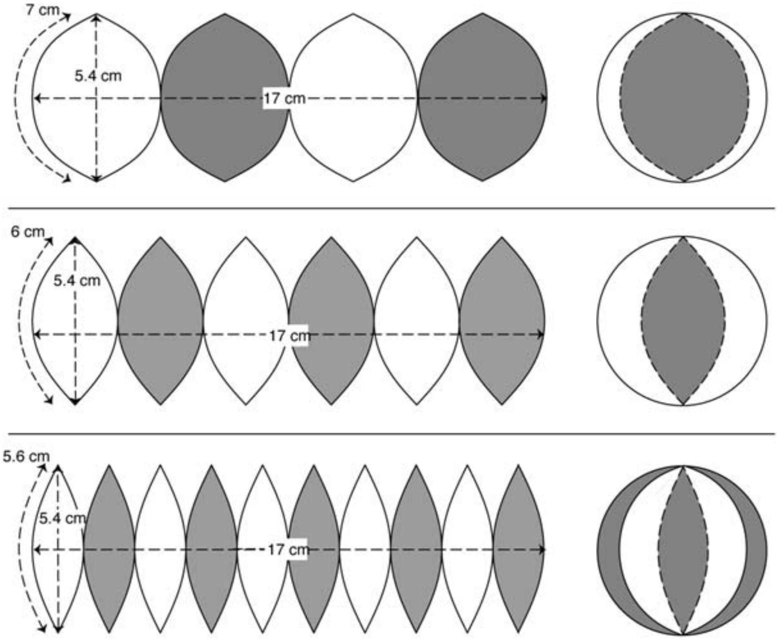
2.2.3 Garment and pattern geometry

The construction of pattern geometry (pattern-making) is more often than not a process carried out in a 2D computer aided design (CAD) environment, but drawing patterns by hand and draping fabric on human form remain common practice even within virtual environments. Inherent in pattern-making theory is the understanding that pattern geometry reflects an estimation of the body-to-garment relationship that requires fine-tuning during the "draft-sample-adapt" fitting process (sampling). Using any of the plentiful resources for 2D garment pattern development ultimately leads to an iterative process whereby a sampled garment is found unsatisfactory, and the pattern must be iteratively adjusted. Depending on the complexity of garment design, the properties of the material to be used, and the human form to be clothed, the draft-sample-adapt pattern-making process may take several iterations.

The majority of garments originate from 2D geometric fabric shapes that are connected (sewn) to form more complex shapes. Simple garment designs, such as seamless tube t-shirts, are frequently produced from single 3D geometric shapes (circular knitting or 3D printing) but breaking the shape into sections (pattern pieces) is usually more practical; both for reduced production costs and for customizing shaping ("fitting devices") to unique body morphology. Separating pattern geometry along shoulder and side seams is common practice but pattern geometry may be split anywhere.

Through careful origami-like folding, it is technically possible to create any garment from a single pattern shape (Demaine & Tachi, 2017) but this is not the norm. Seams offer perimeter locations where pattern geometry may be shaped to body form. Fewer seams translate to fewer shaping and the likelihood of fitting error (more or less ease than desired) or internal fitting devices such as darts. As illustrated with the sphere pattern in Fig. 2.1, direct translation of non-developable measurements to 2D pattern is in many cases impossible given the fact that with multiple non-developable areas the human form is exponentially more complex making shaping pattern geometry to body form that many times more difficult.

Just as it is far easier to demonstrate putting on a shirt than to write detailed instruction on how to do so, so too is it easier to demonstrate fitting practice than to record intuitive procedure. Having "seen" how a sphere pattern is created, most people could replicate the procedure through an heuristic draft-sample-adapt workflow. Yet writing detailed instructions for that process is considerably more difficult. Garment fit has remained largely an heuristic endeavor for similar reasons.



Non-developable surfaces, such as spheres, are not easily flattened to 2D geometry.

By cutting and re-arranging the pattern pieces illustrated, countless variations on the basic sphere pattern are possible; but as a general rule, fit error away from the original shape is decreased as "shaping" through seaming is increased.

Figure 2.1 2D sphere pattern geometry.

Indeed, within the time constraints of apparel production models, the sampling and heuristic fitting practice has remained the most time effective solution.

Mapping of body morphology (non-developable areas) to pattern geometry is further complicated by the dynamic nature of the body; the ribcage expands and contracts with breathing, tissue swells and shrinks with fluid and gas, muscles move limbs and alter morphology, the breast is redistributed with supporting structure (corset vs soft bra) (Wang & Zhang, 2007), and body tissue may be compressed and manipulated. Mapping is largely a honed skill acquired through experience whereby practitioners mix and match learned measuring techniques with acquired ease practice. Accounting for the dynamic nature of measurements between landmarks is heavily directed by the product. A cycling garment requires substantially more ease for arm range of movement than an evening gown. A lingerie practitioner measures to account for specific breast morphology while a practitioner concerned with outerwear measures the breasts as one with the body. The resulting ease amounts will be a balance between design esthetic, mobility requirements, and fabric extensibility.

To add order to the process of mapping human form, traditional pattern-making practice sub-categorizes body-shape variation into age and gender (men, women, children, infants), and limited shape sub-categories (husky, plus-size, tall, petite, maternity, portly, etc.). Variations within these specific sub-groups are accommodated with a level of fit tolerance (ease). Tolerance is built in partly to accommodate non-developable body areas (shoulders, breasts, joints, torso curvature) and partly to make body-to-pattern theory relevant to a broader spectrum of morphologies (body shapes) within the sub-categories (Chen et al., 2008).

Essentially, the art of creating pattern geometry relies heavily on decisions regarding where best to allocate ease error. Understanding fit tolerance and isolating ease from body-shape has been the subject of much research, with further study being suggested urgent (Alrushaydan et al., 2020; Brown et al., 2012; Bye et al., 2008; HwangShin et al., 2011; Makhanya et al., 2014; McKinney et al., 2012; Song & Ashdown, 2012; Tama & Öndoğan, 2014; Wu et al., 2018; Xia & Istook, 2017; Zhang & Jin, 2021). As will be discussed, only through the use of 3D technologies can the multiplicity of factors defining body-shape and ease be sufficiently tracked for quantification.

2.2.4 2D body-shape and pattern geometry

A block, reflecting a process through which body dimensions have been mapped to a garment pattern, is the starting point for traditional pattern-making. From this foundational 2D geometric shape, core principles of dart manipulation, slash and spread, and seam relocation (Heisy's "fitting devices") are used for infinite variation. What is not readily apparent in texts demonstrating these techniques is that application on different body shapes changes pattern geometry in very different ways. As pattern geometry changes, ease error changes, fabric properties change (as seams angle toward bias), style lines change, and even details such as closures must be adapted (e.g., waist-to-hip drop can change zipper length). *Without an understanding of the foundational shape of human form (body-shape) prior to addition of style and/or* *material variables, the opportunity to build in error is profound and this error greatly contributes to the costly endeavor of sampling*. Fig. 2.2 illustrates how minor deviations in body-shape change fitting devices, which in turn change pattern geometry, and have further compounding effects on finished garment design.

Body-shape blocks have traditionally used standardized fitting devices because quantifying body-shape outside of virtual environments requires a level of mathematical assessment impractical for apparel business models. Quantifying body-shape involves assessing variation and inter-relationship in weight distribution (e.g., heavy on top, middle or bottom), height distribution (e.g., short or long torso, upper to lower limb length variability), morphology (e.g., shoulder slope, arm shape, limb attachment shape) as well as a keen understanding of fitting non-developable areas (as illustrated with the 2D sphere pattern). It is here that 3D technologies have, and will continue, to radicalize apparel and fit. Flattening of avatars into 2D form has provided great insight about the relationship between shaping devices and body-shape.

Examples of body-shape origami are close to the body-fitted lingerie patterns and patterns (blocks) for mannequin covers. They are body-blocks with bare minimum ease and pattern geometry reflective of body morphology. Developing body-blocks can be a painstaking process considering the best-compromised choice for

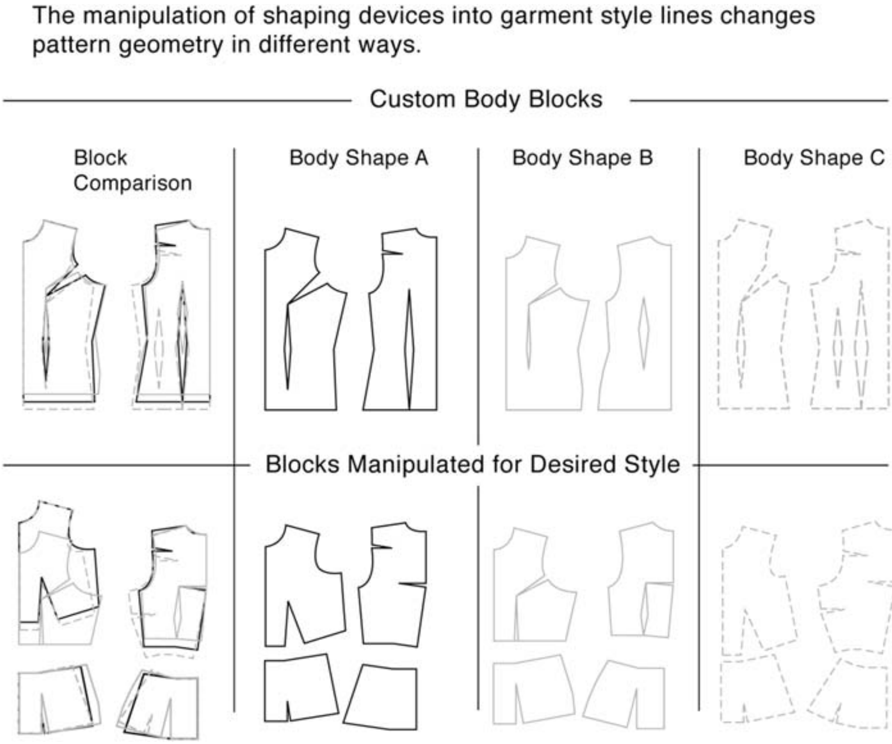


Figure 2.2 Body-shape drives pattern geometry.

shaping and darting ("fitting devices"). As with all origami, a degree of error is inevitable; so, inherent in the development of a body-block are decisions on acceptable degree and placement of error. Complex morphologies such as those with rounded shoulders, back curvature, asymmetry, large breasts, stooped postures, protruding abdomen, large buttocks, bow-legs or knock-knee, scoliosis, etc. can require several pattern iterations (draft-sample-adapt).

Methods for creating body-blocks as a "flattened layer" from a scanned body mesh are an invaluable learning tool for contemplating body-to-garment relationships but the resulting patterns do not always adhere to foundational principles correlating material properties to human form. Flattened meshes, while a near-perfect mathematical reflection of human form, do not necessarily reflect a shape conducive to origami-like folding and shaping relevant to garment materials. The resulting block patterns have proven to be more accurate than blocks created with current body-shape parameterization methods but, since the blocks must be used in conjunction with stretch materials, a true definition of origami body-shape remains hidden and intertwined with fit tolerance. A fit unique to body will result but, given it's reliance on fabric with stretch, a geometrically defined body-shape has not been achieved.

2.2.5 Fitting and sampling

It is very rare for a first-round body-block to fit successfully. In theory, any child pattern that results from the parent pattern (block) will have the same intended fit. Available literature presents a deceptively simple process suggesting that the fit of the child pattern maintains that of the parent. In practice, however, the compounding effects of design, fabric, and body-shape quickly render the fit of the child pattern unpredictable, making the draft-sample-adapt iterative pattern-making process yet again necessary. Virtual sampling has proved an effective tool for fitting and sampling, as well as drastically reducing associated material costs, but fit optimization continues to require both a virtual and a physical sample. With the ultimate goal of 3D CAD environments being design concept to finished pattern through virtual sampling only, fit optimization continues to inhibit automation (Zangue et al., 2020). Most 3D apparel CAD environments can entertain concept-to-pattern to one degree or another, but its current effectiveness is limited mainly to RTW, with only some MTM effectiveness (Istook & Guo, 2020), and very limited bespoke effectiveness.

2.2.6 Grading

Once the draft-sample-adapt garment design process has achieved a satisfactory sample product, the pattern must be made ready for product manufacturing. If the product is being made as a bespoke product, the process is straightforward: seam allowances, closures and findings are finalized. For RTW and MTM manufacturing, the pattern must be graded (resized or parameterized), both smaller and larger, into a size range suitable for demographic reach. Traditional grading changes perimeter pattern geometry, but not internal shaping. Without a change to internal shaping devices, all patterns graded from the original parent pattern will have the same inherent body-shape. Since weight gain or loss frequently involves a change in body-shape, bodies do not necessarily change from one size to another. For example, an hourglass body-shape could become more oval with weight gain around the waist or pear shaped with hip weight gain.

The infinite variations of human form driving pattern geometry in only moderately related relationships which, combined with infinite and changing preferences for fit, are impossible to assess outside a digital environment. As illustrated in Fig. 2.2 body-shape affects pattern geometry in complex ways. Consequently, methods to evolve grading practice have been the subject of much research. Grading is currently most effective at creating a size range for a single body-shape. Further research into body-shape categories will continue to offer improved fit opportunities for forward thinking apparel manufacturers.

2.2.7 Fit assessment

A fit assessment offers a spectrum of perspectives on the customer's body-to-garment relationships. This spectrum, outside of full discussion here, ranges from a fit estimation (synthetic 3D model with estimation of 2D garment shaping) to a forensic fit analysis (twinned 3D model relative to a body-block). With diligent consideration given to the complexities concerning body-shape, ease, and pattern geometry, it becomes clear that traditional methods of fit assessment must evolve to better apply the wealth of digital data now available. Methods for improved application of digital data stand to improve fit assessment, which will translate to customer satisfaction, and thereby fewer garment returns, and lead to viable on-demand manufacturing, ultimately driving sustainability. Fit assessment can be summarized as follows:

- A 1D fit assessment compares tape measure to size chart dimensions or tape measure to garment dimensions. This reflects the offering of current size prediction engines where fit tolerance and preference are used for an estimation of fit only.
- A 2D fit assessment offers an objective quantification of both customer fit preference and body-shape as geometric pattern dimensions. This offers the possibility for precise fit assessment using tech pack data referencing geometric body-shape. Since customer fit preference also has a mathematical reference (geometric dimensions beyond body-shape), the opportunity for fit assessment to go far beyond current estimation practice is very real.
- A 3D fit assessment offers a visual representation of an avatar-to-garment relationship where critical fit data (heat map, body-to-garment air gap, or compression) can be incorporated in parameterization engines to automatically drive pattern geometry. This reflects the possibility of critical real-time fit assessment satisfying both physical and virtual fit and sampling environments.

2.2.7.1 Challenge for 3D technology

With the body-to-garment relationship driving all decisions from design concept to customer purchase, the need to mathematically define heuristic fit processes has become critical. A current lack of theory regarding our geometric understanding of fit is inhibiting widespread use of technologies that have demonstrated much possibility. The challenge for 3D technologies is twofold:

- To quantify heuristically assigned pattern adaptations that are intuitively assigned during the design and sampling process.
- To quantify body-shape such that automated pattern blocks can be generated from any scanned body data regardless of age, gender, or dysmorphia.

The remaining of the discussion will elaborate on the decades-long quest (Ashdown & DeLong, 1995; Song et al., 2020) toward quantifying the decisions that transpire during the complex draft-sample-adapt workflow to achieve customer-defined satisfactory fit (fit preference).

2.3 Geometrically defining body-shape

Utilizing Heisy's concept of "fitting devices" leads to an understanding that a geometric representation of body-shape is possible through the use of fitting devices to remove unwanted pattern dimension (ease). The resulting pattern block (body-block) is therefore an origami simplification of human morphology using established priciples darting and shaping pattern geometry to suit unique body-shape. Fig. 2.3 illustrates how a quantification of body-shape permits an understanding of ease as distributed values.

Establishing garment fit as body-to-garment variables (body-shape and ease) permits the linear tracking of these variables through the garment production workflow and lays the foundation for an in-depth geometric explanation of garment fit. A linear pattern-making workflow allows for a mathematical description of the compounding effects of body-shape on design decisions previously estimated by an heuristic draft-sample-adapt workflow. Fig. 2.4 illustrates a linear approach to pattern-making provided with recognition of a geometric definition of body-shape. The workflow does not vary from traditional practice sufficient to require "change management," nor does it attempt to add rules or procedures to the "art of design." It simply outlines a digital means of quantifying the complex body-to-garment relationship simply referred to as fit. It permits the tracking of immense volumes of fit data through the art of design. A linear approach to pattern-making brings order and awareness to processes hidden within the familiar practices of pattern-making, sampling, and fitting suitable for both computer coding and the artistic endeavor of design (set, line, balance, ease, and grain) (Ashdown et al., 2004).

2.3.1 Measuring process for body-shape using landmarks

Landmarking is the basis for measuring and the foundation for establishing the body-to-pattern relationship. The methods used to landmark the body directly correlate to methods of pattern-making and human modeling. In physical measuring settings, landmarks are located through palpation of bony reference points projected

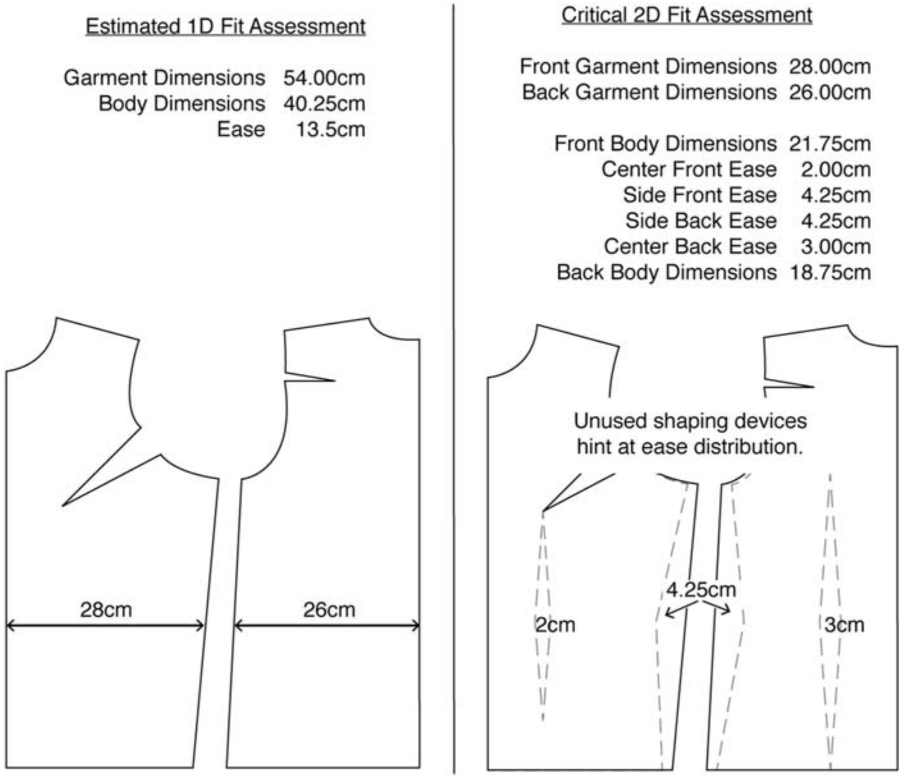


Figure 2.3 Critical fit assessment.

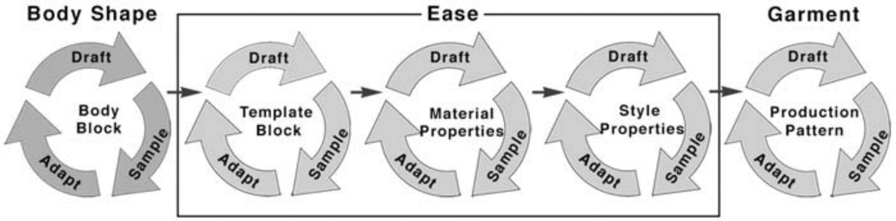


Figure 2.4 Linear approach to fit.

on the body surface. The process is often fraught with ambiguity, especially on highly muscled individuals or bodies with high fat composition, and misinterpretation between practitioners is common. With computer algorithms attempting to mimic flawed real-world processes and workflows, translating these practices to virtual environments has proved equally as problematic. Further difficulties with landmarking arise from body scanning restrictions. To avoid occluded scan areas (such as limbs appearing as an extension of the torso), it is necessary to scan the body with arms and legs in a splayed position (A-pose). With even minor shifts in posture having been noted to alter measurement data, concerns regarding how a ground truth can be defined frequently arise. Technologies that allow the study of a garment's range of movement ease and the ability to compare static and dynamic body anthropometry will go far to resolve these scanning obstacles.

2.3.1.1 Patch boundary landmarks

For anthropometric study, it is necessary to break up the human body into sections by denoting critical breakpoints where body dimensions morph with movement: arm and leg joints, or where the torso bends between the ribcage and iliac crest. Virtual technologies frequently refer to these areas as patches. Pattern-making practice is built around geometry (pattern blocks) made to fit these sections. To divide the body into either patches or blocks, points of reference (landmarks) must be established. While pattern-making methodologies will differ slightly for each use case, all methods build upon a set of common boundary landmarks for which the International Organization for Standardization (ISO) has established guidelines.

2.3.1.2 Sub-divisional landmarks

Accounting for unique body morphology (non-developable areas) requires further internal sub-division of the patch/block boundary areas for which direction from standards is less clear. This lack of clarity stems from the fact that pattern-making for non-developable areas frequently requires "product driven data." Fig. 2.1 illustrated different pattern geometry for spheres. Similarly, non-developable body areas will be fit differently depending on the garment. For example, the breasts are measured as one with the body when collecting measurement data for outerwear products but should be measured as separate and individual appendages when gathering data for bra products. The waist reflects another body area greatly influenced by the product and where standards for landmarking and measuring have subsequently had difficulty offering one singularly clear definition. For example, a product developed for a waistband sitting high on the body requires body dimensions near the bottom of the ribcage, whereas a low-waisted pant can require body dimensions below the navel. The waist landmark is as relevant to style (which is the best location for a waistband relevant to dynamic movement, comfort, and body morphology) as it is to anthropometry (where the waist is a landmark between the lowest rib and the iliac crest) or personal fit preference (where waist shaping is deemed aesthetically pleasing). Due to the nature of apparel design with its evolving trends, developing standards for product-driven landmarks has proved difficult. This has resulted in compatibility issues between different scanning applications. How physical practice can be evolved for novel practice toward methods inclusive of gender, age, and dysmorphia is an extensively studied and highly controversial field. The discussion here will focus on the common ground. Fig. 2.5 illustrates the boundary landmarks that divide the human body into twelve areas for analysis. It is worth mentioning that this simplified illustration does not begin to hint at the complexities of placing landmarks on complex morphologies. (e.g., highly muscled, obesity, dysmorphia, etc.) or the intracacies of landmarking the head, neck, breasts, hands, and feet (Fig. 2.5).

2.3.2 Body-block

With complex pattern-making being driven by dart manipulation (Fig. 2.2), the need to begin from a block reflective of accurate and precise body morphology is imperative. The process of mapping measured distances between body landmarks to 2D pattern landmarks is complex and may be accomplished in many ways. As illustrated with the sphere origami, translation is not always direct, and methods will vary; the three-sphere patterns presented in Fig. 2.1 all do a reasonable job of replicating the sphere, but each would offer a different degree of error. Similarly, there are many methods for creating body-blocks with varying degrees of error all suited to application (Cumming & Weaver, 2019; Kim, Han, & Shin, 2021). Standards development in this direction will have to be sensitive to conflicting methods and set an acceptable degree of ease error possibly offset against a test fabric buckling factor. For example, a body-block created from a flattened mesh body scan provides

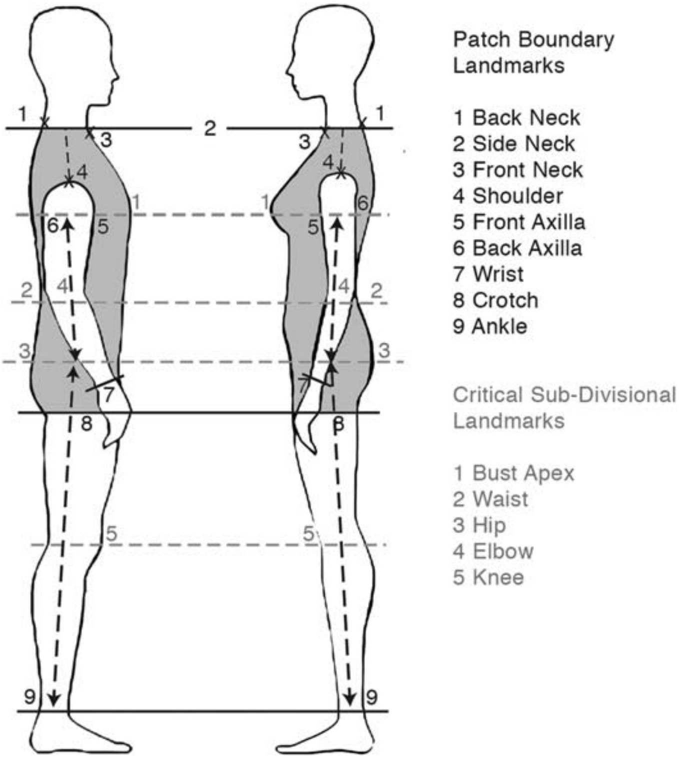


Figure 2.5 Boundary and sub-divisional landmarks.

a block with technically zero degree of measurement error yet reveals substantial buckling when sewn due to conflicts with fabric grain. On the other hand, a block pattern developed through a traditional draft-test-adapt workflow will reveal minimal buckling but a higher degree of ease error. The ideal would be to find the best possible balance between block ease error and fabric buckling. In this regard, a variety of body-block methods could be gauged against an efficiency scale.

The concept of a body-block builds on established shape theory based on relationships between key girth measurements (Carufel & Bye, 2020; Devarajan & Istook, 2004; Simmons, Istook, & Devarajan, 2004a,b). The result of these pivotal works suggests MTM adaptations are better achieved (customized) from a block more closely resembling the individual's body morphology. Fig. 2.3 illustrated the opportunity for critical fit assessment with consideration for the body-shape within a dimensional size. Without a body-block baseline, only a rudimentary fit assessment can be offered. From a body-block ground truth, further study can consider scope of fit tolerance needed to accommodate natural morphological change (e.g., gas causing swelling of waist and abdomen dimensions, lactation causing changes in breast size) as well as dynamic change required for movement.

Study toward the placement of body-block shaping devices has inspired much research (Carufel & Bye, 2020; Gill et al., 2018; Inui et al., 2020; Mesuda et al., 2018; Song & Ashdown, 2012; Wu et al., 2018; Zhang & Jin, 2021). The need for flexible body shaping rules, coupled with non-standardized sub-divisional landmarking procedure, greatly complicates theory toward universal body-to-pattern theory. Placement of body-shape "fitting devices" is strongly correlated to garment design with the manipulation of internal darts being a critical component of the design process. Darts may be revealed as a single take-up device or split into several darts. Placement of patch perimeter lines is equally as fluid. Shoulder and side seams may be moved forward, backward, or eliminated. Figure 3.8 illustrates the somewhat flexible nature of body-block shaping devices. The use of caliper body widths could help direct standards toward a universal quantification of body-shape, with an understanding that seamlines (patch perimeter lines) are somewhat flexible in their position and therefore mainly determined by garment style and fit preference (Fig. 2.6).

2.4 Geometrically defined ease

A complete discussion on the complex interplay between body and garment must consider the heterogenous nature of both the body and garment materials and is beyond scope of the discussion here. Much effort has been dedicated to a better understanding of the dynamic relationship between morphable body and materials (Fung et al., 2020; Gazzuolo et al., 1992). Without the means of quantifying and mathematically tracking ease through the complex garment design process, however, the studying of this relationship in a quantified manner has been fraught with difficulties. Such study is made yet even more complex by large data sets resulting

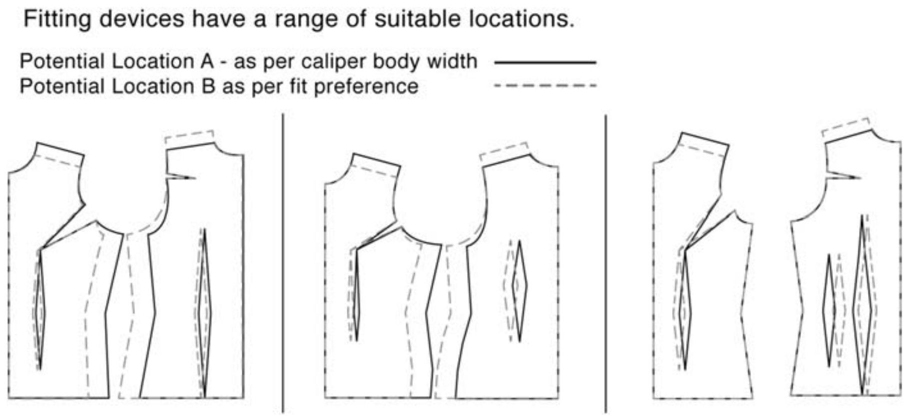


Figure 2.6 Body-block shaping devices.

from both body and fabric being heterogenous materials. *Fit will further be discussed with reference to a non-compressible body, in a static pose, and with fixed body dimensions. This presents a baseline from which other fit scenarios may be considered.*

Ease categorization (movement ease, style ease, fabric ease etc.) is critical for establishing theory suitable to product design and brand fit identity, but from a fit perspective it is the tracking and quantification of ease that are of priority. Once quantified, ease can be further broken down into categories suitable to product design and use. Discussion here will build on a geometric definition of fit (garment fit equals body-shap plus ease) and discuss how a linear pattern-making workflow (Fig. 2.4) presents a means for tracking ease (any amount that varies from body dimensions) through a virtual design process. The focus will be on quantifying fit in a digital environment such that it becomes part of a garment's digital identity (digital tech pack) for further study. 3D environments will be critical for further study related to the tracking of ease through dynamic movement.

2.4.1 Ease as tool for fit assessment

When considering simple garments, such as tube t-shirts, it is easy to discount the relevance of isolating body-shape from ease. With consideration for Heisey's explanation of using shaping devices to mold fabric to the human form, we can understand that a tube represents a geometric shape that has largely ignored the fitting devices. In other words, there is potential to shape the tube to the body but the "potential shaping" (revealed by buckling and wrinkling) has been ignored. Ignoring a "fitting device", however, does not negate its relevance to origami body-shape and garment fit. Ignored "fitting devices" become hidden ease (Scott & Sayem, 2018). Fig. 2.7 illustrates a t-shirt pattern which could be manufactured as a tube (e.g., circular knit t-shirt with no side seams). From this example, we can understand ease as a very personal experience directly related to the unique

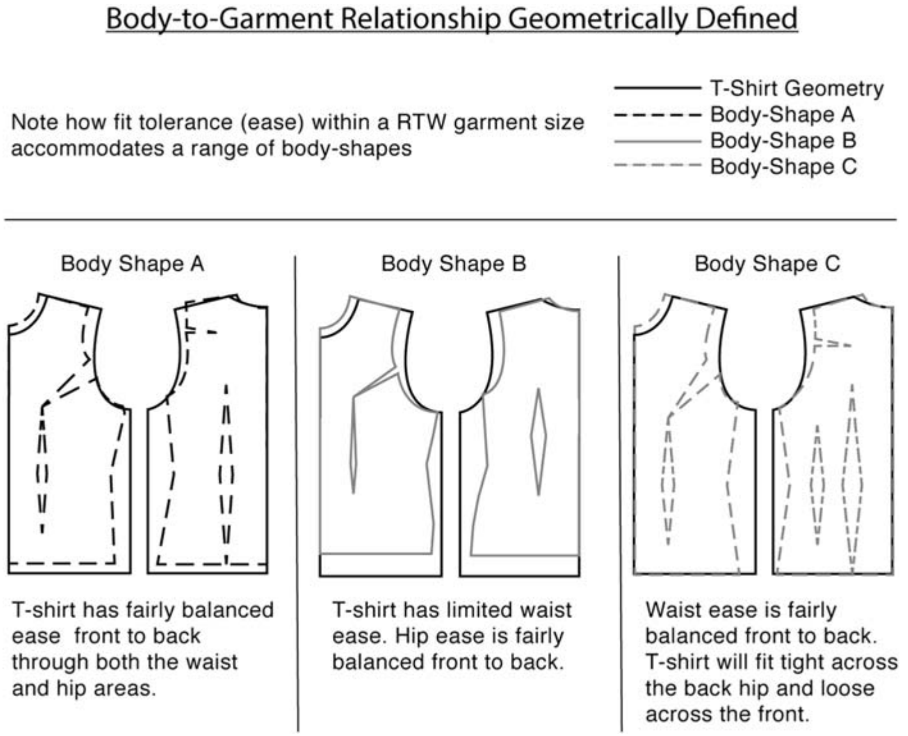


Figure 2.7 Fitting devices' effect on fit.

relationship between individual body-block and garment. Most importantly, with fit digitally attached to both digital and physical product, the assessment of fit may follow a product through its lifecycle. (e.g., size prediction, MTM pattern parameterization, on-demand manufacturing, lifecycle shrinkage study, re-sizing of resale garments). Tech packs have long been industry standard practice for breaking down product specifications into those for procurement, manufacturing, and quality control. The evolution of tech packs to digitally include fit assessment parameters (body-shape and ease) permits fit prediction engines to evolve to the level of critical fit assessment detailed in Fig. 2.7.

2.4.2 Body-block ease

With complex origami, it is understood that a degree of error must be introduced to convert non-developable areas (those with curvature and not directly relevant to triangulation) to 2D geometry. The same is true with pattern-making. A "degree" of error is therefore expected in any fit scenario, but the goal is to first minimize ease error, and second quantify unavoidable ease error. *Lack of error quantification is the flaw within traditional pattern-making that persists in virtual environments. Without a means for tracking errors in fit, loss of fit accuracy starts very early in* *the design process and is quickly exacerbated.* For example, if a pattern-making goal was to add 6 cm of ease to a particular girth, and the body-block was known to have 2 cm of ease error in the pattern geometry, only 4 cm of ease would be added to achieve the desired goal. While there appears to be little mathematical complexity involved with this thought process, it must be recognized such equations are required for *multiple* non-developable areas with multiple *compounding* effects. Only from an established static baseline can a fit further be studied for relevance as to how the 2D pattern must morph through a range of movements. Fig. 2.8 presents a visual illustration of the complex tracking of ease error possible utilizing a body-block approach in a virtual environment. With an acceptable "ground truth" agreement on body-shape, 4D technologies present the opportunity to go beyond simplistic static garment-to-body models (body and fabric at a single moment in time) to more relasitic but complex dynamic garment-to-body models (body and fabric morphing through mulitple moments in time).

2.4.3 Template block ease

In both physical and virtual environments, template blocks provide control parameters to design teams. Sometimes referred to as a garment or fit blocks, the template block is the starting point for garment design with a geometrically defined fit (body-shape plus ease). They reflect a pre-defined “body-to-garment fit relationship” geometrically explained relevant to a chosen fit model. Template blocks are the parent blocks from which infinite child iterations may be birthed. Iterations on these blocks (changes to seamlines, findings, fabrications, etc.) permit infinite style derivatives from a single template. The template block, therefore, references pattern geometry suitable for a “type” of product line with a geometrically defined fit (body-shape plus ease); where the desired change in fit requires a new template

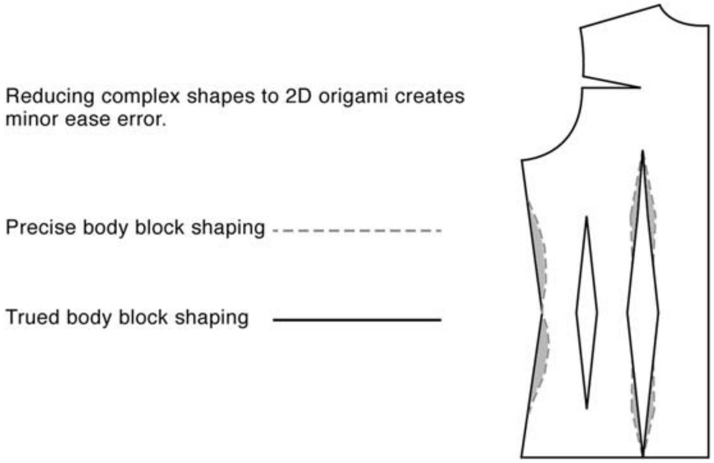


Figure 2.8 Body-block ease error quantification.

block. For example, a slim-fit pair of jeans would have a different template block from a relaxed-fit pair of jeans.

Ease simply as a linear amount added or subtracted from a side-seam does not adequately define fit, explain a customer’s desired fit preference, or direct how fit may be corrected. As illustrated in Fig. 2.9, critical analysis of fit must consider how ease is distributed relative to body-shape.

2.4.4 Material ease

The properties of the material used greatly affect the template block. The effects of fabric on pattern geometry can be so drastic that best practice dictates a newly defined template. For example, a pair of pants from stretch and non-stretch fabrics will require different template blocks. Fig. 2.10 illustrates how a garment made from three different fabrics “technically” requires three different patterns. In traditional manufacturing environments, time constraints often make the practice of creating multiple patterns for a single design simply impractical. Utilizing a linear pattern-making workflow within digital environments, however, makes it possible for multiple “child” template blocks to be adapted from the base template quickly. The user works on one pattern, knowing *ease attributed to material properties* is being managed in the background. Current practice, lack ing a means for critical fit analysis, neccessitates the labour intensive heurisitic draft-sample-adapt production workflow.

Dimensional changes to pattern geometry to adjust for material properties are extensive and there is much opportunity for 3D environments to reduce heuristic practice with regard to material driven pattern geometry. Fig. 3.11 offers an

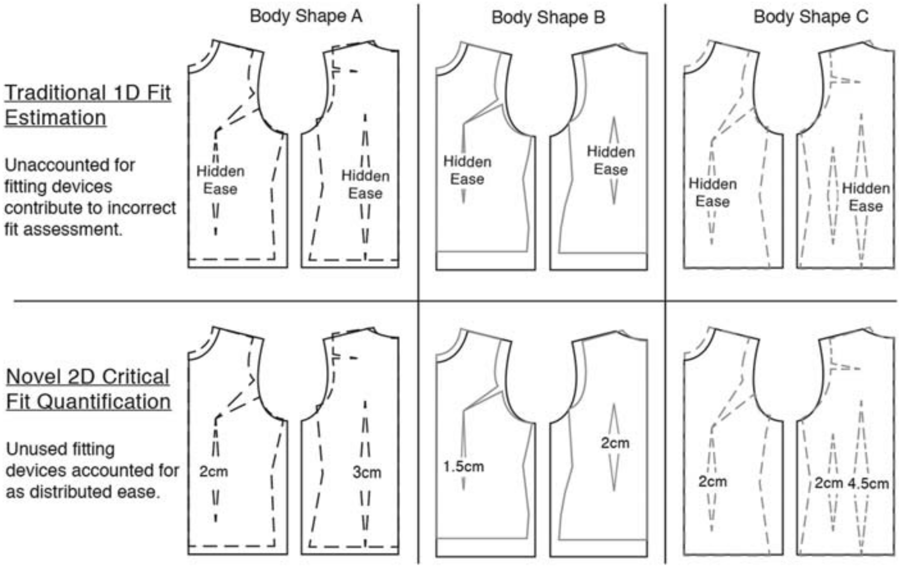


Figure 2.9 Ease distribution

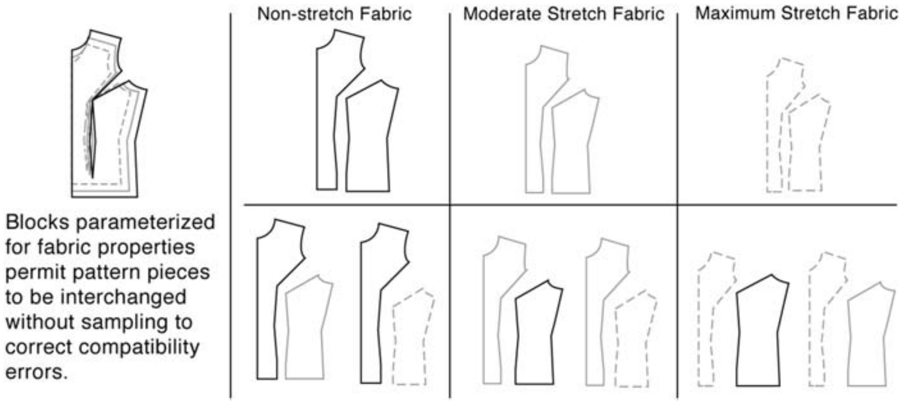


Figure 2.10 Parameterization for materials.

example of where material property feedback can direct improved pattern geometry *prior* to any sampling and fitting session. There is much opportunity for 3D environments to manage substantial fit data, leaving the user to focus on design (Fig. 2.11). The material property feedback can improve pattern geometry in situations where:

- Fabric cut on an angle away from the horizontal or vertical grain can stretch to the point of requiring pattern alteration, or at the very least easing during the construction process.
- Dye lot changes within the same fabric category have been known to change fabric extensibility (Hasan, 2015).
- A pattern made for 30% stretch fabric will "work" with a 20% stretch fabric, in that it is possible to stretch the fabric beyond its recommended use, but only at the expense of integrity of wear (over-stretched fabric breaks down quicker).
- Some fabrics require dimensional support from another material underlayer causing radial changes to body dimensions due to underlayer thickness.
- Negative ease suitable for stretch fabric usage requires adaptation (Tsai et al., 2002).
- The compounding effects of fabric on *both* body-shape and pattern geometry must sometimes be considered as is the case with compression garments where body tissue is redistributed causing changes to body dimensions.

2.4.5 Style ease

The opportunity for virtual environments to guide physical space practitioners through decision processes that would otherwise require a sampling and fitting session is tremendous. Efficiencies in traditional pattern-making practice frequently rely on reusing patterns, digitizing hand-drafted patterns, and reverse engineering finished garments. All of these shortcuts run the risk of compounding fit error, or, at the very least, create an environment where loss of fit quantification is inevitable. In a physical environment, data regarding the originating body-shape from which the pattern geometry was conceived will have long been lost making sampling an expected part of the design process. In a digital environment, fit data can be

Fabric on bias stretches, requiring post production correction.

3D fit data can predict inevitable fabric property changes permitting proactive pattern adaptation prior to sampling.

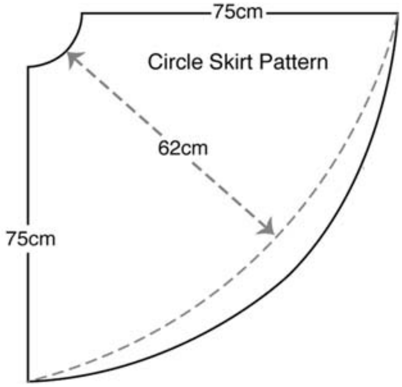


Figure 2.11 Material effect on pattern geometry.

retained as part of the 3D garment's digital identity (tech pack). This permits a geometric quantification of the heuristic decisions that transpired during pattern production such that a style may be more effectively reused. For example, a suit jacket pattern could be reused for a stretch or woven fabric by simply updating (parameterization) material properties relevant to pattern geometry. Similarly, the suit jacket pattern could be further parameterized to accommodate an underlayer thickness and reused as an outerwear garment.

Algorithmic support from 3D environments will be invaluable for quantifying and recording heuristic decisions (unconscious math regarding ease, grain, set, line, and balance) to the 2D pattern. As illustrated in Fig. 2.12 this will ultimately drive more effective MTM parameterization with patterns being updated for body morphology (driven by the body-block) and not just 1D girths and lengths.

2.5 Garment fit as a driver for sustainability

On-demand manufacturing is an important production model for sustainability initiatives. Such models demonstrate how the draft-sample-adapt pattern-making process can be optimized for direct-to-consumer distribution, but have lacked widespread application despite "3D washing" (Gerald Ruderman, 2019) claiming otherwise. A lack of ability to quantify fit preference is likely an inhibiting factor. Regardless of speed of access, choice of color, or design desirability, a garment must, above all else, satisfy a customer's preference for fit.

The term "forensic fit analysis" describes a reverse engineering approach to garment fit assessment that is only possible with recognition of a geometrically defined body-shape (body-block) and only practical through the use of 3D technologies for parsing vast volumes of fit data. The body-block offers an advanced study of ease as it relates to the customer experience. It provides a baseline from which decisions regarding ease and fit may be managed in a less heuristic manner.

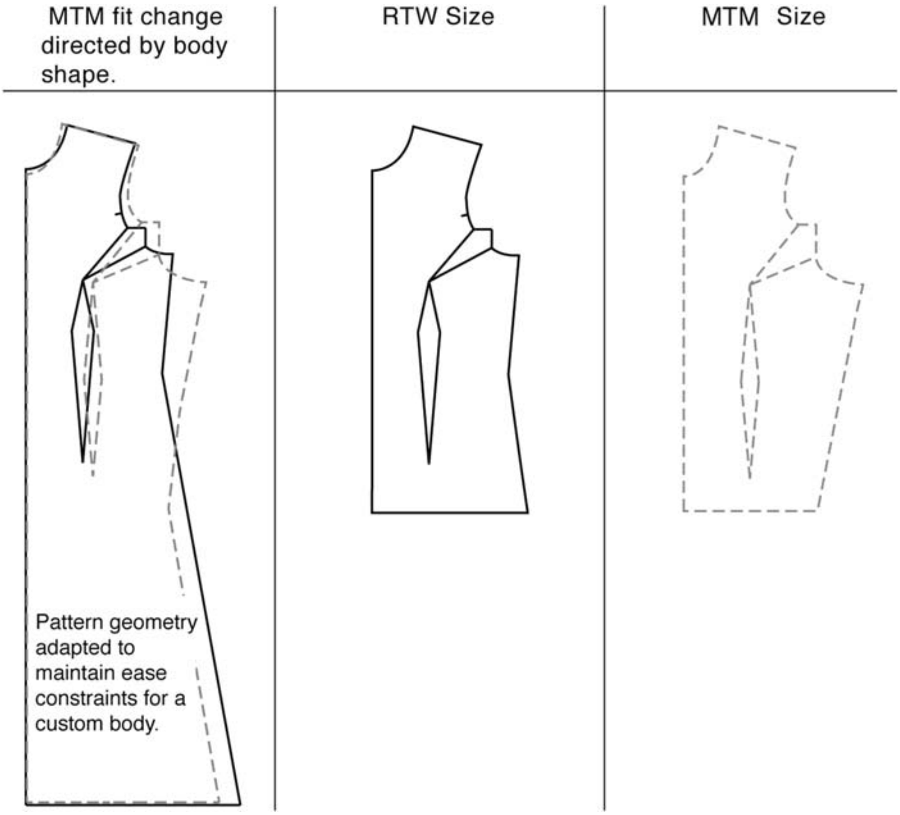


Figure 2.12 Body-shape driven pattern geometry.

2.5.1 Improved application of fit preference data

From a sales perspective, ease added to suit design esthetic is only relevant as to how it captures a customers' attention and, most importantly, how it drives sales. Beyond all effort on the draft-sample-adapt sampling process and all resources aimed at production, a brand's fit intent becomes irrelevant against the customers' fit preference. In other words, *a brand or retailer has no control over how their product is used; therefore, fit preference ultimately trumps any available principle identifying suitable proportions or sizing*. Since any derived fit rule is made obsolete by a wearers' preference, fit prediction engines must be able to analyze and translate customer fit preference requests to pattern geometry. For example, a garment with 10 cm of hip ease may be worn loose by one person and form fitting by another. With an account of the body-block it can be understood that the first season's product had sufficient tolerance to accommodate the desired fit preference while second season's product no longer fulfilled the customer's desire. Similarly, fit prediction engines must be able to direct a person desiring a snug waist toward a smaller size and a person desiring a loose waist to a larger size, while also weighing such decision against the compounding effects on other body dimensions.

2.5.2 Improved garment fit

Considering the discussed complexities regarding garment fit, it is reasonable to ponder how RTW garment fit has found any success at all. A very lucrative apparel market, using mainly fit tolerance for accommodating a breadth of body morphologies, speaks to the robustness of current RTW sizing strategies. It also speaks to the potential for improved fit. Just because it is possible to create a "precise fit" does not mean it is always the best option; the option for flexibility of fit, to accommodate dynamic and normal changes in individual morphology (changes to breasts with lactation, ribcage expanding with breathing, waist area swelling over course of day, unique effects of normal body weight fluctuation), is essential. It may very well be the case that the ability to quantify garment fit leads to less of a desire for bespoke fit, leaving one to ponder not on the difficulties with traditional sizing strategies but rather the possibility for improvement with a geometric understanding fit. As sizing lines evolve specific to body-shape categories (Devarajan & Istook, 2004), the possibility for forensic fit analysis strategies to improve the fit of RTW such that bespoke product is no longer desired is tremendous. Body-shape sizing strategies hold much potential.

2.5.3 Driving circular production models

Sustainability models rely on decreased sales. To supplement these "lost sales," and capitalize on product lifecycle data (shrinkage and product wear), foreword thinking brands are embracing circular production models and the resale of used goods. Without fit data however, this critical aspect of circular production models will inevitably face the same "customer dissatisfaction and high return rates" that have plagued online sales. The 3D environment and a linear perspective on the pattern-making workflow make the tracking of fit variables through a product's full lifecycle a natural extension of the digital environment. This serves customer desire for improved fit recommendation, directs improved product development, and drives sustainability models.

2.5.4 Bridging virtual-to-physical practice

The further bridging of physical space pattern-making to virtual space pattern-making will require a critical analysis of heuristic practice drawing on a large expanse of disciplines. The discussion, here, has focused on the required application of 3D acquired data as it relates to quantified garment fit. Further study must now illustrate successful 3D application of the 2D body-to-garment theory presented here.

2.6 Conclusion and future trends

Directly "sketching" style lines on 3D avatars has provided a glimpse into the possibility of fully automated design-for-body-shape 3D-to-2D environments but "3D-washing" has quite simply overstated the current state of size and fit prediction. Traditional methods of 1D fit assessment, even from a very accurate 3D source, are sufficient for only a rudimentary estimation of fit. 1D fit defines how garment dimensions vary from body dimensions within an acceptable tolerance but *only from a 2D perspective is the opportunity to quantify garment fit and fit preference translated to* actionable solutions. The use of 3D technologies for acquiring fit data is critical but equally as important is correct application of this data.

Media discussion lamenting high volumes of garment returns and discussions pondering on the slow adoption of 3D technologies rest as evidence the nuances of garment fit that have yet to be digitally quantified; and, as a result, garments that fit don't get returned and technology that addresses user need is readily adopted. The current state of apparel digitization is perhaps best summed up by Gill's comment "*there may be insufficient recognition of the complexities inherent within the current art of clothing product development*" (Gill, 2015).

As 3D environments evolve to quantify fitting techniques leading to pattern geometry, machine-learned heuristic practice will be coded for the automated design environments of the future. Where this theory exists within current practice and how technologies can be used to access and apply this data rest with a recognition that the 2D process (pattern) is as important as the 3D result (garment). The standards promoting this are critical for apparel digitization movement to move forward (digital tech pack data). Recognition of a body-block presents:

- a means by which the wealth of data coming from 3D environments may be better applied for critical fit assessment.
- a "forensic fit analysis" perspective to "see" beyond size chart data to address customer fit preference, suggest nuanced sizing, and reduce garment returns.
- a quantification of heuristic practice suitable for fourth industrial revolution thinking.
- an understanding of the body-to-garment relationship as a series of 2D linear pattern decisions toward a 3D model.

With the use of 3D data driving pattern-making, the possibility for 3D acquired demographic data to drive customer fit satisfaction within traditional sizing systems is very real: size inclusivity, application of fit preference to product, accurate size prediction, and even tailoring of resale goods. Fit understanding will gradually blur the lines between RTW, MTM, and bespoke product categories, making the opportunity for near-bespoke fit from RTW very real. For the numerous body types ostracized from traditional sizing this simply means inclusion. For others, it means garments offering a level of comfort unavailable with traditional fit or simply a customized design esthetic. For manufacturers, it means fewer returns, more efficient manufacturing, and less waste. Collectively, it translates to a more sustainable practice driving urgent global change.

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Social manufacturing in the fashion industry to generate sustainable fashion value creation

3

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3.1 Introduction

One of the basic principles of fashion is that it is in a constant state of evolution and rarely is it revolutionary, unless the micro- and/or macroenvironmental factors necessitate it to go into a revolution. As Amanda Hallay states "Fashion is not an island but it's a response"; hence, it cannot be understood in a vacuum. It is extremely dynamic and constantly changing. We, as fashion innovators, influencers, designers, and consumers, have moved through from manual to technological and digital ages, from doing business locally to catering to the global consumers. We have moved away from looking inside and outside of our businesses as today we engage in internal and external partnerships between various constituencies of business for effective quality management. Success of a fashion business today has become multifaceted and multichanneled with diverse directional approaches. It thrives on innovation and its application to blend functionality with esthetics.

3.2 Paradigm shifts in the evolution of fashion business

In the times of fast fashion, it's quick response, timeliness, and agility that continue to be key approaches to quality management. Philosophy and concepts of Right First Time, Just In Time, Six Sigma, Juran's Quality System, etc. continue to drive business of value with innovation and excellence. To compete with multiple brands, and with e-commerce penetrating through many layers of supply chain along with diversity in consumerism, computers, and information technologies, sound enterprise resource planning systems have become vital for any type of business to survive.

At last, with an understanding and by deep diving into these profound relevant subjects, one comes to realize that, finally, it is a matter of choice and one chooses between alternatives from the multiple ones available and from those which are

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accessible. The approaches as deemed fit and convenient to one's culture and belief need to be adopted and these will be time-, context-, and people-specific. In India, we drive with all of this to being vocal for local upholding great value for the earlier propounded theories of quality enhancement, value creation, and societal welfare. The choice is ours and so is our future!

The fashion industry is a multibillion-dollar industry and the revenue is expected to show an annual growth rate of 7.18% with a projected market volume of 1,002,215 m US dollars by 2025. Fashion thus has a great impact and, in turn, is impacted by several factors. The traditional definition of fashion is that when a style is adopted by the masses it can be termed as fashion, and directional flow is observed according to the theory of fashion adoption propounded by Thorstein Veblen in 1889. However, one theory that does not completely explain the adoption of style is that there are many diverse factors including technological advancement and globalization that explain the mass adoption of a style as fashion. Dynamism with the fashion business indicates that the adoption of style can be understood as 360-degree impact and whose epicenter is rarely identifiable.

Fashion being a dynamic ever-changing field of expertise, skill, and knowledge is constantly influenced by social media and in which celebrities and leading fashion icons feature prominently. For example, Queen Elizabeth I, (1533−1603), Charles II (1630−85), Louis XIV (1638−1715), Marie Antoinette (1755−93), Empress Eugenie (1826−1920), Coco Chanel (1883−1971), Audrey Hepburn (1929−93), Steve McQueen (1930−80), Diana Ross (1944-present), Prince (1958−2016) and many more have added grace, class, and glamour to the world of fashion. Being world leaders in their own capacities is not sufficient for creating an impression on the minds of consumers, and their biographies have shown that they had a sense of where social upheavals are going, where their affluence along with their concern for society majorly led to them to move the fashion scenario to what it is today. Fashion icons, and their relation with social manufacturing, are significantly known for their concern for societal welfare which has prompted them to work in teams with a sense of their own proactiveness for the betterment of the weaker sections of the society.

The question that arises is that "Is social manufacturing a recent phenomenon?" Looking at the history of fashion, it does not seem so. Social manufacturing is a form of social and economic transformation in the way that people organized themselves and their communities to produce what one needs as human society. It's man's nature to move with the times for man throughout the history of the evolution of society has always explored his environment and has been in quest of innovative ideas and opportunities to make living better by the wise utilization of indigenous resources that have been known to exist in abundance in his habitat. Social manufacturing is an impact on human society of technological revolution. Currently, worldwide national economies have taken to the philosophy of producing native resources, skills, and knowledge by producing goods and devising services that affect the small to large scales, from households to laboratories and from small plants to industries. Thus social manufacturing requires creating a new ecology of production and consumption.

3.3 Some directions for developing and implementing a social manufacturing ecosystem

1. Steps to blur the lines between production and consumption
2. Hitting new kinds of crowd phenomena with new patterns of funding and remuneration
3. Inculcating democratic systems of production to engage more diverse actors at different levels
4. Leveraging open-source systems, online, and physical for sharing resources necessitating balanced interactive and collaborative working thereby creating new value
5. Stimulating innovation by fusing and adapting ideas, processes, and products
6. Thinking maker cliques and mobs with online presence visibility and expansive reach

Organizations of all sorts need to work in the field of social manufacturing and construct a map of paths to develop social manufacturing set-ups. It will need thorough longitudinal studies, ethnographic interviews, and foresight workshops in maker communities. It will involve gathering ideas from experts with the visioning process; identification of communities in different countries at different levels of development within and across economies; devising fabricating and social production networks; crowd-based forecasting to anticipate future paths to development; and, creating a graphic recording, game, and narrative scenarios. The ultimate aim is matchmaking, relating the producers-consumers toward hybridization, better understood as prosumers. It is time that new business models identify and harness the power to lead and strengths to commune of individuals and develop digital content production. Hence, a deep SWOC analysis is the requirement for establishing and sustaining a business.

How can this be done? It will involve:

1. Identifying individuals who practice arts and crafts as hobbies
2. Identifying people and groups of persons driven by nonmonetary benefits
3. Investigating the nature of the firm-individual collaboration
4. Focusing on the role of individuals and responsibilities of companies/firms
5. Identifying and developing community networks

3.4 What is the advantage of engaging in social manufacturing?

Social manufacturing in fashion can potentially reap multiple benefits including becoming a repository of fresh ideas, extending broader design support, with extensive networking ensuring quick delivery times that are extremely critical in the fashion business, and value creation. Social manufacturing may be described as a disruptive business model as one needs to break through the conventional business systems and move from centralized to centerless technologies, processes, and systems. It has to exploit the rapid technological development in information and communications where it makes appropriate use of social media applications, brings

IoT and Cyber Physical Systems (CPS) into real operation, adopts additive manufacturing along with digital fabrication, 3D Printing, CAD-CAM technologies, and quick response to meet everchanging demands of consumers. These technologies are becoming inexpensive, with increased accessibility, rapid advancement, and deeper penetration to different levels of individuals and communities simultaneously. Service production is revolutionized by employing diffused private agents and multiple stakeholders resulting out of an intricate web of people and multifunctional groups. Household work and consumer goods can be recycled, and personal financing can be merged with corporate financing. This brings us to the concept of a shared economy by sharing excess resources and liabilities. Thus central to the concept is a collaboration between different business heads, participants in the process of sharing, and beneficiaries of economic wellbeing by collapsing the gap between producers and consumers known as prosumers.

A prosumer is an individual who consumes and produces as well. It is a portmanteau of the words producer and consumer. Research has identified six types of prosumers: DIY prosumers, self-service prosumers, customizing prosumers, collaborative prosumers, monetized prosumers, and economic prosumers. The terms prosumer and presumption were coined in 1980 by American futurist Alvin Toffler and were widely used by many technology writers of the time. A technological breakthrough and a rise in user participation blur the line between production and consumption activities, with the consumer becoming a prosumer.

The review of literature delineates the vision of and the promise in social manufacturing in the fashion business as the predominant way of running the fashion business in the future and has a special WOW factor attached to it. The profundity in the subject is enormous and various models, theories, and algorithms have been proposed and employed that have been described in different articles and books. However, there is no clear definition of how social manufacturing for fashion business can be undertaken with an outlining of the concrete steps to its accomplishment, given the fact that it is a subject that grows out of the specific times, contexts, and people to which it relates. Qualitative approaches will lead to more understanding of this phenomenon. The aim is to empower individual entrepreneurs, and small and medium-sized firms by being firm-centric or in phase with being individual-centric, thus diffusing the discrete classification blur.

Manufacturing covers different domains of knowledge from idea generation to resource identification and allocation, operations research, optimized use of the resources and their management, capitalization on resources, and a system approach with input-process-output. Production is streamlined with steps of design development starting from doodling-design illustration-preparation of technical specification sheets with tech packs, prototype making, and samples at all levels of product manufacturing. Equal emphasis on quality control systems and checkpoints and mechanisms, quality assurance, packaging, distribution and rapid-time marketing, retailing on e-platforms, and social media will be of importance. It is claimed that e-commerce in the fashion industry will increase by 1 trillion US dollars by 2025.

At all times, fashion businesses, whether individual, SME, or MSME, must try and integrate social manufacturing to whatever extent possible while exercising intellectual property rights and abiding by business ethics and ecoconsciousness in fashion. Social manufacturing will be beneficial, one, due to the elements of ease in running the business, speed with flexibility, fast prototyping, and product making, and two, due to its tapping on lower cost with shared resource utilization and design support through the effective academia-industry interfacing with communities for a stronger nexus.

The core of any social manufacturing system will have to be an active Innovation Incubation Council (IIC) that will be constituted with robust network between academicians, researchers, industries (private or public), government organizations and nongovernmental organizations, people working at the grassroot levels including cultivators, manufacturers (fiber, yarn, and fabric), converters, chemical manufacturers, garment manufacturers, packaging industry and market analysts and professionals, ecological and environmental professionals, certification bodies, designers, fashion trend forecasters, trend analysts, life-cycle assessment experts, hardware and software professionals, business developers, and investors. These stakeholders of the fashion world will use the cyber physical space and network closely in the form of consortia for every sector of fashion, for example womenswear, menswear, kids wear, contemporary unisex fashions, home décor and lifestyle, fashion accessories, cosmetics, leather and fur industry, smart technologies and ecofashions, and allied fields, with the core goal toward maintaining sustainability in design, production, packaging, marketing, retailing, servicing, and recycling and, thus maintain end-to-end perspective of and intervention in industry. Vertical growth is going to be seen in fashion apparel. Vertical building and working in effectively managed teams will be the "*mantra*" for success. Hence it is a process of co-creation and value enhancement. The complete life cycle of fashion products designed and proposed for commercialization will be framed and brought into the purview by each of these consortia. The paradigm shift is from PDCA (Plan-Do-Check-Act Cycle) to DCIC (Do-Create-Innovate-Change).

Against eMarketer's +9% YoY change, statistics show slight declines in 2020 versus 2019. Vertical by vertical examination in the US reveals marked disparities, with luxury products and accessories (i.e., watches, jewelry, luggage, and bags) bearing the brunt of losses accessories: -12.69%, Luxury: -11.11%, Footwear: -5.54%, Eyewear: -4.9%, and Apparel: -2.88%. Such trend analysis can be fruitfully used to direct potentials and resources in the more prospective areas of business.

Refer to Fig. 3.1, which gives the pictorial representation of the theory describing the role of IIC in social manufacturing. The dynamic consortia for social manufacturing in the fashion business toward value creation need smart thinkers and smart team workers with deep imagination rather than shallow cleverness who can build on strengths. It needs all members to share, listen, and learn from each other with curiosity and quest for opportunities to facilitate growth and enrichment. By executing responsibilities fast and embracing competition while being realistic at the same time and engaging with people who enjoy the manufacturing work with innate passion are the driving forces to greater social manufacturing.

It is proposed here by the authors that this needs to be executed with mass crowdfunding from the corporate sector who could think of investing (approximately 1.0%

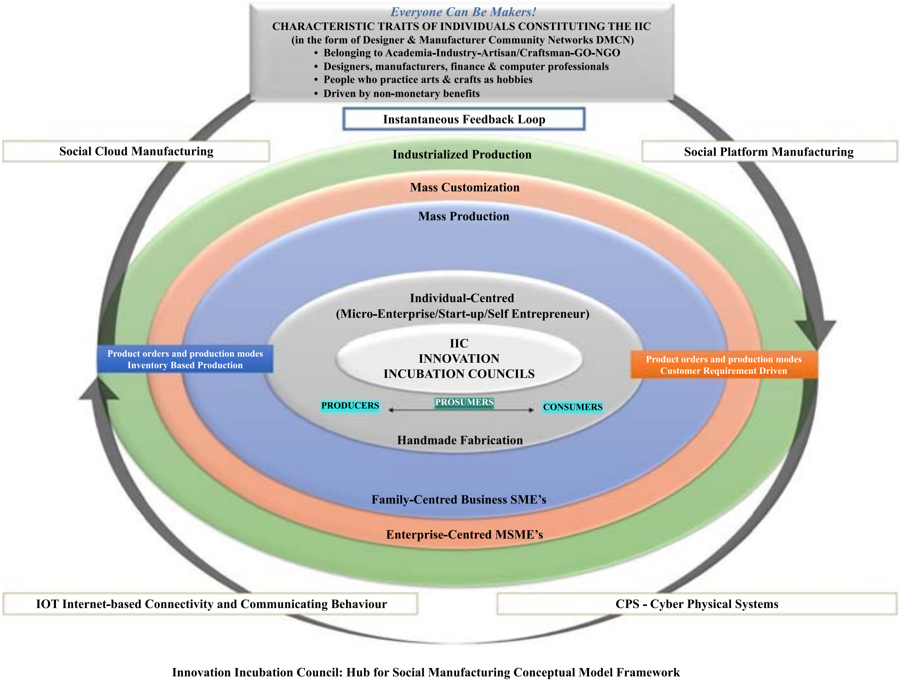

Figure 3.1 Innovation Incubation Council: Hub for Social Manufacturing A Conceptual Model Framework.

of their annual budget and/or turnover) in fashion design and encourage innovation that stems from social manufacturing, wherein fashion businesses that run on social manufacturing basis are given the push forward as well as those that show potential for meeting customers' needs with personalized and customized products are patronized. The customer is looked upon as the fulfiller rather than an end to earn profits. Fashion design and innovations have to see the light of commercialization; hence, there is the need for making it cost-effective, economically and technologically viable in the given context, apt to its time and amongst the given people and their culture that will have to be prioritized. This will be the core of social manufacturing in fashion business.

Kumar and Rajeev (2016) in their article have quoted "Barbon (1969) stated that "By value, is to be understod as the price of things; that is what anything is worth to be sold at that time's value"; but Coyle et al. (1996) stated "An important consideration is that value must be viewed from the customer's perspective, because it is value to the customer that is most important. The value is the condition which motivates people across cultures and which emphasizes needs, requirement, wishes and ultimate demands of the consumer." Michael E. Porter was the first to have introduced the value chain model and the Five Forces Model that many companies and businesses use to figure out how well they can perform in the existing marketplace.

Value chain analysis relies on the economic principle of advantage, that is, businesses are best served by operating in areas/sectors where they can have a relative productive advantage over their competitor companies. At the same time, businesses should also ask themselves where they can provide the best value to their customers. This is in complete alignment with the crux of social manufacturing. Hence, social manufacturing is best seen as a strategic system for value creation in the fashion business. After having understood the meaning of value, value creation is integral to the manufacturing of fashion as it revolves around consumers and their fast-changing preferences. Since fashion has a global influence and is understood best as a global phenomenon, the theory of the smile curve with its relevance to the global value chain becomes pertinent.

3.5 The smile curve in the global value chain in the world of fashion

The fashion business with internationalization in retailing, and due to the impact of social media and its role in business, and due to the ubiquitous use of computer and cyber systems for manufacturing and marketing, the value creation in fashion business has to be on this plane of global value chain. The smiling curve is extensively discussed in literature in the context of global value chain.

Stan Shih propounded the phenomenon of the smile curve in the early 1990s to explain the phenomenon of where the value is generated in the manufacturing industry. The central part of the curve that is the lowest point of value creation is where the actual manufacturing takes place. The highest points of value creation are located at the rising ends with R&D at the beginning and customer service at the other end. The Smile Curve Manufacturing Value Theory states that the ends of the product value chain—R&D/Design and Marketing/Support—command and drive higher financial value to the product than the middle (manufacturing part of the value chain)

Refer to graphical representation below in Fig. 3.2 wherein the description of the smile curve in relation to social manufacturing is elucidated. With social manufacturing, the value creation process is siphoned and centralized to the manufacturing base as R&D and customer satisfaction result in maximization of output and optimization of resources invested by the entire global team engaged in social manufacturing. Thus challenging the smile curve is to complete a full circle with a closed feedback looping system.

3.6 Big data and IoT will impact the fashion manufacturing industry

A collection of functions is performed to design, produce, market, deliver, and support fashion products. All these activities can be represented using a value chain, and there are specific steps or procedures to be followed. An organization’s value

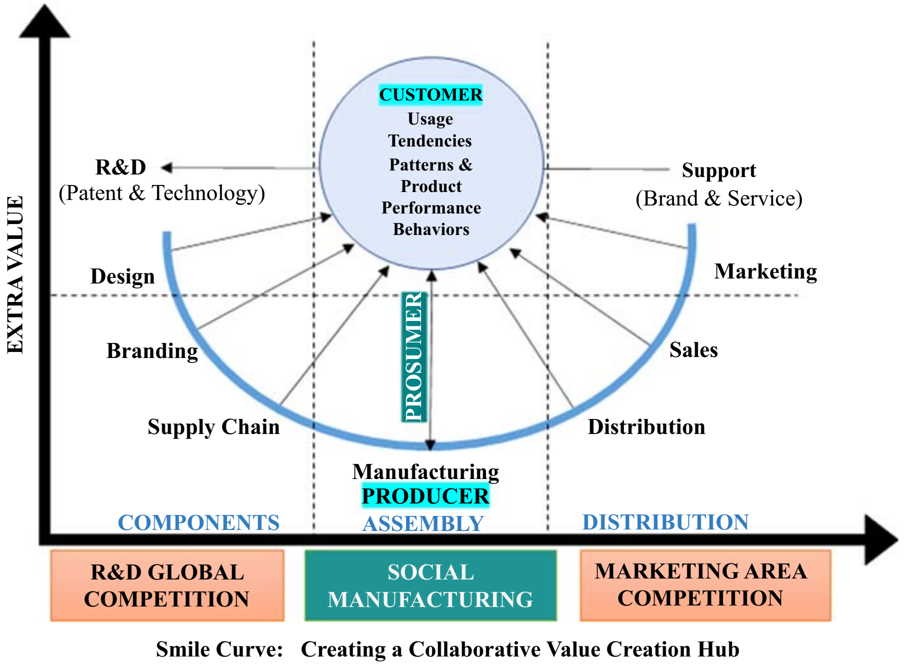

Figure 3.2 Smile Curve: Creating a Collaborative Value Creation Hub.

creation is empowered by the firm's value chain that is how it performs individual functions. The functions are governed by the personality of the organization which is reflected in the vision, mission goals, standards, and policies of that organization. It is also a reflection of its history and provides a lens into the future. It is the cultural ethos of the organization.

Big data, POS data, and IoT along with the digital twin which is the virtual prototype allow the company to visualize the status and condition of an apparel product that is physically distant, providing insights into how products can be better designed, manufactured, operated, and serviced. The powerful new data available to companies, together with new configurations and capabilities of smart and connected products, is restructuring the traditional functions of business, and that too radically. This transformation started with product value chain; and, as it spreads, functional boundaries tend to shift, and new functions are always getting created (Figs. 3.3 and 3.4), (Table 3.1).

3.7 Social cloud manufacturing

The fashion manufacturing industry is essentially a buying-sourcing industry with intricate networking, partnerships, and alliances. A general overview of the fashion

Scope for Application of IoT in Social Manufacturing of Fashion Products

Figure 3.3 Scope for Application of IoT in Social Manufacturing of Fashion Products.

business across places and people, and B2B and B2C supply chains have shown an astronomical rise. B2B or B2C relations are nonlinear and complex. Hence providing an excellent timely purchasing experience becomes a prerogative for fashion business houses. Wholesalers and retailers are embracing e-marketplaces more than ever these days wherein using cloud-based systems expands and strengthens the manufacturing and commerce systems. It creates opportunities for creating marketplaces with immediate visibility, standardized delivery, meeting compliances, and maximizing overall sales and distribution strategy. Information technology enables the maximization of machine resources and improves production efficiency in the fashion manufacturing industry. Cloud computing technology provides a hardware environment enabled with cloud servers, cloud databases, and cloud memory along with internet and intranet networks. Thus it calls for the integration of Infrastructure as a Service (IaaS) and Software as a Service (SaaS) where these

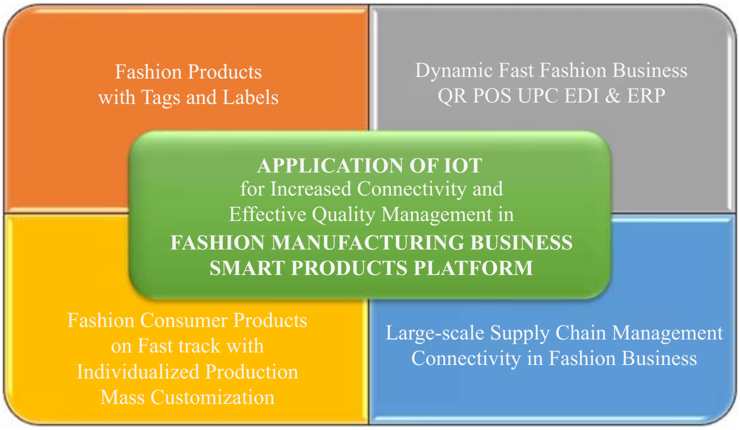

Figure 3.4 Role of IoT for Increased Connectivity and Effective Quality Management in Fashion Business.

have become must-haves for modern fashion businesses. SaaS is expected to grow to $220.21 billion at a compound annual growth rate (CAGR) of 13.1% through 2022. Betterbuys report reveals that the specific expenditure in the US SaaS industry is forecasted to reach $55 billion by 2026. In the current times, 64% of SMBs depend on cloud-based SaaS and 88% of companies are considering investing in new SaaS applications within the next 2–3 years.

Artificial Intelligence (AI)-based SaaS improves personalization and responsiveness throughout the processes of manufacturing and selling. AI facilitates companies to address customer service operations promptly. Micro-SaaS is explained as a cloud-based system integration that targets a niche market run by one person or a small team with small costs and a dedicated user-base. Hence integrating micro-SaaS into social manufacturing seems most relevant as a starting point for social manufacturing models.

Social manufacturing needs to capitalize on the ever-rising trend of mobile-first mindset. Amongst the world's population, 72.6% will use their mobile devices to browse the internet. Hence, it is time for fashion businesses to invest in developing ICT and e-tools by creating and exploring dynamic mobile interfaces to workload dashboards. Platform unbundling is another trend wherein there is a new breed of start-ups that do not offer full-featured SaaS products but package their core service as an Application Programming Interface (API) and a suite of small tools. Platform bundling works well for customers whose needs have to do with having a more customized experience. Vertical SaaS is a trend that is more cost-effective and offers effective customer intelligence and improved data governance with predefined metrics and key performance indicators.

In 2021, with the global annual cellular data usage on the rise, the use of data was projected to reach roughly 650 thousand petabytes (PB), with approximately 639 thousand PB coming from the use of mobile handsets, in other words, mobile

Table 3.1 Application of IoT in Fashion Business in relation to the Smile Curve.

Fashion business manufacturing functions	Application of IoT
R&D testing and quality assurance	Customer psychographics and buying behavior aligned with decisions of improvising products and their features validating their performance, new products, and processes and identifying opportunities of novelty through experimentation and research.
Designing and development *Manufacturing and Production*	Integrating design thinking in fashion creation process to align product development to customer preferences witnessed in market demands for and the willingness of customers to purchase and use new products, preparation of design sheets and use of CPS to develop products postanalysis with Electronic Data Interchange and Point of Sale data. Use of computer hardware and software for rapid manufacturing cycles maintaining versatility and flexibility of the production runs.
Labeling and branding	Quantifying the sale and usage of products by customers, shopping behavior, using RFID tags, and NFC technologies to track fashion products and their usage.
Supply chain	IoT data and supplier analytics are explored to lower cost increase efficiency, reliability, and agility enabling quick response to changes in market demands with changes in customer requirements, consumer taste, leveraging component, and material availability and accessibility.
Manufacturing	IoT sensor data real-time tracking and enterprise resource planning, with the analytics helping reduce the costs of manufacturing processes, maintenance contracts tenures, and process time scheduling which can be well planned and implemented, together with inventory management, planning model stock, and assortment variety and volume. All of this can be well factored with sales ratios for reducing excess and obsolete or dead stock.
Distribution	IoT data can be synchronized with external data sources, namely weather forecasts, traffic status, and special events, thus saving on costs in case of unforeseen circumstances, improving on-time delivery, and electronic article surveillance.
Sales and marketing	Identifying and establishing revenue opportunities, targeting existing while penetrating new markets, larger audiences, multichannel retailing and marketing in diverse modes, analyzing social and current trends, and exploiting market segmentation data.

(*Continued*)

Table 3.1 (Continued)

Fashion business manufacturing functions	**Application of IoT**
Support and services	Care and brand labeling, customer buying and usage behavior, problems with regard to use care and maintenance, realizing that customers do not purchase products for the product alone but for what the product does to him/her. Personal gratification of consumers and customer satisfaction, net promotion value, and advocacy of customers for the provision of good quality products and services thereafter.

phones. Tablets and cellular IoT devices currently do not compare to mobile phones in terms of data usage, but they are expected to grow in the upcoming years. Thus the way forward is to network far and wide and make use of social cloud manufacturing through smart mobile apps and smart home ecosystems.

3.8 Social platform manufacturing

Social media and digital manufacturing platforms have to be synchronized to create, generate, develop, and diffuse knowledge, skills, and resources to people and communities at different levels. Digital manufacturing is integrated manufacturing that is centered around computer integrated manufacturing, flexible and lean manufacturing, and closely relates to design for manufacturability (DFM). Additive and rapid manufacturing facilitates 3D modeling and adds to the flexibility in customized production. Social media platforms increase access to customers and producers as these widen accessibility and availability of the customer base. Diversification and penetration into different market levels are magnified exponentially. LinkedIn for B2B clients, boosting posts on Facebook, YouTube videos on the company and product profiles, and many more with the help of content blogs/vlogs, product comparison guides are meant to maintain an expanding reach to customers. There are also several specialized services as “solution providers” who make social manufacturing more impactful through social platforms. Seeking momentum to manufacturing business by appropriate use of social cloud and social platform manufacturing is one of the goals for businesses.

The world is witnessing a parallel evolution of the social movement. Social networking sites LinkedIn, Facebook, WeChat, Twitter, and Instagram and the likes are not limited to the purpose of communication and interaction but are also turning out to be professional platforms for business networking. Fashion is to do with glamour and, hence, imagery and visibility of brands can be heightened through the effective use of social media, and reaching out and expanding into unknown markets and unknown people in this virtual world.

New manufacturing opportunities through social manufacturing can be explored as value creation through the generation of collaborative hubs. Manufacturing in the fashion business cannot happen overnight. It undergoes phases of growth and digital transformation moving from business monitoring to business insights, business optimization, insights into monetization, and finally business metamorphosis with complete integration of IoT.

3.9 Gaining edge with social manufacturing for green fashions

With social manufacturing on the march, the initiatives are directed toward identifying indigenous resources and capabilities, to maximize their utilization and to coexist and progress. Most individual people's passion, skills, and talents stem from traditions and culture. Cooperative working brings to the limelight these native resources and provides opportunities for larger enterprises to capitalize on them. Going back to roots indirectly brings with it the philosophy of sustenance with minimal resources that are essentially natural and renewable; thus adding value to products and processes. Sustainable practices, processes, and methods need to be recognized and concretized for growth and development. Green fashions essentially involve making the right choices of resources, processes, and products for utilization and manufacturing. It is the vital responsibility of all stakeholders in the business of social manufacturing to place importance on the impact on their lives of the choices they make right from selection of raw materials to the endpoint of the product with an end-of-life cycle approach. Zero wastage or minimal wastage must be the focus at all levels of manufacturing, including packaging and distribution. Environmental impact needs to be assessed using appropriate tools and equations. The carbon footprint of social manufacturing and user footprints have to be well studied, and life-cycle evaluation has to be the focus all along.

3.10 Global trend for fast fashion to slow down

The global fashion market is expected to grow from $25.09 billion in 2020 to $30.58 billion in 2021 at a CAGR of 21.9%. The growth is mainly due to the companies resuming their operations and adapting to the new normal while recovering from the COVID-19 impact, which had earlier led to restrictive containment measures involving social distancing, remote working, and the closure of commercial activities that resulted in operational challenges. The market is expected to reach $39.84 billion in 2025 at a CAGR of 7%.

At the same time, there are communities of manufacturers and ecoconscious consumers who realize the importance of slowing down fashions. Slow down fashion describes the process of manufacturing clothing ethically, taking into consideration the workers and environment. Postpandemic, people as consumers and makers have realized value for resources, people, and the environment reemphasizing the need for sustainable resources and ethical practices. Businesses ensure that the workers are paid fair wages and are provided a safe working environment. Ethical manufacturing methods are mostly costly, resulting in more expensive clothes. Concepts of reduce, reuse, recycle, and remodel are making themselves heard in conversation amongst environmentalists and sustainable fashionistas.

3.11 Some key policies, strategies, and goals to maintain sustainability in the fashion industry

1. Develop standards and practices for designing garments that can be easily reused or recycled. The Sustainable Apparel Coalition has created an index for measuring the full life-cycle impact of clothing and footwear products.
2. Devise systems that are analyzed with the help of life-cycle assessment models and derivations thereof.
3. Invest in the development of new fibers that will lower the environmental effects of production and garment making.
4. Support research on improving the sustainability and efficiency of fashion manufacturing.
5. Encourage consumers to appreciate the value of fashion products and to care for their clothes in low-impact ways.
6. Steer consumers toward clothing-care practices that have a smaller environmental toll and keep garments in good shape for longer.
7. Incentivize manufacturing of products that adopt social manufacturing set-ups that will have higher sustainability value.
8. Support the development of mechanical- and chemical-recycling technologies.
9. Establish higher labor and environmental standards for suppliers and set-up mechanisms to make supply chains more transparent and ethical.
10. Provide suppliers with guidance and resources for meeting new labor and environmental standards and hold them accountable for performance shortfalls.
11. Provide solutions to develop and strengthen social manufacturing systems with ICT.
12. Increase visibility access and boost social media presence to be instrumental in contributing to the social manufacturing set-up.

3.12 Conclusion—social manufacturing with synergy for sustainability

The term “Social Manufacturing” was coined as recently as 2015, but the concept may be older in most communities and civilizations. In every village in the olden days, each family practiced a particular craft and their livelihood depended on all the others who approached them to fulfill their needs as and when needed or during festivals and celebrations. Here, the keywords are “as and when needed.” The artisans, or maybe we could call them the “manufacturers”, had a small collection of ready-to-sell stuff, and thus not a lot of “unsold inventory” would be left with them.

The limited and careful use of natural resources; and raw material or energy sources for manufacturing these goods made it easy to dispose of the “unsold inventory,” if and when the time arose. Each family in the society would be a producer as well as a consumer, and goods or services would be made or provided according to the exact need; that is, each consumer would be able to get exactly what he wanted, by conveying the same to the producer. This brings us to the next important word in the concept of social manufacturing—the “prosumer”—a proactive consumer who also doubles up as a producer because of his involvement in the designing or customizing the product to suit his needs, which is not much different from a consumer’s role of the yesteryears.

The advent of mechanization after the industrial revolution changed the complete scenario, slowly but surely. The machines increased production manifold. But this was not the only development; there were increased mechanization, decreased demand for handmade goods, and rendering of the traditional manufacturers to those with lesser business leading to migration of employment to factories. The increased production made goods available at lower rates, increased income led to higher consumption capacity, and a whole new section of consumers emerged who would buy goods, not because they needed these products, but because they desired to and could afford to buy them. Increased exploitation of natural resources for untamed production led to their depletion, and a new problem of increased disposal raised its head. The ecological and health problems faced today are a result of this extremely consumerist society.

However, every dark cloud has a silver lining, and the realization that untamed production, consumption, and disposal have very frightening consequences was assimilated into a shift toward conscious consumerism. This coupled with the power of communication technology has given today’s consumer a wide choice from whom and from where to buy, and that too to suit every detail of his liking. Harnessing the power of communication technology has made it possible to contact anyone across the globe in a matter of a few seconds. Just like consumers now have this facility, manufacturers too have used technology to provide customized products to their consumers. It may be creating single customized products at their factories or outlets or getting it outsourced from willing individuals in the society from across the globe. The bottom line here is that production is done exactly according to the preference of the consumer; thus going back to what happened in the earlier days, where there was never a problem of plenty. It will not be wrong to say that social media that has harnessed this immense power of communication technology, has shrunk the globe to literally “fit into one’s” fists, and the power of social media can be taken advantage of to extend the concept of social manufacturing to the masses. What is needed is the ability to contact the right person at the right time, may it be the producer or the consumer.

This is where the next challenge lies. The buzzword today is data, and here, too, creating effective databases is the key to getting the ball of social manufacturing rolling. Just like LinkedIn is a database of professionals, it is very important that common databases be created for people in different professions. The possibility of showcasing pictures or videos in these also has to be explored to make them an effective mode of advertising. The use of social media to advertise these databases can help in getting good publicity for business. The fact that most of us on this earth are consumers and that each one, therefore can also be a producer is the biggest advantage of the concept of social manufacturing. The impact of social manufacturing will have far-reaching effects on each one of us and, thus on the environment. Producing as and when required and exactly in the manner that a product is needed will prevent huge amounts of wastage as saving in terms of natural resources used for production, packaging, transportation, warehousing and promotion is realized. This will, in turn, make a huge difference to the consumption and disposal patterns. The synergy between educational institutions, government and nongovernment organizations, and the industry can help make this concept a reality quickly and effectively. Just like there is vertical integration in industries, there is a possibility of having a virtual vertical integration or network model in social manufacturing too through this synergy.

This vertical integration or network creation can be very advantageous, especially, in the Indian context. The deep-rooted Indian culture of using hand-me-downs, that is, reusing old stuff, helps in decreasing disposed waste. Also, the waste collectors who separate the disposed of matter into recyclable and nonrecyclable items have their importance in this whole network. The availability of recyclable material that can be plowed back into the production system makes it possible to use lesser virgin raw material from the already depleting and exploited environment. The academia can then play their part, as the creativity of students and faculty can be put together for product development to create innovative products and put their thinking caps on to bring into use methods of converting this “waste” into useful products. The rich native traditional craft that is practiced by many artisans all over the country—be it in textiles, metal works, or numerous types of handicrafts—can also be harnessed to create value addition in these products.

2021 is earmarked as the International Year of Creative Economy for Sustainable Development by UNESCO. Today, increasingly people are venturing out to translate their ideas and imaginations into innovative products and services, and turning these into livelihoods. One of the world’s most rapidly growing sectors of the creative economy contributes 3% of the global GDP. Creativity is seen as a resource that is infinite, sustainable, and renewable being ubiquitous. With the pandemic crisis unfolding, people have realized the importance of the value of resources and have directed their abilities in creative pursuits. Business is becoming human-centric and all-inclusive. The professionals in the industry, the financial institutions, and investors play their part by adapting their methods and processes with creativity, or funding innovations so that every effort that has the potential of creative use can be encouraged to thrive. Legislations and laws by the government can then in the final step in a creativity-generating value chain help in giving a legal form to all these efforts. Thus vertical integration or rather a network created can help provide a level playing ground for all these various players. A model so created can be sustainable in itself and can help each stakeholder remain relevant, whether as a consumer, a producer, or as a prosumer. The future of manufacturing is indeed “social manufacturing” described as the third revolution characterized by enterprise collaboration.

Social manufacturing is, thus definitely a workable option and the way forward to a more inclusive type of growth and development of each individual in a civilized society that will have far-reaching benefits for the individual, at a micro level, and the planet, at the macro level.

Sustainability does not always imply resorting to rudimentary materials and processes, hand-made over machine made/digitally made, or shifting completely to natural over the synthetic which is quite unthinkable. Maintaining the balance is the trick of the trade and making the choices judiciously is imperative. Similarly, the social manufacturing model cannot completely replace the current business scenario with manufacturing, at one end, and consumption, at the other end. Social manufacturing as a concept has to be integrated not as a replacement of the existing manufacturing organizational structure but as a collaborative solution toward sustainability in the fashion business. That is the proclamation put forth herein in this chapter. On a lighter note a few words of lyrical wisdom are here:

"*Equiponderance*"
Why should something only be this and not that?
If it's this then it can't be that?
Why so? Just let it be.
Natural or manmade fibres should it be?
Organic or chemical/artificial substances should they be?
Natural or synthetic colors should they be?
White or red should it be?
If it's a food source,
should it be a textile resource?
Why so, just let it be.
Research into finding the unknown and not losing what is known?
Duality or dichotomy is perplexing.
Nothing and we mean nothing is a substitute for anything????
Nothing is indispensable and
Nothing is completely sustainable?
Can I hear "*Suntulan*" as in Hindi meaning Balance.

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Part 2

Technology and Application of Anthropometric Data

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Reliability and ethical issues in conducting anthropometric research using 3D scanner technology

4

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4.1 Introduction

With current scanning technologies, a body scanner holds the key to body measurement problems. The scanner can expedite the measurement process, and also, the customers can easily measure themselves (Durá-gil et al., 2019). Three-dimensional (3D) body scanning technology has emerged as a potential replacement for the conventional measuring tape method of collecting body measurements. 3D body scanners are quick, effective, highly reproducible, and virtually error-free in human intervention. The earliest 3D body scanning technology was a shadow scanning method named the Loughborough Anthropometric Shadow Scanner developed by Loughborough University, UK (Jones & Rioux, 1997).

Over the last few decades, scanning technology advancement enables the body to be scanned in a few seconds (Alemany et al., 2019). The 3D body scanner can save time and be relatively less expensive for numerous data collection (Liu et al., 2012; Rissiek & Trieb, 2010). The 3D body scanning technology is currently utilized in various disciplines, mainly in the ergonomics, engineering, biomedical, and apparel industries (Ballester et al., 2015; Lerch et al., 2007). While the capacity for revolutionization of industrial and science practices in this technology has been developed, its reliability in recognized allowable error has not been adequately addressed. At the same time, ethical issues also need to be taken into consideration.

An important aspect that underlies the application of 3D Body Scanning is its ability to produce accurate measurements within the confidence range of manufacturers or designers as a manual measurement method. This is in alignment with Istook and Hwang (2001) who opined that fit apparel depends on a comprehensive and accurate set of measurements. The measurement error must be avoided for a product, particularly apparel, to fulfill the requirements of body dimensions. Park et al. (2009) suggested 3D erroneous data detection for data inspection before the data can be used to design any product development. The 3D body scanning enables subjects to measure themselves, but it often leads to an inaccurate measure

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(Liu et al., 2017; Wang et al., 2019). The scanning process also requires the subjects to stay in a specific position for scanning; having said that, it is not easy to control the position, especially for children (Agha & Alnahhal, 2012).

With the advent of 3D body scanning technology, there is a greater emphasis on ethics in conducting anthropometric research. Since anthropometric research involves direct or indirect human participation, it is necessary to consider the ethical implications of their study. All possible aspects of risk should be minimized to avoid any harm to subjects (Gelling, 2016). Even though the 3D body scanners capture the outside body surface image without physical contact (Istook, 2008), there are still privacy and ethical issues. The scanning process requires subjects to be naked or to wear tight-fitting clothing to get the exact point of the body for correct measurement, about which some people may feel uncomfortable (Wang et al., 2019). At the same time, the image captured involving sensitive data of personal bodies that are improperly stored can be potentially misused by irresponsible people (Bragança et al., 2016).

4.2 Importance of anthropometric research in the apparel industry

The importance of anthropometric research cannot be denied. Anthropometric research is an important aspect of ergonomic approaches to the use of technology, for instance. Proper anthropometric layouts, items, and work tools can affect safety, comfort, and health. Particularly in the apparel industry, anthropometric research is very important, especially in designing apparel that fits individual body dimensions (Istook & Hwang, 2001).

The variation of body dimensions encourages anthropometric research to resolve the apparel "misfit" (Dianat et al., 2018). Each body dimension is unique, varying from one person to another. The uniqueness is influenced by various factors such as ethnicities (Karmegam et al., 2011; Shan & Bohn, 2003; Widyanti et al., 2017; Yap et al., 2001), gender and age groups (Bari et al., 2015; Dawal et al., 2012; Shan & Bohn, 2003; Yuhaniz et al., 2016), as well as countries (Abd Rahman et al., 2018; Ball et al., 2010; Ran et al., 2018).

Anthropometric research requires anthropometric data which include measurements of body dimensions, such as height, arm length, hip-width, hip circumference, and thigh circumference (Attwood et al., 2004; Marshall & Summerskill, 2019). The complex characteristics of the data make anthropometric research more challenging and exciting to be explored. The lack of anthropometric research results in a lack of standardization of sizing systems across retailers and brands, which creates problems for customers to carry out apparel size selection. Different brands use various attributes (i.e., height, weight, waist) as an indicator of the size reference chart (Saaludin et al., 2020) as different countries use different sizing systems (Song et al., 2017). The differences in sizing codes (such as age, numbering, and alphabets) in classifying the apparel size can be misleading (Laitala et al., 2009).

The main reason for fitting issues is that the sizing system was not created or derived from empirical data of body types and dimensions (Zakaria, 2011). Body measurement is the precursor process in designing apparel (Abu Bakar, 2012; Carufel & Bye, 2020; Gupta, 2014). In the ready-to-wear segment, anthropometric data is very important to profile body dimensions and categorize them according to apparel sizes (Liu et al., 2016, 2017; Wang et al., 2019; Wren & Gill, 2010; Zakaria, 2016).

4.3 The 3D body scanning technology and anthropometric sizing surveys

The progressive advancement of technology has resulted in bigger innovative ideas of manufacturing higher-quality products than its predecessors being generated, positively impacting the community. Being aware of the importance and uniqueness of the data, many countries, such as the United States, United Kingdom, Japan, France, Germany, Portugal, Italy, Korea, Spain, China, Romania, Brazil, India, and Thailand, have developed their anthropometric database as shown in Table 4.1.

4.3.1 The 3D anthropometric sizing surveys

Anthropometric research has been conducted extensively worldwide using 3D body scanning technology, mostly to address the assembly problems of the apparel industry. The related anthropometric surveys are the Civil American and European Anthropometry Surface Resource (CAESAR) project, SizeUSA, SizeUK, SizeGermany, France Sizing Survey, SizeKorea, SizeThailand, SizeIndia, Spain Survey, SizePortugal, SizeItaly, Smartfit and SizeBR, Romanian Survey, SizeChina, and SizeNorthAmerica.

The CAESAR project was the first large-scale 3D scanning technologies anthropometric survey (Bragança et al., 2016) conducted by Air Force Research Laboratory. The survey involved the population of three North Atlantic Treaty Organization (NATO) countries: the United States, the Netherlands, and Italy. The data collected were for research related to workstations and cockpit design, body-fitting apparel, and facial equipment (Cheng et al., 2007).

SizeUSA was the major player in measuring the American population accurately. The subjects were scanned across the country in 12 cities, leading to a database of 10,000 subjects scanned (TC2, 2020). The SizeUK was conducted by the British government in collaboration with major UK apparel companies, academic institutions, and several technology companies such as the non-profit Textile Apparel Technology Corporation (Treleaven, 2004).

In a separate anthropometric survey, SizeGermany was carried out by Hohenstein Institute, and Human Solutions GmbH in collaboration with industry partners (Staff, 2014). The Spain survey was conducted to characterize the body measurements of the Spanish population to solve the issue of fit in the apparel industry. The survey

Table 4.1 Summary of 3D anthropometric surveys conducted worldwide.

Project	References	Year	Sample size	Country	Age range	Body scanner company
CAESAR	Suikerbuik et al. (2004)	2000	2500	The United States and Canada	18–65	Cyberware
		2000	2500	The Netherlands and Italy	18–65	Human solutions—Vitus Pro
SizeUK	Bougourd and Treleaven (2010)	2001–02	10,000	The United Kingdom	16–65	TC2
SizeUSA	TC2 (2020)	2002–03	10,800	The United States	20–65	TC2
SizeGermany	Staff (2014)	2007–09	13,362	Germany	6–87	Human solutions—Vitus Smart
France Sizing Survey	Kennedy and Vic (2008)	2003–04	11,562	France	5–70	Human solutions—Vitus Smart
Spain Survey	Ballester et al. (2015)	2007–15	12,000	Spain	3–70	Human solutions—Vitus Smart
SizePortugal	Ramoa et al. (2018)	2014	1864	Portugal	17–75	TC2
SizeIndia	Kulkarni et al. (2011)	2009–10	5028	India	18–45	Human solutions—Vitus Smart
SizeItaly	Stampfli et al. (2012)	2012–13	6000	Italy	18–75 6–17	Human solutions—Vitus Smart
SizeThailand	Charoensiriwath and Tanprasert (2010)	2007–08	13,442	Thailand	16–60 +	TC2
6th Korean Survey	Lee (2010)	2010	14,016	Korea	7–69	Hamamatsu
SmartFit	Cools et al. (2014)	2013	2500	Belgium	3–70	Telmat SYMCAD II and TC2
Romanian Survey	Niculescu and Ionescu-tirgoviste (2012)	2009–10	4000	Romania	20–65	Human solutions—Vitus Smart

SizeChina	Ball (2011)	2008	2000	China	18−70 +	Cyberware
SizeBR	Ferreira Bastos et al. (2013)	2014	6941	Brazil	18−65 + (women)	TC2
SizeIndia II	Wright (2018)	2018 (in progress)	25,000	India	15−65	N/A
SizeNorth America	Kuebler et al. (2019)	2019 (completed)	18,000	The United States and Canada	6−65 +	Human solutions—Vitus Smart

was conducted with the cooperation of the Spanish Clothing sectors, the national association (FEDECON), and the regional association (ATEXGA).

The government of Thailand, through the Thai Industrial Standards Institute, National Statistical Office, the Federation of Thai Industries, and the National Science and Technology Development Agency, developed an anthropometric survey named SizeThailand. The success of the project was attributed to the cooperation between the Thai government with textile organizations, clothing retailers, academia, and automotive sectors, which jointly funded the anthropometric database for Thailand called SizeThailand. Details of other studies can be referred using Table 4.1, which shows that anthropometric surveys were conducted primarily for the establishment of apparel sizing for their respective population.

4.3.2 The 3D body scanning technology for anthropometric surveys

There are four types of body scanning technologies: Laser-based system, structured Light-based system, multiview camera system, and radio-wave linear-array image capture, also known as millimeter-wave.

4.3.2.1 Laser-based system

The scanner works on the principle of triangulation (Treleaven & Wells, 2007) projected laser line on the body from different sides and viewed by the camera under a fixed angle (Daanen & Ter Haar, 2013). A single line has the advantage of being easily detected by the sensor and is calculated precisely based on how the projected 2D line is deformed on a 3D surface. The 3D line will then form the entire 3D image (Bragança et al., 2015). The manufacturers of laser-based scanners are Hamamatsu and Human Solutions.

4.3.2.2 Structured light-based system

The 3D scanners project patterns of light on the body. The video projector generates the pattern, and the cameras record the distorted pattern (Treleaven & Wells, 2007). The structured light scanner's advantage is its speed. The fast characteristics of structured light scanning make it suitable to be used for 4D scanning, that is, real-time 3D scanning at 200 Hz. It provides good possibilities for registering movement with 3D form (Mochimaru & Kouchi, 2011). Manufacturers of this type of scanner include TC2, and Wicks and Wilson.

4.3.2.3 Multiview camera system

To create 3D images, this system uses two or more cameras. The stereo camera takes two views from different points at the same time. The body depth can be measured and transformed into a compact 3D image in real-time based on the quality of the two images. The advantage of a stereo camera system is that there are no laser lines or light patterns transmitted, so sunlight cannot interfere with the pattern.

However, using lines or patterns allows for higher resolution and precision in 3D images.

4.3.2.4 Radio-wave linear-array image capture, also known as millimeter-wave

This 3D scanner uses linear linear-array radio-wave technology. The scanning can be done through clothing. The company using this kind of 3D is Intellifit (Treleaven & Wells, 2007).

The 3D body scanner manufactured by Human Solutions and Textile Clothing Technology Corporation (TC2) is among the most popular brands used for anthropometric surveys. The 3D body scanners system produced by these two manufacturers is integrated with computer-aided design, which can be used not only to collect databases but also for designing furniture, and workplaces and, most importantly, to design apparel (Istook & Hwang, 2001). It is important to test its reliability and validity when using anthropometric data as these factors can affect both the measurement and the interpretation of results obtained. The next section will discuss reliability issues and concerns related to 3D scanning technology.

4.4 The 3D body scanning technology: types and reliability

The development of a 3D whole-body scanner opens up opportunities for measuring the human body more efficiently. Based on Kouchi and Mochimaru (2011), the main source of error in measuring the human body can be traced to the devices used and the person involved in the anthropometric survey. According to Wang et al. (2007), the fundamental issues in data reliability were landmark identification and data measurements; and they suggested the marker placement on the human body to be all-important in facilitating the correct correspondence between the subjects, on one hand, and across scans for anatomical locations before scanning, on the other. The procedure of placing markers is very tedious. Landmarks can be placed manually with a traditional coloring marker because scanners can sense color differentiation (Bragança et al., 2016), but it will tend to human errors (Bragança et al., 2019). However, with the current advancement of the 3D scanners, the tedious process of marking which are the points of interest on the body for garment fitting can be considered as a thing of the past. Several automated landmarking have been proposed. Buxton et al. proposed silhouette or body surface image to identify the points (Buxton et al., 2000). The body surface can be used to extract body landmark features and anthropometric information. In a different proposal, Allen et al. suggested a template mapping approach, which utilized the 3D scanning data to identify the proximity of the transformation vertices to the data range of the template surface that resulted in the sparse marker distance appropriate locations on the template target body surfaces (Allen et al., 2003).

Furthermore, a 3D Scanner reduces the repetitive manual measurement to be done by a measurer. It also reduces the time spent by the measurer to interact with the specimen. Two questions arise on the use of manual or automation using the 3D scanner: firstly, which would give more reliable data? Second, how can we give evidence of reliability and validity of the collected data regardless of the methods?

Quantitative research is the process of collecting and analyzing numerical data, in which an anthropometric survey produces numerical data. Quantitative research can be used to find patterns in data and deduce averages to understand the nature of data collected, make predictions, define causal test relationships, and generalize results to broader populations. Hence, there are higher chances that researchers would conduct quantitative research to get anthropometric data.

When conducting quantitative research, one must consider the reliability and validity of his research methods and measurement instruments. Reliability shows how consistently a method measures something. It is expected that when applying the same method to the sample under the same conditions, one should get the same results. If not, the method of measurement may be unreliable. The validity, on the other hand, describes the accuracy of a measure. For this research, the focus is on reliability instead of data accuracy, even though the latter is as important.

Nevertheless, it is essential to consider both reliability and validity during research design, planning methods, and writing up results, especially in quantitative research. The reliability and validity of research methods depend on how one collects, measures, and analyzes and interprets data. The inconsistency in the data can be caused by several factors such as the apparatus used, the measurer's skill in conducting the procedure, the collection method or process, and the environment and time of the day. Three assays can be made to evaluate the measurements of the 3D body scanner: (1) compare the 3D body scanning measurements with manual measurements (Abu Bakar, 2012), (2) repeat the scan-derived measurements (Robinette & Daanen, 2006); and (3) repeat the scan-derived of the landmark, the location from the same object image (Kouchi & Mochimaru, 2011).

There are four different types of reliability measurements mentioned by Middleton (2019), as shown in Table 4.2. They can be used to measure the consistency of results due to time, people, different versions of the instrument used, or internal consistency.

Choosing the correct reliability measurements would ensure that fewer errors crop up in the data sample. For example, when the consistency of the results over the same sample is weighed, one should repeat the same test over the same sample size a few times but at different points in time. The process would eliminate other influences over the sample. The researcher should use interrater reliability measurement to rule out the possibility of the measurer influencing the result of the measuring data; again, parallel forms reliability measurements are used when two different assessment tools or sets of questions are designed to measure the same thing; lastly, to measure the internal consistency, a researcher can calculate internal consistency without repeating the test or involving other researchers. The correlation between multiple items in a test that intended to measure the same construct can be measured. Besides testing the validity and reliability of the anthropometric data, the

Table 4.2 Type of reliability to measure consistency (Middleton, 2019).

No.	Type of reliability	Description	Measures the 3D consistency
i.	Test–retest	Test–retest reliability measures the consistency of results when one repeats the same test on the same sample at a different point in time. A researcher uses it when he measures something that he expects to stay constant in his sample selection	The same test over time
ii.	Interrater	Interrater reliability measures the degree of agreement between different people observing or assessing the same thing. Researchers use it when the collected data require assigning ratings, scores, or categories to one or more variables whereby the variable is an attribute to the object of study. Interrater is also known as interobserver reliability	The same test conducted by different people[a]
iii.	Parallel forms	Parallel form reliability measures the correlation between two equivalent versions of a test. A researcher uses it when two different assessment tools or sets of questions are designed to measure the same thing	Different versions of a test are designed to be equivalent
iv.	Internal consistency	Internal consistency assesses the correlation between multiple items in a test intended to measure the same construct. A researcher can calculate internal consistency without repeating the test or involving other researchers, so it is a good way of assessing reliability when there is only one data set	The individual items of a test

[a] In 3D scanning, data are usually collected by one measurer. To enhance the reliability, it is advised that a pilot test be conducted.

protocol before and after the survey must be taken into account, where the protocols must be clear so that the survey can be conducted smoothly to avoid any distraction during the implementation of the survey, which can impact data, subjects, and the team who handle the survey.

4.5 The 3D body scanning: test of validity

Other than reliability issues, it is also important to focus on data accuracy. Data accuracy relates to data validity which determines the accuracy of the components of a measure. If a method measures what it claims to measure and the output closely corresponds to real-world values, then the data can be considered valid. There are four types of validity tests to be considered: construct, contents, face, and criterion validities (Middleton, 2019). First, construct validity ensures that the method of measurement matches the construct to be measured, where a construct is a concept or characteristic that cannot be directly observed but can be measured by observing other associated indicators. It can be (almost) anything. Simple constructs include height, weight, and IQ.

More complicated constructs include characteristics of individuals, such as intelligence, obesity, job satisfaction, or depression, which can also be broader concepts applied to organizations or social groups, such as gender equality, corporate social responsibility, or freedom of speech. Second, content validity assesses whether an instrument is representative of all aspects of the construct. It uses a formal, statistics-based approach, usually with experts in the field, and these experts judge the instrument on how well they cover the material. Third, face validity is like content validity but is a more informal and subjective assessment given it checks for validity at face value only. Finally, criterion validity evaluates how closely the results of one test correspond to the results of a different test, where the criterion is an external measurement of the same thing and the test is usually an established or widely used test that is already considered valid. For an anthropometric survey using a 3D body scanner, we suggest that criterion validity is applied to ensure data accuracy.

4.6 The 3D body scanning anthropometric survey protocols

As of now, there are no standard protocols for the 3D body scanning anthropometric survey, especially in capturing body scan data, resulting in discrepancies and issues in a scientific field (Gill et al., 2016). Two studies have been reviewed to develop 3D body scanning anthropometric survey protocols. The anthropometric survey protocols proposed by Zakaria (2016) and Gill et al. (2016) have covered procedures before and after the survey was conducted, as shown in Tables 4.3 and 4.4, respectively. However, by 2019, the WHO and UNICEF (2019) had produced a guide for anthropometric surveys for children below 4 years old.

Based on the review of both protocols mentioned earlier, approval from the ethical committee is a must before conducting the anthropometric survey. Research ethics govern the codes of conduct for scientific researchers. To protect the integrity, freedom, and health of the subjects researched, it is important to follow the ethical guidelines of the World Health Organization [World Health Organization (WHO), 2011a]. All research involving human-related research must get approval

Table 4.3 The 3D body scanning protocol for anthropometric data collection (Zakaria, 2016).

No.	Procedure	Description
A	Ethical committee approval	• The university ethical committee approval is a must. • Several issues that need to be addressed to get approval are: • Nature of digital image. • Confidentiality issue. • Digital image storage issue. • The use of data. • The outcomes of data can benefit the research overall.
B	Medical doctor as consultant	• Appoint a medical doctor as a consultant to ensure that children undergoing the scanning procedure will not have any negative physical and psychological effects.
C	Consent letter	• The form must contain comprehensive information such as: • Purpose of study. • Steps before and after the scanning procedure. • Details about the 3D body scanner will be used for surveying, including the scanner and scanning procedure, which will not harm children physically. • Research expected outcomes. • The form must be written in layman's terms; this enables the public to understand the research. • The form must clearly state: • Data confidentiality. • Open to withdrawal from being a subject term. • The research is not for commercialization purposes.
D	Step-by-step procedure	
D1	Registration of subjects	• Each subject will be provided with a barcode number. • The barcode will be a reference for the team to identify the subject, such as filling out questionnaires and body scanning.
D2	Weight and height measurements	• Weight and height will be measured.
D3	Explanation about the body scanning process	• The subjects must be explained the scanning procedure from beginning to end, including the attire they need to wear during the procedure. • Subjects will view the video demonstration.
D4	Changing clothes to tight-fitting	• Subjects will use a private changing room to undress. • Change clothes to tight-fitting.

(*Continued*)

Table 4.3 (Continued)

No.	Procedure	Description
D5	Body scanning in booth	• Subjects will be assisted in a suitable position for scanning. • Subjects will hold the hand railing in the scanning both and stay at that position for about 10 seconds for the camera to scan the whole body.
D6	Changing clothes to school uniform	• Subjects will return to changing cubicle for getting dressed in the uniform.

Table 4.4 The 3D body scanning protocol for anthropometric data collection (Gill et al., 2016).

No.	Procedure	Description
A	Ethical committee	• The university ethical committee approval is a must, and any deviations from the scanning procedure require the ethics committee for their consideration.
B	Step-by-step procedure	
B1	The subjects' recruitment	• The subjects are invited to be scanned OR. • Use social media, posters, and word of mouth to invite subjects to be scanned. The invitation confirmation is made through the online booking system located on the university website.
B2	Explanation about the body scanning process	• The subjects have been explained the scanning procedure from beginning to end, including the attire they need to wear during the procedure. • Scanning will be taken by the trained scanning personnel, whose names are listed in the consent form. • The scanning procedures will be under scanning personnel responsibilities who are among university staff. The details of their contact numbers must be clearly stated in the consent form.
B3	Subjects fill in the details in the database	• Subjects will fill in the details such as gender, ethnicity, and age directly to the encrypted PC. The database is equipped with being password-protected. This data must be separated from scanned data. • Each participant will be assigned a unique code to name the scan file and retain the anonymity of the scan participant whilst linking it to the database.

(*Continued*)

Table 4.4 (Continued)

No.	Procedure	Description
B4	Print and sign the consent form	• Subjects must read the signed consent form before proceeding with the scanning procedure. • A copy of the consent form will be kept and stored properly. • The blank copy is available on the website for scrutiny by subjects.
B5	Manual measurements before the scanning	• Several manual measurements will be taken before scanning so that subjects will understand the purpose of measurements, such as: • Height – no shoes allowed during height measurement • Head Circumference – for clothing opening requirements • Min Max hand – for clothing opening requirements • Hand length – for clothing opening requirements • Measurements are taken manually to illustrate taking measurements for the subject's view before giving consent and during the process.
B6	Provide a private changing cubicle to change into underwear and record weight	• Subjects will use a private changing cubicle for getting undressed, and appropriate underwear is provided if they do not have tight-fitting underwear. • Subjects will remotely be helped to take their weight from the private changing cubicle. • A particular gown will be provided for subjects to move from changing cubicle to the scanner booth.
B7	Enter the scanner booth and stay with the right body posture	• The scan body position and posture will be explained to the subjects before their entering the scanning booth. • Subjects will key in the unique personnel code from the consent form to name the scan file before scanning. • The participant must remain in a standing position until the procedure of scanning is completed (estimation duration of scanning approximately one minute). • The team will check the image captured through the screen, and the repeat process will be requested (if necessary).
B8	Leave scanner booth and proceed to the changing cubicle for dressed	• Once the scanning process is done, the participant will return to the changing cubicle for getting dressed.

(*Continued*)

Table 4.4 (Continued)

No.	Procedure	Description
B9	Offer for data softcopy/ hardcopy	• The participant is offered a softcopy/hardcopy of the weight, height, and scan data.
B10	Notes on the procedure	• The participant is allowed to withdraw from the activity at any time, even though the consent form has been signed. • If a participant withdraws from the survey during the data collection period, all data will be destroyed immediately.
B11	Data usage and storage	• Any anonymous scan data retrieved from the scanner location is stored on an encrypted computer or encrypted folder on a storage device. • All scan data is backed up on an encrypted external hard drive and stored in a secure locked location with controlled access.
C	Protocol for data management (storage and back-up file)	• All body scanning activities were performed to understand that all data collected contributed to a general data set. • Any data usage embargo is stated in detail in the ethical approval documentation of a particular project whose copy is stored with scanning technology, and references are made, with ethical approval notes and codes. • All data collected is stored in the PC and is backed up in encrypted Hard Drives or USB. • Copies of the participant records database are kept in the FileMaker Pro database format. • The data will only be used for the study. The data will be extracted from the database into excel sheets; the scan code will refer to the related subjects' data.
D	Use of body scan data	• Any use of body scan data complies with the following conditions unless the participant has given consent, and the ethics committee has agreed to this from the University of Manchester. • Data is blinded (named with a code) upon receipt and stored as blinded and double-blind (named with a secondary code) before being used in the publication. • Double-blinded scan data issued in publications and lists of anonymous double-blinded scan measurements may be used in teaching and research development. • Before scanning • Before subjects are scanned, they are given details that explain the process through video.

(*Continued*)

Table 4.4 (Continued)

No.	Procedure	Description
		• Post scanned ◦ Subjects will be offered a hard copy of their body scan, including a complete list of body measurements. All subjects were offered to have a copy of their electronic scan data.
E	Database and rationale for data collected	• Subject's details are recorded in a database using an eight-character unique ID. The code consists of a four-digit unique number for identification, a digit code for gender (M or F), a letter code for ethnicity, and a two-digit code for age. • The code will help the team organize data stored and match specific scans with specific data during analysis.
F	Scanning personnel and training	• Only trained and experienced personnel, in scanning, among university staff will conduct the scanning process. • He/she will also be supported by trained scanning personnel such as postgraduates or current students who have been provided with in-house training on capturing scans and dealing with scan subjects. • Names and contact details of the staff scanning personnel are recorded in the consent form and made available to subjects.

from an ethics committee to ensure that the relevant ethical guidelines are followed (Gelling, 2016; Newson & Lipworth, 2015).

The World Health Organization has published Standards and Operational Guidance for Ethics Review of Health-Related Research Human Subjects to reference the ethical committee before rewarding researcher/s with approval to conduct a survey. The guidelines also recommend for the committee to provide a consultant as an expert in the team. It was recommended that the team of survey appoint a medical doctor as a consultant of the research project so that he/she can give appropriate advice, especially in the case such as anthropometric survey using the 3D body scanner involving children as mentioned by Zakaria (2016). A consent letter is also an essential thing to have before proceeding with the survey. All the information related to the survey involving subjects must be clearly stated in the consent form to avoid negative perception or survey misconduct.

The data storage also must be appropriately planned as data is private and confidential. At the same time, the individual data must be anonymous. That was the reason Zakaria, and Gill et al. suggested a unique code to represent subjects. Gill et al. have recommended eight characters for the unique identification coding (ID).

The code consists of a four-digit unique identifier, a code M or F for gender, a letter as a code for ethnicity, and age denoted by a two-digit number.

4.7 Ethical issues in conducting anthropometric research

Adhering to ethical norms in research is of paramount importance to achieve the basic aims of research to promote truth and minimize error. Ethical matters in conducting research include, among others, getting consent, data handling, data rights, respecting privacy and human and animal rights, and managing the risk of harm to subjects and other stakeholders. Ethical issues in conducting anthropometric research can be viewed from two main perspectives: general research ethics and the other concerns relating to specific ethical issues surrounding anthropometric research. In its recent comprehensive guide on data collection, analysis, and reporting on anthropometric indicators in children under 5 years old, the UNICEF provided an extensive guide on good practices which can be useful to guide ethical conduct in anthropometric research (WHO and UNICEF, 2019). The report's target audience is technical staff experienced in conducting anthropometric surveys such as survey managers, technical assistance providers for national surveys, national survey organizations (reporting to government on SDG; and to WHA, implementers of representative surveys that include child anthropometry, etc.), international and national organizations with interest in data quality, researchers, and public health nutritionists. If we were to consider ethics review, as proposed by Rivière (2011), as practice, as policy, as a relationship, and as a performance, the step-by-step recommendations of the UNICEF report could indicate the important ethical issues to be considered along the research process.

4.7.1 Obtaining ethical approval

During the planning stage of data collection, it is important to obtain ethical approval where necessary. UNICEF and WHO stress the importance of obtaining approval which could be sourced from the local, national and international ethics review boards. For example, if a country does not have a local ethics review board, approval should be sought from the national review board. Furthermore, if there is no national review board, then approval should be sought from an international ethics review board. One common pain point in the ethics review process is the long process to obtain ethical approval and other authorizations. Thus researchers are advised to identify key people handling the process, allocate sufficient time for this process, and prepare flexible resources to manage the process.

4.7.2 Ethical conduct in research as practice

If we were to view ethical conduct in research as practice, then for anthropometric research, good research practices can be considered as part of ethical conduct aligned to both teleological and deontological theories of ethics, that is, the utilitarian principle of the greatest happiness for the greatest number (of people), and the Kantian ethics, which is based on pure reason. Going back to the UNICEF's report, ethical conduct can be guided by the suggestions for good practices along with the anthropometric research processes, which constitute three areas, that is, organization and survey design, fieldwork procedures and data processing, quality assessment, analysis, and reporting. First, in organizing research and designing a survey for anthropometric research, ethical considerations cut across planning, sampling, questionnaire development, training and standardization, and equipment. Secondly, fieldwork procedures include data collection, interview and measurements, data capture or entry, and quality assurance methods during data collection. All these require ethical considerations and conduct. The third area, which focuses on data processing, quality assessment, analysis and reporting, naturally requires care to be taken to ensure proper data handling and data rights and that consent for the use of data be sought and respected. Thus anthropometric researches can refer to the guidelines for 'must do' and 'good practices' to ensure that ethics is holistically considered. It is recommended that ethics be addressed to acquire the initial ethical approval and also during implementation and ending by taking it up right up to the final stage of each research project.

4.7.3 Specific ethical concerns on the use of an optical 3D measuring system

Going beyond ethics in research to the ethics associated with the use of an optical 3D measuring system in anthropometric research, it has been observed that getting consent, data handling, data rights, and managing risk of harm to subjects and other stakeholders remain major ethical concerns. Body scanners are widely used in the medical field to scan body deformity, glaucoma, orthodontics, orthopedics, surgery, lung function studies, custom prostheses, breast topography, pediatrics, and medical management; in human systems engineering its use pertains to the work environment, population anthropology, helmets and face masks, gloves, clothing, human morphology, human motion analysis, forensic imaging, hearing studies; and in virtual reality and communications, its use can be found in: 3D portraits; computer animation of human models; and in the creation of anthropometric databases (Bragança et al., 2016).

Anthropometric researchers such as Bindahman et al. (2012) highlighted privacy and the invasion of privacy as major concerns. The various issues surrounding privacy touched upon were: one, informational privacy, which in the case of anthropometric research goes beyond personal data to include body images; two, degree of privacy, which varies according to culture and religious belief; three, the fact that invasion of an individual's body could lead to feelings of losing dignity and humiliation; and last, 3D scanning being equated as a strip search. As the optical scanner can capture the visible surface of the whole body without physical contact, this lightens the burden of ensuring ethical conduct in research that requires physical contact. However, the capability of the 3D scanner to produce sensitive images exacerbated the challenges of handling privacy issues. As these sensitive images are revealing and recognizable, most people are reluctant to expose their body dimensions. Therefore, data handling and privacy issues could become more contentious as scanner technology becomes more accurate but intrusive.

Sensitive personal images, for example, that of a seminude body require careful handling to ensure no security data breach. Careless and insensitive handling could be risky and may result in fines, civil lawsuits, criminal actions against researchers, and loss of reputations and other repercussions. Thus there should be a high level of integrity and transparency among those involved in anthropometric research. Research subjects need to be shown the images taken. The revealing images of the fully naked body scanned by the 3D device, if not well protected and securely filed, could be construed as an invasion of privacy and a potential violation of human rights and dignity. Thus privacy protection is crucial to guarantee freedom from the feeling of being violated. The use of the 3D scanner must be guarded against the possibility of information leak, intrusive scanning, as well as careless research and data handling.

As anthropometric research involves human subjects, social and cultural aspects of ethics must also be taken into account, which mainly concern cultural differences and religious sensitivities to be considered. Good knowledge of the international code of conduct must be pursued by anthropometric researchers. Technological advancement in anthropometric research tools must be subjected to ethical considerations. While researchers support the development of 3D scanning technology to enhance the application in surveillance and security at the expense of privacy, others propagate privacy being incorporated in the first stage of information system development. In this way, privacy will not be compromised. For example, developing an algorithm that could recognize body features and blur sensitive areas of the body. Note, however, that this type of scanning is more suitable for surveillance and security purposes. In health applications, the scanning capability would require an algorithm that could produce clear images of body parts under investigation. In principle, good ethics dictate that technology should not be at the expense of privacy.

4.8 Privacy protection

Many principles, rules, and policies have been put forth to address privacy issues. Central to this is the Data Protection Act (International Trade Administration, 2018), which states how data, including images, should be managed, covering data collection, its use, propagation, storage, maintenance, access, and corrections and so forth. Transparency towards those being scanned is an important aspect of privacy protection. Individuals must be allowed to access their data, correct their data, and know how his/her data will be collected, be used, propagated, and maintained. Consent must be sought and given before conducting the anthropometric research. The technology must be explained, and samples of produced images should be shown to the prospective participant, and he/she must also be briefed on the purpose and limitation of the research to be undertaken.

In short, anthropometric research must address generic research ethics, by being transparent about specific ethical concerns of anthropometric research, especially privacy issues, and take heed of guidelines on anthropometric research provided by recognized bodies, such as UNICEF and WHO.

4.9 Apparel industry: moving forward with 3D body scanning technology

Concern over sustainability issues in the fashion industry has led to the formation of a growing number of initiatives, many of which rely on digital platforms and new technology to amplify their impact. The fit issues continue to be a growing concern. Consumers feel they're not happy with apparel that does not provide a good and desirable fit. This is a significant problem for retailers and manufacturers alike. As such 3D body scanning, where new and improved technologies are now available that allow realistic images of human bodies to be used for garment fit to be accurate, shows significant promise.

The technology of 3D scanning will benefit the apparel industry and make online shopping convenient for customers—for now, there's no need to try on apparel in fitting rooms. The technology allows customers to apply a "virtual try-on" application which gives the customers a preview where they can see exactly how the apparel will fit their bodies and even choose sizing and styling modifications. Subsequently, data can be sent to the made-to-measure department for apparel custom-made to their body. The apparel purchased that fulfills the requirements of the body as desired will increase customer satisfaction and enable retailers to reduce return and, ultimately, lead to increased market share and company profitability. The scanning technology can also expedite the tailoring process in measuring, and the conventional tailoring system can be upgraded to the advanced online made-to-measure tailoring system. Therefore, the 3D body scanning technology will be pivotal in launching the apparel industry to another higher and better new level.

4.10 Conclusion and future trends

3D body scanning technology contributes immensely to the apparel industry around the world. The rapid process of measuring body dimensions with a certain range of accuracy allows anthropometric surveys to be conducted efficiently and effectively. To optimize advancement in 3D body scanning technology, continuous anthropometric research is crucial in which developing standard sizing systems of different countries and regions needs to be given more attention to ensure better clothing fit and minimize production and purchase costs. Many issues need to be addressed before this technology can be widely adopted and applied. The issues of 3D scanning, such as identification of landmarking phase, missing data, and inconsistencies caused by subject movements, must be properly handled to ensure the data gathered is valid and reliable to be used in anthropometric research. Ethics in research, of course, is of paramount importance.

The quest for approval of research ethics is an important phase in the planning stage of any research project involving humans as subjects. One common challenge in anthropometric research is that while most researchers are aware of the need to provide information to subjects about potential risks, they often neglect to consider it. Thus a research ethics committee must be appointed to ensure that researchers take precautionary measures to protect subjects from any unethical procedures that tend to harm the subject before, during, and after the anthropometric survey. The standard 3D body scanning protocol for anthropometric research must be developed to ensure all data collection processes can be smoothly conducted without any problems and issues.

No matter how attractive the clothes are, it is pointless if the apparel does not fit the body. The development of a standard sizing system requires numerous anthropometric database collections to classify the body size in terms of apparel sizing. The 3D body scanning technology helps the advancement of the anthropometric survey. Having said that, the research related to 3D body scanning is crucial, especially in relation to the accuracy of the measurements. The accuracy can be improved when the landmarking position for scanning is done correctly. An artificial intelligence intervention, that is, deep learning, is recommended to be further explored to predict landmarking positions better.

The 3D body scanning technology can measure and create a digital copy of the surface of the human body. The technology of the scanner will bring huge success for retailers when scanning is expected to increase the consumer's level of satisfaction in buying apparel and reduce returns. The body measurements can be obtained faster and with more accuracy. The 3D scanner will standardize the tailoring measurements, and it's expected that the adoption of this latest technology will benefit the apparel industry.

4.11 Sources for further information and advice

Further information about the ethical standard to conduct anthropometric research includes:

1. Standards and Operational Guidance for Ethics Review of Health-Related Research with Human Participants (WHO, 2011b).
2. Gelling (2016), through his writing, raised the main issue to occur while applying for ethical approval by answering six questions:
   a. "Do I need ethical research approval?",
   b. "How many applications will I need to make?",
   c. "Where should I apply for ethical research approval?"
   d. "What do I need to include in my application?",
   e. "What do research ethics committees look for?" and
   f. "What other approvals might I need?"
3. WHO and UNICEF (2019) have produced a guide for anthropometric surveys for children below 5 years old.

To enhance the reliability and validity of the 3D body scanning results, it is advised for a pilot test to be conducted before the actual survey. The body dimensions are proposed to be measured manually by experts and also using a 3D body scanner. The results from both methods are compared so that the differences can be analyzed. The differences can be used to adjust the 3D body scanning measurements so that the accuracy and validity of the results may be improved.

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Data management and processing of 3D body scans

5

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5.1 Introduction

Anthropometric data has been used for many years for different applications in the fields of physical anthropology, nutrition, ergonomics, sport wherein human need factors arising in these fields are finetuned. The disruptive 3D body scanning technology ushered in a new way of anthropometric data generation that required the development of new data capturing technology, new protocols for body data gathering, specialized processing algorithms, and software as well as data management tools. All these elements have been developed in more than thirty years of research proving very productive in the generation of new anthropometric databases worldwide. Even so, nowadays, there remain several challenges related to the reliability and compatibility of the anthropometric data and both are related to 3D body scan processing and management.

Using 3D body scanning technology, it is possible to obtain different types of anthropometric data: 3D landmarks, 3D body mesh, digital anthropometric measurements obtained from the 3D body scan (e.g., heights, widths, lengths, girths) or sections. In addition, 3D body captures are processed to some extent to obtain a usable mesh. Given processing means manipulation of the original data captured, therefore it follows that with this idea it is important to take into consideration two aspects that are relevant for the anthropometric data management: (1) the quality of the data, that can be modified by the processing algorithms; therefore it is important to quantify the deviation between original and processed data; and (2) the continuous progress and improvement of processing algorithms suggesting that regular updates of 3D body scan databases may be necessary.

From the point of view of data management, it is important to distinguish between individual data and aggregated data. Over many years, 3D body scans have been used basically for research in experimental studies or gathering databases to describe the size and shape variability of the population. The output of these studies is in the form of aggregated data, mainly statistical summaries or advanced 3D body models.

Nowadays, 3D anthropometric data is a key value in scientific and economic sectors like healthcare, consumer goods, or professional sports. According to the white paper of the 3D Body Processing (3DBP) Initiative of the IEEE

Digital Manufacturing Technology for Sustainable Anthropometric Apparel.
DOI: https://doi.org/10.1016/B978-0-12-823969-8.00007-1

(Stahl, 2017), advances made in the past few years in depth-sensing technologies and 3D body modeling have made it possible to create 3D scanners on tablets and smartphones at $100-250$ times lower the cost of initial 3D body scanners used for research. Hence, 3D anthropometric data is in nascent use to provide specific services to customers such as customized clothing or fitness tracking, or nutrition metrics. In these contexts, what is being used is individual anthropometric data. Whether as 3D models or body measurements, they are a kind of "digital twin" for a specific person; thus it may be necessary to deal with personal information during the data management process.

With current repositories of anthropometric 3D data being separate silos managed internally by different agents (e.g., research organizations, companies, hospitals), data management is a problem nowadays with the progress of big data and artificial intelligence sciences that are increasing the value of access to data. This is the century of data generation, and new initiatives and technology to share the data or to put the data in the hand of the customers will require protocols and tools to harmonize and integrate data from different sources. Standardization of 3D anthropometric data, interoperability, and security will become key elements to cause profit of existing datasets.

The following sections include a review of the processing methods to create usable 3D body anthropometry from 3D scans. The review analyzes, in a step-by-step manner, this process and discusses the potential effects of the technology on data quality, data management, and the need for qualified standards. The increase of 3D body data creation and the question of how to re-value these repositories are tackled from the perspective of the concept of a sustainable ecosystem proposed, including a description of the key elements that are necessary to generate aggregated anthropometric data for the clothing sector.

5.2 Creation of individual 3D anthropometric data

5.2.1 Processing 3D body scans

Measuring the body with a 3D body scanner can be a very fast process but carrying off a good 3D capture and performing a subsequent extraction of anthropometric measurements are complex. It requires experience and knowledge about the whole process and the factors that affect 3D body measurements. The pipeline from the 3D body scan to the calculation of body measurements entails the following steps (Fig. 5.1):

1. Calculation of the aligned point cloud: body scanners use several sensors to capture the full body surface obtaining different point clouds that should be aligned using calibration parameters. The resulting 3D body point cloud presents noise, missing information at occluded areas (e.g., under the armpits) and horizontal surfaces, and redundancies at overlapped regions scanned by more than one sensor. Depending on the technology used, the impact of the noise and artifacts over the resulting 3D body scan can be more or less significant.

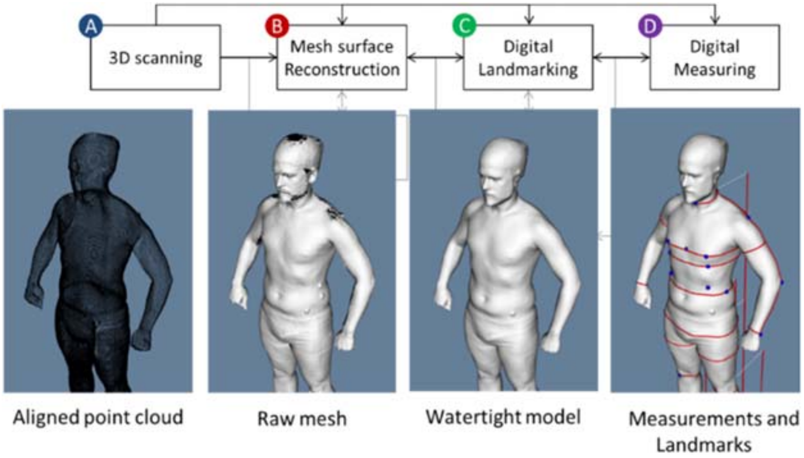


Figure 5.1 Pipeline of 3D body processing.

2. Generation of the 3D body mesh: The 3D point cloud is not very usable. It is an elemental representation of the 3D body that is not the best format to calculate metrics. Therefore after the point cloud is generated, a variety of algorithms (public or proprietary) are used to generate a 3D body mesh. This step usually includes additional processing such as smoothing the data, stitching partial meshes, filling the holes, and/or unifying normals. This is a manipulation of the original data that may add "fake information" that is not real and accurate and depends on the level of refining of the algorithms used. However, most of the scanners deliver directly the 3D mesh and users do not realize the level of quality of the information that they are using. If possible, it is recommended to store both the original point cloud and the processed mesh.
3. Calculation of landmarks: all body measurements are related to landmarks, that are points of the body referred to anatomical or geometric features. The identification of landmarks over the 3D body mesh is a critical step (Han & Nam, 2011). Most of the landmarks defined by standards are related basically to anatomical features or bony prominences that should be located touching the body. This is not compatible with contactless scanning and automatic measurement extraction. As a result, the landmark location criteria are re-defined using geometric features of the body instead of anatomical features, losing compatibility with current standards. This transition from anatomical definitions to geometric-based definitions is not standardized. As a consequence, different automatic landmarking software are not compatible with each other. The alternatives used, especially, in the research context are (Alemany et al., 2010; Robinette & Daanen, 2003): (1) use physical markers during the scanning process locating the bony prominences, where this option adds a new artifact to the 3D mesh; (2) manual landmarking of the digital scan, this is only feasible for easily recognizable points like the center of the eye but is not possible for the other anatomical points that are not replicated on the external body shape (e.g., acromion); and (3) a combination of both strategies. This approach of landmarking is time-consuming and is not usable in the case of new business applications that use 3D body scans of customers for clothing customization or size selection. In the last years, the advance of artificial intelligence (AI) has enabled the use of databases of body scans and landmarks located manually to train data-driven networks that may calculate the set of

landmarks automatically (Lovato et al., 2014). Again, this is an example of the importance of anthropometric databases and why processing and annotations, properly managed, are fundamental for the application of AI methods.

4. Calculation of body measurements: Using as a reference the body landmarks, different functions are implemented to obtain the body measurements (e.g., heights, widths, depths, girths) that are calculated by means of Euclidian distances, projected distances, full lengths over the body scan or using a convex hull. The mathematical definition implemented to obtain the body measurement is important to understand clearly the definition of the measurement and the compatibility of the measurement with other measurements obtained with other software. However, the information reported by most of the commercial 3D body scanning systems does not include this specific information.
5. Watertight 3D body model: For certain applications, it’s required to have a 3D body model closed, artifact-free, and with an invariant topology of the mesh. This format is useful to prepare the body avatar to be integrated with other software in virtual simulation or virtual design of clothing. This processing step, generally referred to as surface registration, is especially relevant to apply shape analysis methodologies to a database of 3D body shapes. The obtained body shapes present a mesh with point-to-point correspondence, as well as are watertight and faithful to the scan while being robust to its noise. Allen et al. (2003) proposed an optimization-based template-fitting method that fits a common template to every scan. The optimization is based on minimizing three terms: the surface distance between the template and the scan, the distance between a set of landmarks that guides the matching, and a regularization term that prevents an excessive deformation and keeps the result smooth. After this processing, all the 3D body scans are standardized to the template topology and are prepared for the generation of a parametric model using shape analysis. In some cases, this processing step is carried out before the calculation of landmarks and the taking of measurements taking advantage of the smart organization of the data points.

5.2.2 Data-driven 3D reconstruction of individual human models

The statistical methodology, Principal Component Analysis (PCA), has been used to analyze 3D body features and to generate a parametric morphable model (Allen et al., 2003; Magnenat-Thalmann & Seo, 2004). PCA requires a representative dataset of 3D body scans previously processed to the same topology with point-to-point correspondence. Before performing the PCA, the processed scans must be aligned which can be done by using generalized Procrustes analysis in which the scans are aligned to the mean shape iteratively until convergence. Another concern is to require the scans to be in the same pose (Danckaers et al., 2019). In general, the scans are placed in the standard, well-known A-pose that is optimal to minimize the occluded areas during the scanning process. For applications such as automobile safety, PCA models have been developed in a seated posture (Park et al., 2017).

The result of the PCA is a compression of the data into a reduced set of variables that can be used to control the body deformation within the space of shapes of the training database. This parametric model can be used to synthesize new individuals by sampling the variance distribution that the PCA represents. The components with a low variance of the PCA are discarded since there are references to detailed features of the body that are not relevant for the product design or ergonomics. In this way, an unlimited number of new individuals can be created with a realistic appearance but which do not look like any particular individual from the training dataset.

The human body is articulated, and digital human models are required in multi-postures or movement. Several models encode the variability of the body in terms of both pose and shape (Anguelov et al., 2005; Hasler et al., 2009) combining the PCA with an internal skeleton to control the pose, which is the most prevalent approach for changing the pose of a scan. Skeleton models associate each vertex of the scan with one or more bone segments that move rigidly (Jacka et al., 2007). The advanced SMPL (Loper et al., 2015) trained with a given a set of registered scans of different people in different poses enables the generation of a person with an arbitrary shape and pose with more realistic soft tissue deformation.

The parametric shape and pose body models are being used as a tool to create individual 3D body shapes using different types of input data that can be measured in nonlaboratory environments (e.g., at home, in shops) by nonexperts without knowledge of anthropometry and body measurements. Three methods are reported in the current literature (Alemany et al., 2019) (Fig. 5.2):

5.2.2.1 Creation of individual 3D body models from anthropometric measurements

This implementation broadly consists of learning a linear regression between body measurements and weights obtained from the PCA (Baek & Lee, 2012; Koo et al., 2015; Reed et al., 2014; Wuhrer & Shu, 2013; Zeng et al., 2018). The training dataset used to obtain the model is usually limited; hence, the resulting 3D body model will be more or less close to the input measurements, depending on the number of body measurements used as input and the atypical values of the input compared to the dataset. To solve this limitation, (Wuhrer & Shu, 2013) introduces a technique

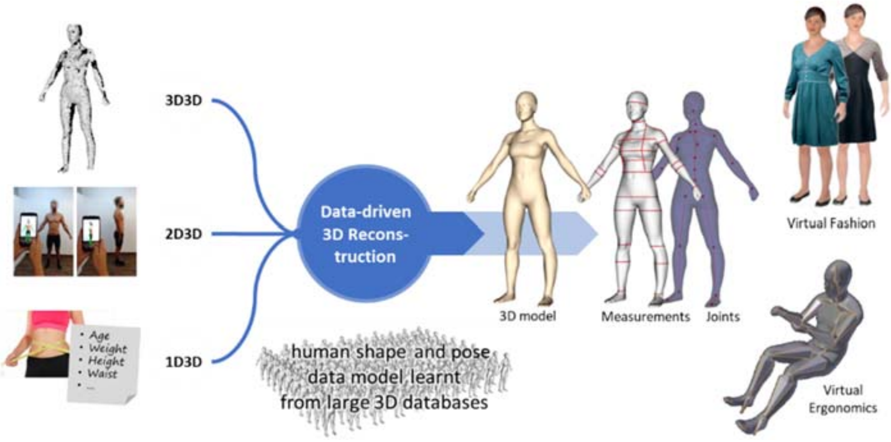


Figure 5.2 Creation of individual 3D body models using data-driven models.

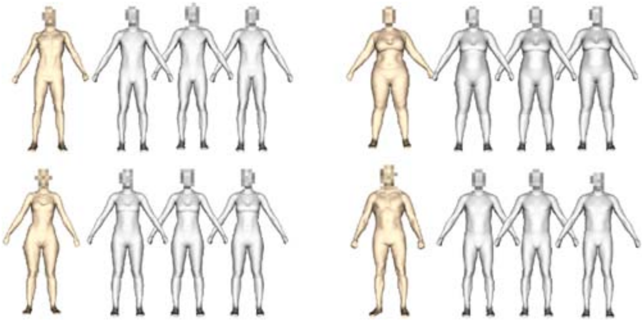


Figure 5.3 3D models of four subjects: 3D reconstruction from scans (golden, left) and 3D reconstruction from measurements with 3 (age, height, weight), 6 (age, height, weight, chest girth, waist girth, hip girth), and 7 (age, height, weight, chest girth, waist girth, hip girth, crotch height) parameters (silver, right).

that extrapolates the statistically inferred shape to fit the measurement data using nonlinear optimization. This approach to create 3D body models works properly when the anthropometric data used are digital body measurements obtained with a precise method from 3D body scans. It is also crucial to assure the compatibility of the 3D body measurement definition between the input measurements and those used to train the model. Examples of the visual comparisons of the 3D bodies created from measurements and the 3D models created from 3D scans are provided in Fig. 5.3. In some of these examples, the addition of measurements just slightly improves the 3D reconstructions (Ballester et al., 2018).

A potential clothing application of this methodology to create individual 3D body models from measurements is related to virtual try-on environments used in the design of new shopping experiences (Santesteban et al., 2019; Yang et al., 2018). Using this technology from home, customers can measure themselves manually and configure their body model. However, customers are not reliable in taking the body measurements; hence, it is important to reduce the input variable to a minimum. (i.e., gender, age, stature, and weight). An example of this application is presented by Ballester et al., 2014 who illustrates the potential of the data-driven recreation of human shapes from a small set of 1D measurement data, comparing these to a 3D representation created with other 3D human models all based on 11 measurements taken from two real women. Results show a more realistic representation of data driving methods.

5.2.2.2 Creation of 3D body models from images

In this approach, the PCA values are calculated optimizing the distance between the 3D model projections and the outlines of the body obtained from the image segmentation (Ballester et al., 2016; Mok & Zhu, 2018; Saito et al., 2014; Seo et al., 2006; Smith et al., 2019; Xi et al., 2007; Zhu et al., 2013). Most of the methods specifically use a frontal and lateral image of the body (Fig. 5.4). An alternative

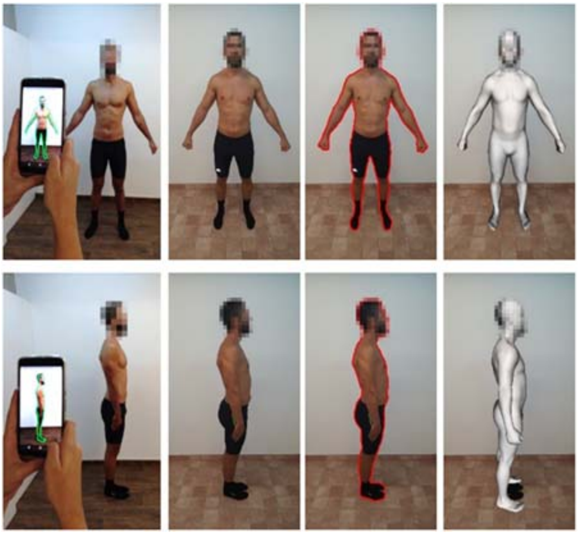


Figure 5.4 3D reconstruction process from images (Ballester et al., 2016).

method proposed by Amazon Body Labs (Smith et al., 2019) estimates a detailed 3D scan from a single RGB image that is translated to depth and albedo values in image space.

5.2.2.3 Creation of 3D body models from low-cost scanners

Affordable 3D depth sensors have promoted the development of 3D body scanning solutions that can be used in scalable business applications. The raw point cloud obtained with these scanners is noisy and presents holes and artifacts due to the duration of the scanning process and the type of sensors used, basically the time of flight. The methods developed to achieve optimal 3D body models in this type of scan use a shape and pose model that can be adjusted to the point cloud filling the holes and smoothing the surface of the original scan (Lu et al., 2018; Park & Reed, 2014; Tong et al., 2012; Weiss et al., 2011) (Fig. 5.5).

Comparing the three methods, it can be observed that the shape of the body becomes more detailed as the amount of input information increases (Fig. 5.6). This is significant in the case of the face. Only with actual 3D body scans the real face of the user can be captured providing a better self-identification experience. In this case, 3D body models can be considered in some way as personal data, requiring a thorough data management structure and protocols to meet the current regulations.

Nowadays, many applications are using these methods to create individual 3D body models, given some of them are visualization (e.g., the virtual trying on of clothing, animation), some are digital anthropometry extraction for retail (e.g., bespoke clothing, size recommendation) (D'Apuzzo & Gruen, 2009; Istook & Hwang, 2001), some, sport (e.g., training monitoring), and some, health (e.g., obesity monitoring)

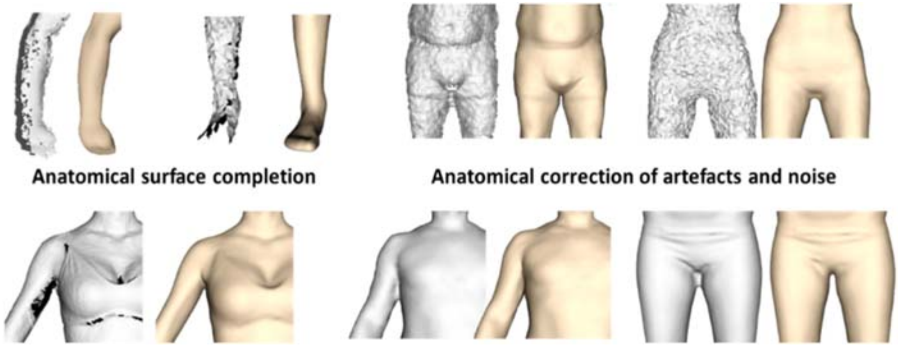


Figure 5.5 Examples of 3D reconstruction of a high-resolution scan and a noisy scan (Ballester et al., 2018).

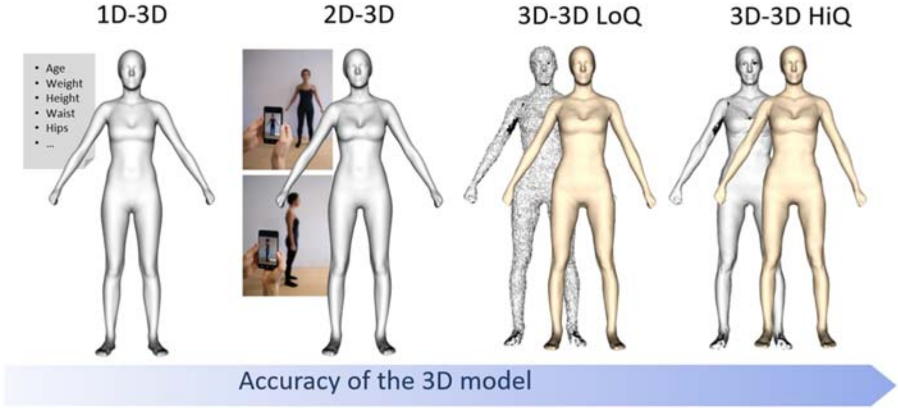


Figure 5.6 3D body reconstruction of the same subject using different methods (Ballester et al., 2018).

(Treleaven & Wells, 2007). Each of them is designed for a specific context of use and should meet different requirements in terms of reliability, body features and measurements, visualization of the data, and posture of the user during the capture. The difference in the range of available methods used to create a 3D body models provides flexible options to design the optimal process.

5.3 A sustainable ecosystem for anthropometric data management and re-valorization

Anthropometric data is a key value-add for the clothing sector. Fitting and sizing are both main issues for companies and also for the customer who has problems finding good-fitting garments. Hence, more than 20 large-scale national or specific population surveys have been conducted across the world using 3D body scanning technologies of different kinds (Durá-Gil et al., 2019) most addressed to the apparel industry to contribute to the improvement of the fit of garments. In this respect, the apparel industry was a pioneer sector using and adopting 3D scanning technology to take body measurements.

Although the economic investment required for large-scale 3D body surveys has been very high, the exploitation of the surveys and industry uptake of the results obtained from these studies have not been comparable. The 3D body databases gathered with a high economic investment was a boost to a fruitful period of research but they were generated too early for the massive adoption in the design and manufacturing processes of the clothing companies. The lack of common guides for patternmaking, the voluntary character of sizing standards, the different language and definitions of body measurement, and the lack of common criteria and rules relating to body measurements and garment measurements are the main barriers to the transfer of the results of anthropometric surveys to the apparel industry (Ballester et al., 2014).

Nevertheless, these projects and the databases, obtained, boosted the development of different tools to enhance clothing fitting. Some examples of these results are the new 3D mannequins, physical and virtual, designed with realistic dimensions and body shapes [https://alvanon.com/ 2021 (March 31, 2021); https://www.avalution.net 2021 (March 31, 2021)], portable and low-cost 3D body scanning systems for retail applications (https://3dlook.me/ 3DLOOK, 2021; https://www.ibv.org/en/3d-avatar-body-3/ Instituto de Biomecánica, 2021) and virtual try-on software that includes more biofidelic libraries of 3D bodies [https://browzwear.com/ 2021 (March 31, 2021); https://www.clo3d.com CLO Official Site, 2021].

Nowadays, the successful experiences reported by early adopters of 3D body scanning technology and the digital transformation process that companies are undergoing in the clothing sector have meant an inflection point in the adoption process from slow to pick up in speed that may accelerate the integration of digital body dimensions and shape in the value chain of clothing. Each brand requires information about how the body shape of its customers at its variability considering the specific niches is addressed in terms of age range, geographic locations, and/or preferences. 3D body scan databases, and the transference to the industry by means of sizing tables, digital mannequins have today more value than ever. At the same time, advanced technology, such as 3D body capture apps, body scanners for brick and mortar stores, online virtual try-on solutions, clothing customization solutions, or size selection services, are under exploration or in the piloting stage by many companies. However, several reasons suggest the need for and update of 3D body databases: (1) most of the 3D body databases were gathered more than 15−20 years ago; (2) some of the studies were done with experimental scanners with lack of standards; and (3) the use of current databases are limited due to ownership conditions.

New 3D body data pools are essential resources to improve the fitting of new products while analyzing the data in aggregated form. For clothing applications,

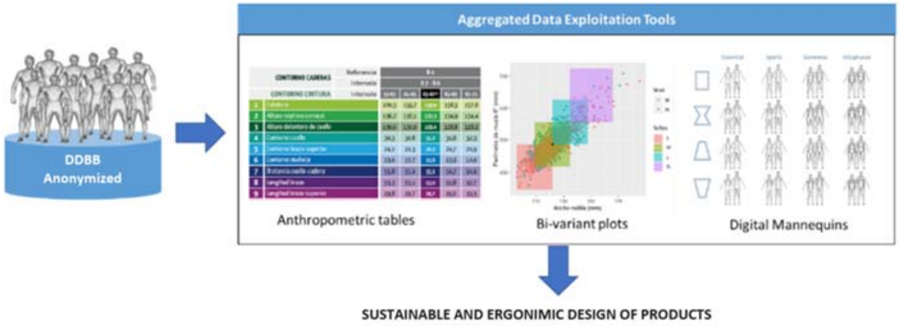


Figure 5.7 Aggregated data obtained from 3D body anonymized databases and used to improve the fitting of the clothing.

data analysis can also be extended to any other wearable product, but there are three main tools to generate aggregated anthropometric dimensions and 3D body shapes to improve and optimize fitting: anthropometric tables, bi-variant plots, and digital mannequins (Fig. 5.7). The results obtained with these tools are highly dependent on the data repository used, the partial selection done to represent the target population of the new product, as well as the algorithms used to process the data. The ideal situation is to use contemporary data with a representative sample size distributed in age and geographic locations. However, this is not possible with the current available anthropometric databases.

In the era of big data, the vision is to build a sustainable ecosystem to generate new 3D body databases. Nowadays, many start-ups and well-established companies around the world are setting up the offer of new products and services supported by the creation of individual body models. The generation of new datasets by streaming in different environments and contexts of use is being set a trend that will drastically increase the growth of the number of 3D body scans measured worldwide (Fig. 5.8). In this context, different players developing new business solutions around the 3D body scanning technology and creating different types of 3D body data will have to face the results of fragmentation and incompatibility across datasets (Stahl, 2017). Although this is not relevant for the use of individual 3D body models for customized services (e.g., bespoke garment, a size recommendation, virtual try-on visualization), the exploitation of the data in aggregate form requires special attention to the compatibility and harmonization of the data.

A system to share anthropometric data would allow the different data consumers to get access to larger datasets and also to reduce the data acquisition costs, increasing their scientific or business opportunities. Besides, data holders would be able to extend the economic benefit reported by their data.

The development of an effective data-sharing environment is challenging. Success requires a system that gives support to interests from any participant, forming a symbiotic ecosystem. Participants of a data-sharing system can be categorized as data providers and data consumers. Regarding this categorization, the

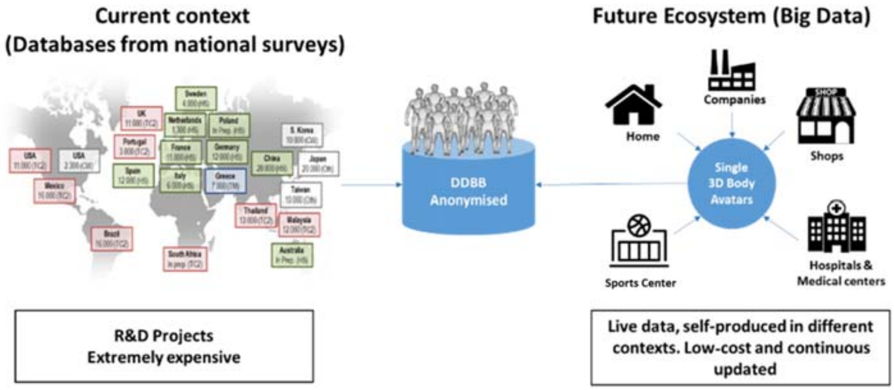
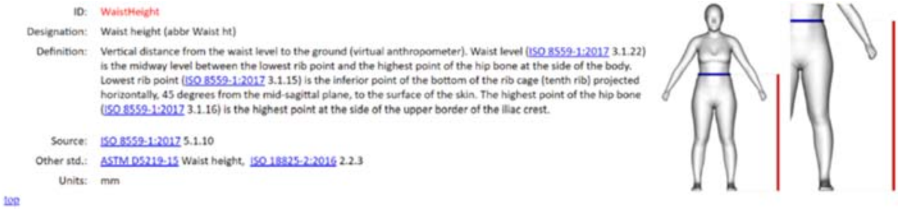


Figure 5.8 Concept of the future ecosystem of creation and management of 3D body databases.



ID: WaistHeight
Designation: Waist height (abbr Waist ht)
Definition: Vertical distance from the waist level to the ground (virtual anthropometer). Waist level (ISO 8559-1:2017 3.1.22) is the midway level between the lowest rib point and the highest point of the hip bone at the side of the body. Lowest rib point (ISO 8559-1:2017 3.1.15) is the inferior point of the bottom of the rib cage (tenth rib) projected horizontally, 45 degrees from the mid-sagittal plane, to the surface of the skin. The highest point of the hip bone (ISO 8559-1:2017 3.1.16) is the highest point at the side of the upper border of the iliac crest.
Source: ISO 8559-1:2017 5.1.10
Other std.: ASTM D5219-15 Waist height, ISO 18825-2:2016 2.2.3
Units: mm
top

Figure 5.9 Detail of the definition of a metric in the anthropometric Instituto de Biomecánica dictionary.

participants will have, at least, the following requirements (Ducret et al., 2020; Gil et al., 2020): (1) A data provider will want to preserve its data, avoiding other users from replicating his dataset. Also, due to legal restrictions, a data provider may need to anonymize any data before sharing it; (2) A data consumer needs to know, in detail, the type of data available at any dataset (a sort of data dictionary). The availability of tools to query for specific data (i.e., data filtering tools) is another important requirement (Fig. 5.9).

An optimal capitalization of the data following this new approach requires addressing three main challenges:

1. Standardization and interoperability of the anthropometric measurements and the 3D body modes. It is necessary to assure compatibility between the datasets and the integration for any application. Two elements of the anthropometric data are the key to achieving compatibility:
   a. The design and creation of an anthropometric data dictionary that clearly defines every metric. This dictionary must be open to all users and data providers, so they can validate that metrics in their databases are compatible with that in the dictionary (e.g., same metric units are employed in all databases).

  - **b.** To agree to a common 3D body template mesh. Such reference mesh can act as a kind of "Rosetta stone" to translate body semantics between different mesh topologies and allow the building of compatible body surfaces coming from different sources. It is also the basis to align the anthropometric data (body measurements, landmark, joints, and shape) over a common compatible structure.
- **2.** Compliance with personal data protection regulation. The possibility of data anonymization is a basic tool for the managing and exploitation of the data.

5.3.1 The anthropometric data dictionary

To measure a human body presents important challenges stemming from the difficulty to meet key features as repeatability, extrapolation of metrics, or accuracy (Gordon & Bradtmiller, 1992; Gordon et al., 1989; Kouchi & Mochimaru, 2008; Kouchi et al., 1996). Some problems rely on the fact that the human body is not rigid, but a soft, articulated, and never a fully static body. Some other problems rely on the measuring tools, methodologies, or different interpretations of the metric. For these reasons, anthropometric data has motivated several research efforts to standardize and effectively measure a human body (ASTM International, 2015; ISO 18825−1:2016, 2016; ISO 7250−1:2017, 2017; ISO 8559, 1989). Although these standards are a reference to harmonize protocols for both, traditional and digital anthropometry, a reality in the case of anthropometric measurement definition is that they introduce misunderstandings while comparing with databases from different sources. Each standard includes slightly different sets of anthropometric measurements depending on the application addressed. In addition, anthropometric measurements that are included in several standards are not always defined in the same way or refer to the same anatomical point or posture.

For the particular case of digital body measurements, the majority of the systems did not include a detailed description of the measurement definition. The interpretation of the standards to implement the body measurements is not clarified and there are discrepancies among measurements leading to, for instance, different definitions for the same designations.

In the context of combining datasets of 3D body scans and sharing data to obtain a harmonized data pool, it is necessary to include: (1) an automatic digital measuring tape (Ballester et al., 2014; Ballester et al., 2018) and the anthropometric data dictionary based on international standardization efforts from organizations as ISO[1] or ISAK[2]. Every metric is defined by the following fields:

- **1.** Mandatory fields:
  - **a.** ID: code that identifies the metric. It is defined as a string that partly includes the metric designation.
  - **b.** Designation: it is a self-descriptive name of the metric.
  - **c.** Definition: unambiguous description of the metric.

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[1] International Organization for Standardization (http://iso.org).

[2] International Society for the Advancement of Kinanthropometry (https://www.isak.global/Home/Index).

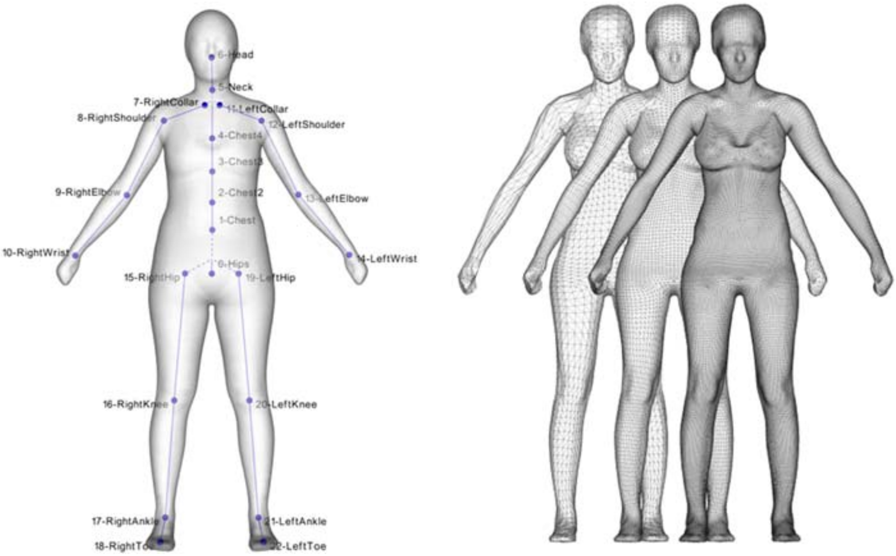

Figure 5.10 Left: Template and skeleton. Right: Multiresolution topology templates.

   - **d.** Source: reference to the company or organization that defined the metric. It usually refers to a standard definition.
   - **e.** Other std.: other standard definitions that can be compatible with the metric are defined.
   - **f.** Units: metric units employed.

2. Optional fields:
   - **a.** PartnerCodes: list of tuples "partner-code" where partner represents one of the project's partners and code is the internal ID used on the partner's database to identify the metric.
   - **b.** Media: URLs to media files (images, 3Ds, or videos) that facilitate the metric understanding.

The anthropometric data dictionary created by the IBV includes about 100 body metrics and is available via API. To facilitate the dictionary consultation to data providers, IBV lists all the metrics available on a webpage[3]. For every metric, the web displays the content of all the mandatory fields and also the related images in the dictionary. Fig. 5.10 shows the description of a metric in the aforementioned webpage. This particular metric is defined in three standardization international publications, two from ISO and one from ASTM[4]. Its definition includes two images that facilitate its understanding.

In this way, the anthropometric data dictionary, or data catalog is a semantic annotation of data that enables one to accomplish seamless integration with and smart access to the various heterogeneous data sources.

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[3] https://services.ibv.org/3dmodel/doc/DigitalMeasuringTape_3dModel.html.

[4] American Society for Testing and Materials (http://astm.org).

5.3.2 The 3D body templates

The harmonization of 3D scan data consists of fitting the same template mesh topology equipped with a skeleton to the surface of each of the raw scans of a database, obtaining a homologous structured representation of all the individuals in the database with point-to-point correspondence (Fig. 5.11). Then, the skeleton can be used to revise all the individuals of the database to the same posture.

The template structure used by IBV was developed by Ballester et al., 2014. It is constituted by a single closed mesh surface made up of 49.530 vertices, 99.056 triangle faces, and a 17-bone and 14-joint skeleton (Fig. 5.10). Its structure features a high local density providing sufficient resolution for an accurate representation of body shapes from 3D raw scan data (i.e., point-to-point average error below 0.5 mm) and light enough to follow a multivariate analysis of large target population selections (i.e., thousands of individuals).

The process consists of three main steps: preprocessing, template-fitting, and posture harmonization, and it is a requirement to perform in advance the statistical analysis. This structure enables the association of anatomical references/landmarks

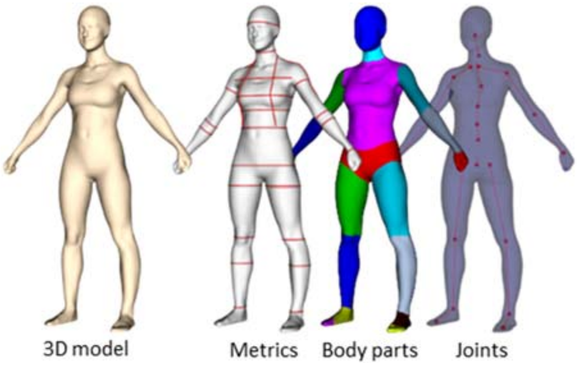

Figure 5.11 Anthropometric semantic data structured over the 3D body models generated according to the 3D template: metrics, body parts, and joints.

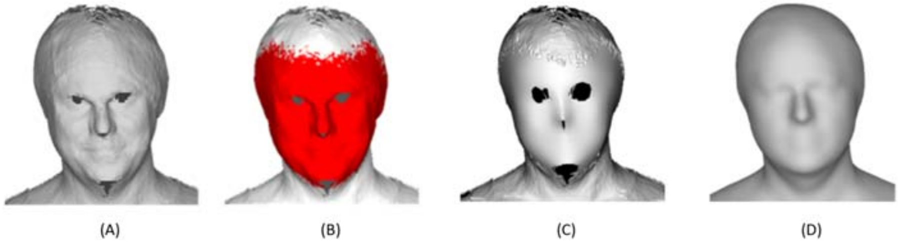

Figure 5.12 Anonymization process: (A) raw scan; (B) automatic identification of vertices in the face; (C) smoothed face (anonymized raw scan) and (D) synthetic face (anonymized 3D body model).

to concrete vertices, the segmentation of the mesh into its different semantic parts, and the adoption of a virtual skeleton (Fig. 5.12). Therefore this property can be used to support the further steps of calculation of landmarks, body measurements, the internal skeleton of the rigging, and to facilitate the integration with other software used in apparel (e.g., 3D virtual simulation, patternmaking).

5.3.3 Anonymization of 3D anthropometric data

According to the General Data Protection Regulation (GDPR) of the European Union (EU), personal data is defined as any information relating to an individual that can be used directly or indirectly to identify an individual. GDPR applies to companies or entities that collect and handle personal data from EU-based individuals, regardless of where the data is processed. The 3D body scans can include personal data in the texture. Although the 3D body scan excluding the texture is not recognizable, it is more secure to remove the 3D facial features. A sustainable ecosystem designed with a vision of adding new data and re-using it in aggregated format recommends including a step of anonymization.

Durá Gil et al. (2020) propose a methodology that incorporates a synthetic human face to every 3D body model. This is performed in a three-step process:

1. The first step identifies the vertices in the raw scan that lay on the model's face.
2. Then, the identified vertices are removed, obtaining a de-faced scan.
3. Finally, the registration process of the 3D body scan will add a synthetic human-looking face to the avatar.

This process presents two main challenges: first, to identify the vertices in the raw scan that belong to the model's face; and, second, to provide the 3D model a human-like face. To identify the vertices which lay on the face, we use AI, in particular, a convolutional neural network. The development of such networks required the exploitation of a large dataset generated in previous projects. The dataset was used to train the network and improve its effectiveness.

The computational kernel developed presents a high performance. Although the time-to-solution highly depends on the number of vertices of the input 3D object, still the regular mesh based on a template can be processed in just a few seconds. In addition, the algorithm presents a high degree of parallelism, allowing the use of massively parallel architectures like GPUs. This brings the possibility to further optimize the kernel, if needed.

Once the vertices are identified, they are removed from the 3D object, obtaining a de-faced version of the raw scan (Fig. 5.12). The anonymization for the raw mesh is done with smoothing algorithms.

Finally, the last step is again a challenging process, we remove artifacts from the input data, including tasks such as hole-filling and noise removal. This is performed using a template-fitting approach (Allen et al., 2003), which provides a realistic 3D closed body model. This process is capable of replacing missing data, that is, holes in the original mesh, with realistic data. In the case of the face, this process means that the final 3D body model will have a face that will perfectly fit the rest of the 3D body model and also present a human flavor.

5.4 Conclusions

This chapter includes a review of the value chain of the anthropometric data. It points out that anthropometric data are not only body dimensions but also other body data such as landmarks and 3D body shapes. The pipeline to process 3D body scans obtaining the usable anthropometry has been described to emphasize the need of controlling the quality of the process and the compatibility.

The relevance of 3D anthropometric databases has been demonstrated in the state-of-the-art with different applications: (1) improvement of the product fitting; and (2) the potential of data-driven 3D body models that are used to create, and are an easy way of generating, 3D body models. Thus it is important to enlarge current anthropometric databases trying to rethink with a sustainable alternative to expensive large-scale surveys. For this purpose, it is essential to assure the harmonization of data obtained from different sources. The anthropometric data dictionary and the use of templates have been proposed as key elements of this standardization process. The difference between individual data and aggregated data as well as personal data versus nonymized data in the context of an anthropometric data management structure is also considered.

The scope of this chapter has been limited to static anthropometry; however, the irruption of 4D scanning technology is boosting the generation of anthropometric databases obtaining sequences of 3D body scans describing movements (Parrilla et al., 2019; Parrilla et al., 2020). The capacity of data generation of these systems is huge, and it includes additional data such as those related to the biomechanics of the body. Body measurements in any posture will be a new type of data resulting from these scanning systems. Today, more than ever, it is necessary to address the standardization of anthropometric data to avoid fragmentation of the research and resources worldwide.

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3D anthropometric i.Dummy for sustainable clothing design and fit*

6

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6.1 Introduction

The birth of a garment starts with the designer of the garment with questions such as what is "in fashion" and how to wear clothes from the designer's vision for a piece of clothing. Also, as important, are a designer's needs to know which are the garment sizes to make and which the customers to fit on a particular size. The fashion industry is made up of two branches: bespoke tailoring and ready-to-wear (prêt-a-porter). In the former, the customer's body measurements are taken for his clothes to fit him; and, in the latter, a preset range of sizes and dimensions are available for the manufacturer to follow with items ready to wear from the time it's put on the market. In the fashion industry, the range of sizes is derived from anthropometric studies carried out by various governmental, trade, or educational institutions; and, the studies are performed by taking sample subjects from differing population universes stratified by sample parameters, such as age, sex, location, etc. As such, studies can take a considerable amount of time and resources, and by the time they are completed, they may become historical data. Any population's anthropometric profiles are dynamic, that is, they are changing over time due to many factors, among them, mention may be made of age, immigration, racial mix, etc. The anthropometric data derived from the studies will have many statistical values, and it is up to the brands to interpret them into meaningful figures to construct their size charts (Chan & Fashion Design, 2015; Chan et al., 2013).

Due to their experience with and focus on meeting their customers' requirements, each brand interprets their size charts differently. To carry out better physical profiling of these sizes, a brand will procure dummies that are supposed to represent the physical sizes of their customers. Taking a hypothetical brand in the

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* Authors' Note: i.Dummy was originally invented and patented by Dr. Allan Chan and his research team at the Hong Kong Polytechnic University. It has fetched a number of awards including the Grand Award, the Design for Asia Award (DFAA) 2014, the World Intellectual Property Organization (WIPO) Prize and Gold Medal with Jury Congratulations in Geneva Inventions 2015, the Gold Award, and the A'Design Award 2015 and 2016. It has been successfully commercialized and used by the industry.

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United Kingdom, they identify five sizes to cover their customers' range of sizes, such as 8, 10, 12, 14, and 16; hence, they have to make available five different dummies to reflect the various sizes. This is costly in monetary terms and space and most of all, as mentioned, since anthropometric measures of population change over time it makes these dummies redundant in the end and not environmentally sustainable. This brought about the idea of a "3D anthropometric dummy" that can change its physical and morphological profiles to match the changing profiles of the current population/customers.

(Note: A dummy can also be called a mannequin, manikin, dress form, model form.)

6.2 Product design

The design of the "3D anthropometric i.Dummy" covers the following steps: (1) shape design involving 3D scanning body profile data preparation, (2) cross-section level design, (3) B-spline curve construction, (4) shape generation, (5) panels and kinematics design, (6) validation, and (7) development of the i.Dummy (Chan, Peng, et al., 2014).

6.2.1 Shape design involving 3D scanning body profile data

The initial shape of the dummy is built by generating a loft surface fitting through the body cross-section outlines which are presented in the form of a B-spline. The configurations of the cross-section are developed based on the scanning data of female subjects and dummy profiles. It involved the body profile data for shape extraction in which an alignment process is implemented.

The 3D body scan data was generated by parallel slices of points from the neck to the feet. The raw scan data was processed to transform the vertices and triangle mesh information to the vertices coordinates' information which is only in the form of the triangle mesh information. Fig. 6.1 shows the result of a sample of the 3D body scan data by the 3D body scanner, while the right figure shows the y-direction which is the front direction of the body, the x-direction which is perpendicular to the y-direction and pointing to the left-hand side of the body, and the z coordinate which is the perpendicular to the ground pointing upwards.

6.2.2 Cross-section level design

There are two main concerns on the layout design of cross-sections. The initial shape is designed, mainly, based on the 3D scanning body profile database. However, the age range of the body data might result in a bias to the initial body shape, especially, the size. Hence, a widely recognized dummy was used as a reference to set the vertical location of the cross-sections first as shown in Fig. 6.2 to compensate for the limitation. Hence, the initial shape size will be close to size 12.

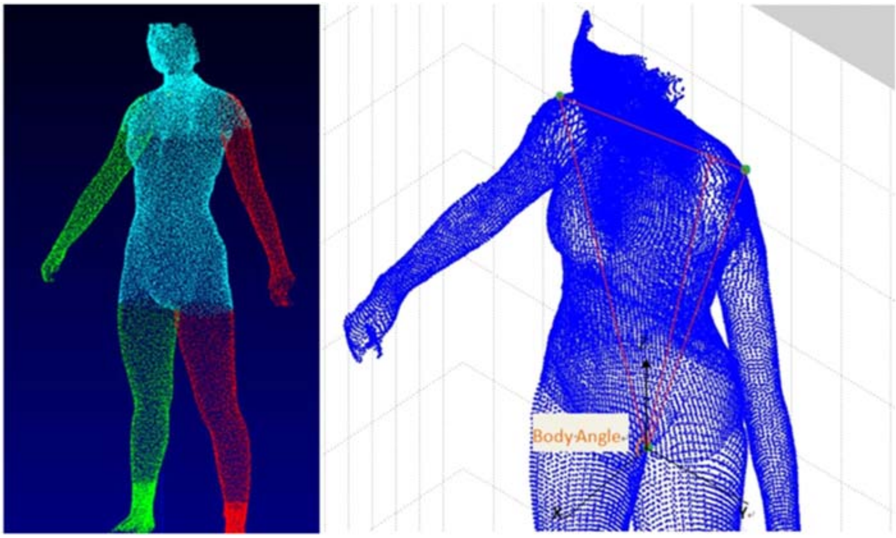


Figure 6.1 3D body scan data.

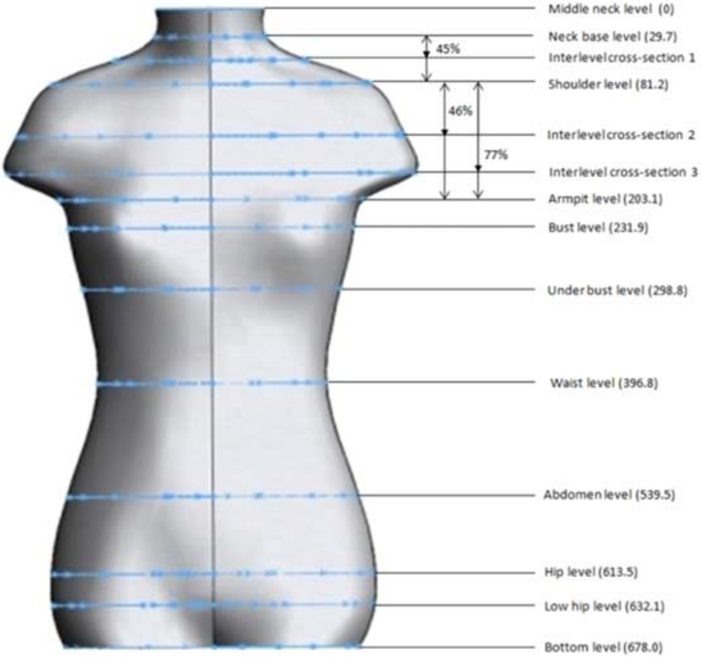


Figure 6.2 Layout of the cross-sections for the initial shape of the digital dummy.

The values in the bracket shown in the figure are the relative distance to the mid-neck level in millimeters.

The quantity and location of the cross-section setup affect the initial shape. On one hand, the initial shape can represent more details by increasing the number of cross-sections. On the other hand, more cross-sections will lead to a more concave-convex profile. As a result, the main cross-sections are relative to the critical body dimensions, such as neck level, bust level, waist level, and so on, which are built to ensure the important information for a garment design and fitting purpose have been reserved. The vertical locations of these levels are determined by the relative distance to the middle neck level, which is the average value of the corresponding values obtained by the 3-D body scanner. The interlevel cross-sections are then inserted to achieve a realistic and smooth shape as shown in Fig. 6.2. The location of the interlevel cross-section is specified by the relative height between specified main levels.

6.2.3 B-spline curve construction

The B-spline curve is generated by control points of a segment by Solidworks. The shape of the B-spline curve can be modified by adjusting the location of these points. The initial locations of these points are determined by the responding points of the 3-D body scanning profiles and the reference dummy. Fig. 6.3 shows the construction of the B-spline curve at bust level, which is identified by eight points. The level of the points with the height value proximate to its bust height from one aligned 3-D body scanning data was obtained to construct the curve. The two points whose angular values are the two closest to 0 degree were determined and their locations were averaged to find the first points for the B-spline curve. The points on the B-spline curve at the angle 23, 45, 66, 90, 120, 137, and 180 degrees can be obtained. The eight points for each subject can then be measured. All the eight

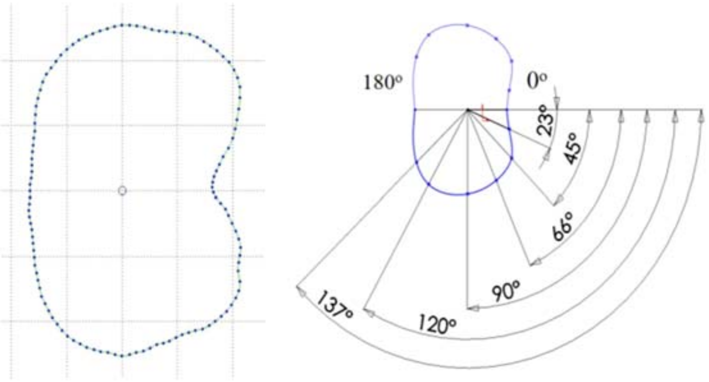


Figure 6.3 Cross-section at bust level constructed by the points and B-spline curve. Left shows the proximate level at the bust level. Right shows the average shape represented by B-spline curve.

points of the bust level were averaged, respectively, to obtain the final eight points which identify the lower segment of the B-spline curve. Since the left and right sides of the human body are assumed to be symmetric, the upper segment of the B-spline curve can be obtained by mirroring the lower segment as shown on the right side of Fig. 6.3.

6.2.4 Shape generation

The final profile of the shape is the surface created through the B-spline curves on all the cross-sections as shown in Fig. 6.4 using the lofted surface function of Solidworks, which can generate a smooth surface.

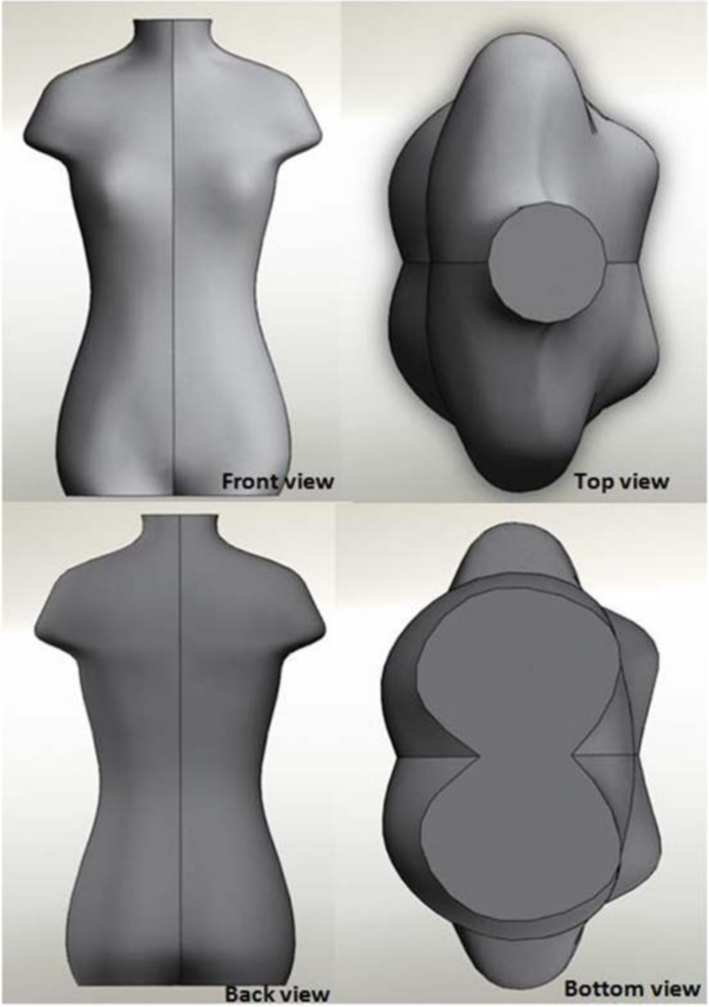


Figure 6.4 Layout of the cross-sections with different views for the initial shape.

6.2.5 Panels and kinematics design

The panels of the dummy were designed by separating the surface of the digital dummy. The kinematic design was then conducted to determine the movements of these shells. The dummy changes into various types of bodies by moving the shells to different positions; thus the virtual dummy became parametric. The parametric model surface was cut into 16 panels (Fig. 6.5).

The panels have the following important features;

1. There are gaps between the neck, chest, waist, and hips to accommodate the physical change.
2. The neck consists of two panels: left and right. The neck girth change is relatively small compared to the other panels.
3. From studying the 3-D body profile database and literature (Taylor & Shoben, 1993), it was found that the grading of major body sections is in the way shown as Fig. 6.6. The variation can be represented using 4 panels moving in four different directions as illustrated in Fig. 6.7. Hence, the chest, waist, and hip parts consist of four panels. The gaps between them are all 2.5 cm and the gaps are designed to close or expand to 5 cm. Thus the chest, waist, and hip girth can reduce and increase by 10 cm which is adequate to cover the adjustable size range. The gap can be covered using cladding made of highly elastic fabric.

6.2.6 Validation

Validation was conducted to verify the concept design of the robotic mannequin. The virtual robotic dummy demonstrated the shape variations from the minimum size to the maximum size. It also mimicked three existing dummies in the market which are Asian Size 10, 12, and US Size 8. These dummies were scanned and displayed in blue point cloud as shown in Fig. 6.8A, B, and C, respectively, were had. The panels of the robotic dummy were shown in yellow color while the red, blue, and green lines indicate the bust, waist, and hip girth, correspondingly.

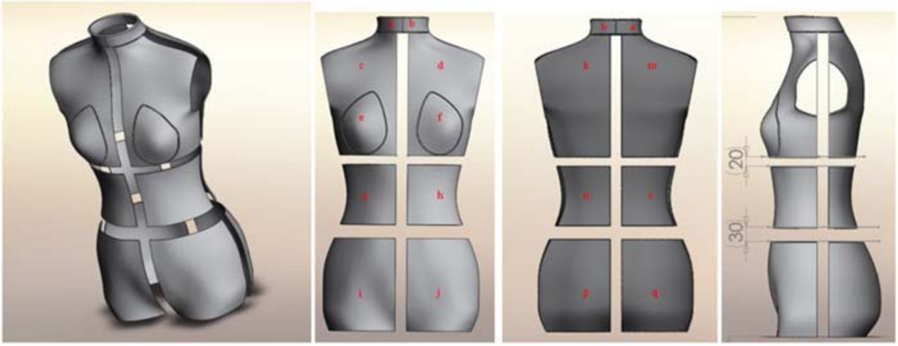


Figure 6.5 The resulting panels of the dummy.

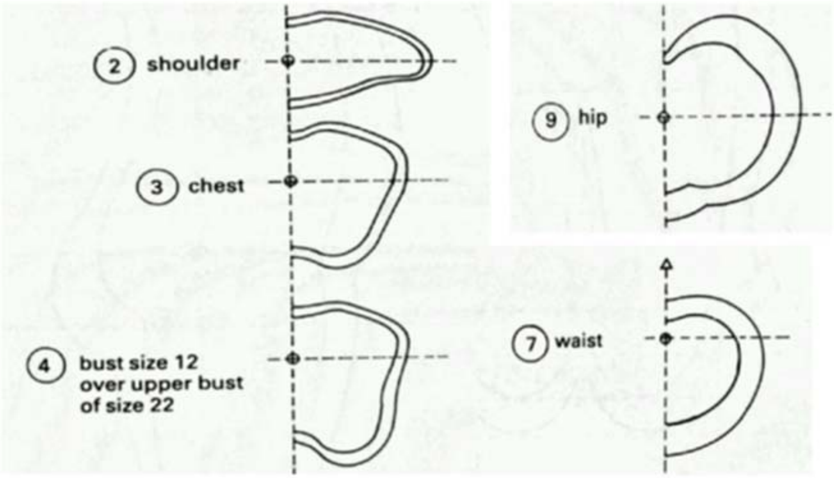


Figure 6.6 Major body sections of UK size 12 and 22 superimposed on each other.

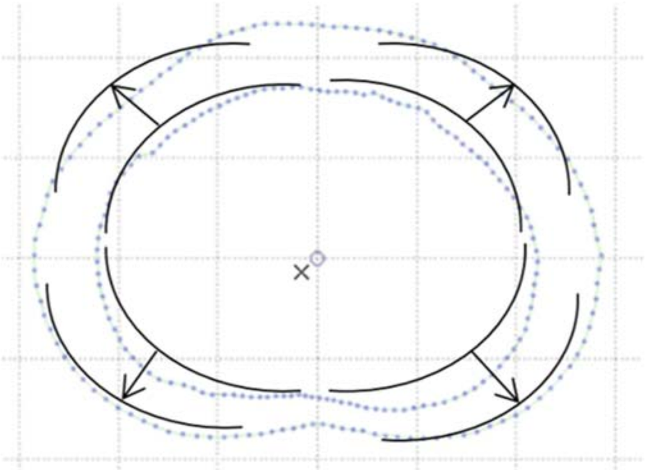


Figure 6.7 Dotted line shows waist cross-sections of 62 and 80 cm in waist girth superimposed on each other according to the center point. The curve and arrow show the general shape can be represented by moving 4 panels in 4 different directions.

6.3 Development of the i.Dummy's technology (hardware and software)

After the panels' design stage, the hardware of the i.Dummy and its motion trajectories were developed using mechatronics design, which includes the selection of actuators and their movement mechanism, control board system, control program,

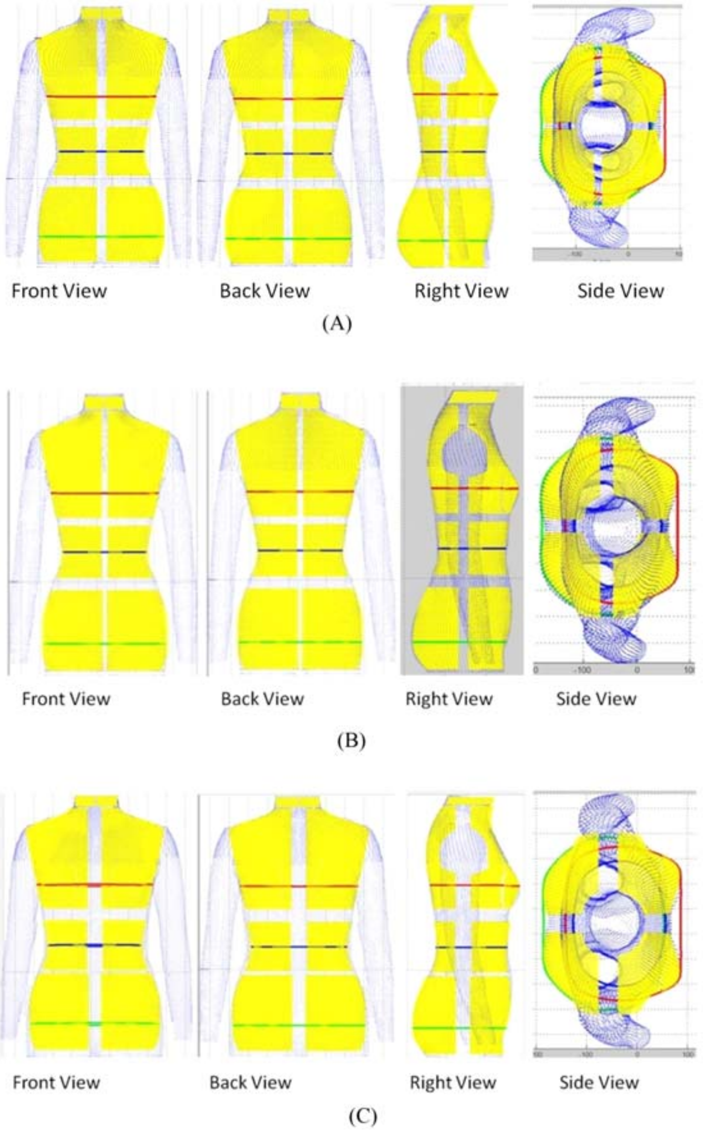


Figure 6.8 (A) Virtual robotic mannequin imitates the shape of an Asian size 10 dummy. (B) Virtual robotic mannequin imitates the shape of an Asian size 12 dummy. (C) Virtual robotic mannequin imitates the shape of a US size 8 dummy.

and user interface. The actual product development of the i.Dummy required product designers, and electronic and mechanical engineers to work together. A bottom-up approach was utilized (Mantyla, 1990) where existing components were selected and integrated into the i.Dummy; for example, the selection of a particular actuator

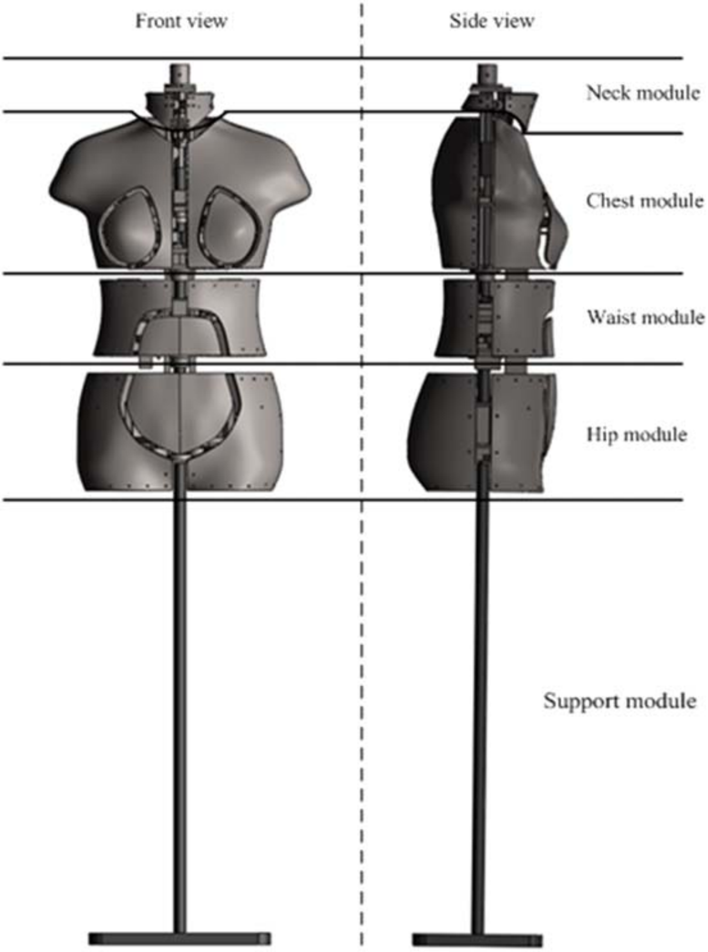


Figure 6.9 Module design.

(servo and linear actuators) and the complimenting components like mounting brackets must fit properly to create a holistic entity that functions or can mimic a person's body realistically. Fig. 6.9 shows the i.Dummy is sectioned by the various modules: neck, chest, waist, hip, and support.

6.4 Hardware design

The mechanical design included three stages. The first stage was the module design where the i.Dummy was divided into several modules: neck, chest, waist, hip, and support modules.

1. Neck module: this realized the change in the neck shape and girth dimensions.
2. Chest module: this realized the change in the chest/bust shape and girth dimensions.
3. Waist module: this realized the change in the waist shape and girth dimensions as well as adjusted the length of the chest-to-waist measure.
4. Hip module: this realized the change in the hip shape and girth dimensions as well as adjusted the length of the waist-to-hip measure.
5. Support module: this supports all the above modules in their functions and the entire weight of the i.Dummy frame to the stand.

The electronic system design includes three parts: servo actuators system, linear actuators system, and control board system.

Servo actuators system: The Servo actuator's (Fig. 6.10) working voltage is 5 V and input pulses could be supplied by a micro-controller or PCBA I/O board. Table 6.1 shows the specification of the servo actuators used in the i.Dummy.

Linear actuators system: the linear actuator (Fig. 6.11) can be driven by sinusoidal wave current. Ding's model 142047D4-200-915 was designed for the i.Dummy. Table 6.2 shows the specification of the linear actuators used which operate at a speed of 800 pulse/second, with a thrust of about 340 N.

Control Board system: The control board as shown in Fig. 6.12 was purposely designed and was able to communicate with Standard RS232 protocol; hence, i. Dummy can be controlled using a computer, a smartphone, or via the internet.

Software design: The software program was developed using Microsoft Visual Studio and the control commands were based on RS232 communication protocol.

User Interface design: The Graphical User Interface (GUI) is shown below in Fig. 6.13. As an example, the "Choose the preset config(uration)" contains the

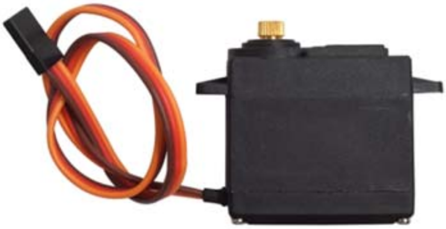


Figure 6.10 Servo actuator.

Table 6.1 Specification of Robotbase RB-150MG servo actuators.

Step angle	2-Phase with 1.8 degree step angle
Phase current	2.0 A
Phase resistance	1.2 Ω ± 10%
Lead wire number	4
Travel per step (1.8 degree)	0.0635 mm
Travel range	38.1 mm

Figure 6.11 Linear actuator.

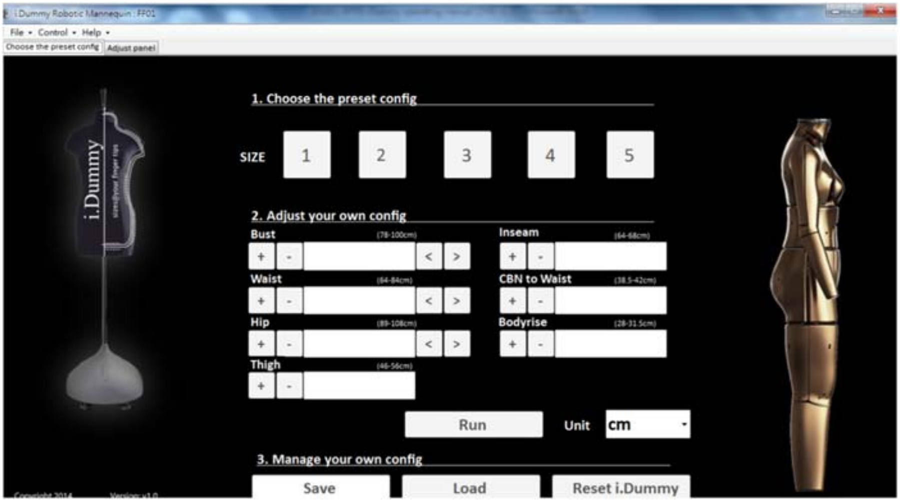
Table 6.2 The specification of Ding's model 142047D4-200-915 linear actuator.

Step angle	2-Phase with 1.8 degree step angle
Phase current	2.0 A
Phase resistance	1.2 Ω ± 10%
Lead wire number	4
Travel per step (1.8 degree)	0.0635 mm
Travel range	38.1 mm

Figure 6.12 Control board system.

required preset mannequin size from, say, UK6 to UK14 (size1 -size 5), and it can be customized according to the requirements of the Brand/User.

The "Adjust your own config(uration)." shows the preset size measurements in (cm or inches) the minimum size to be UK6, maximum size is UK16. Allowances can be adjusted via the (+) or (−) buttons so that size measurements can be changed, as needed, to reflect the changes in customers' physical profiles making it sustainable.



Unit cm

Figure 6.13 Graphical user interface of i.Dummy.

Lastly, the "Manage your own config(uration)" allows users to store any custom measurements as often used in bespoke or tailored garments. This is useful for storing individual measurements and can be changed anytime to update the person's body measurements.

6.5 Full range of i.Dummy series

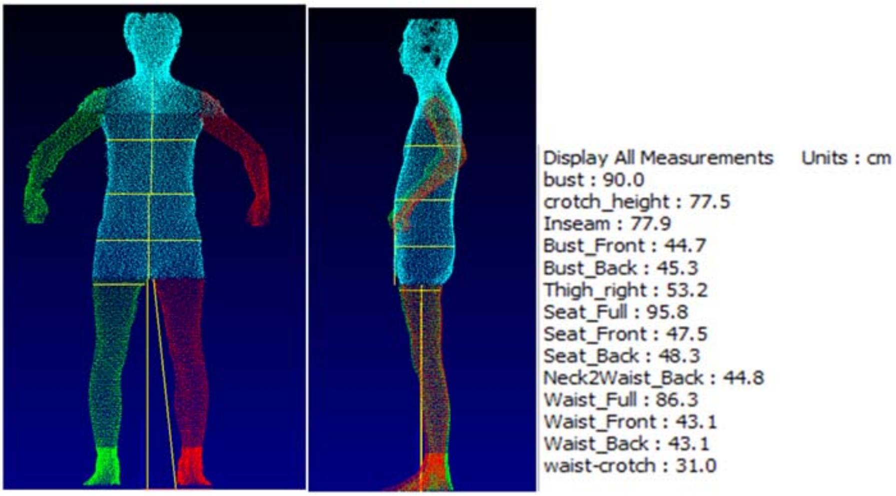
Apart from the initial female top body, the complete development of i.Dummy mannequins contains the below mannequins (Fig. 6.14):

1. Female bottom body (suitable for skirt, trousers, jeans, leggings)
2. Female full body (suitable for dress, overalls, skirt, trousers, jeans, leggings)
3. Male top body (suitable for shirts, jackets)
4. Male bottom body (suitable for trousers, jeans)
5. Male full body, (suitable for a full set of male garments)
6. i.Breast (suitable for brassieres design and fitting)

6.6 Connectivity of i.Dummy to a 3D body scanner

The i.Dummy can be connected to a 3D body scanner and can produce the shape of the person scanned. This can provide better flexibility to i.Dummy. The vital body measurements of the person (Fig. 6.15) are extracted from the body scan and relayed to the i.Dummy where the resultant body shape and dimensions are actuated. This is particularly suited for e-tailing or display at an online platform where the return rates by customers can be quite high (Chan, Yang, et al., 2014).

Figure 6.14 Complete range of i.Dummy robotic mannequins (extracted from product catalog).



```
Display All Measurements    Units : cm
bust : 90.0
crotch_height : 77.5
Inseam : 77.9
Bust_Front : 44.7
Bust_Back : 45.3
Thigh_right : 53.2
Seat_Full : 95.8
Seat_Front : 47.5
Seat_Back : 48.3
Neck2Waist_Back : 44.8
Waist_Full : 86.3
Waist_Front : 43.1
Waist_Back : 43.1
waist-crotch : 31.0
```

Figure 6.15 Scanned body measurements from a TC^2 body scanner.

6.7 Sustainable application of the 3D i.Dummy in clothing design and fit

The application of this technology is on the ladies' fashion including modeling/draping. Draping is the art of manipulating fabric directly on the dummy form in three dimensions. It is the most creative way for a designer to turn design ideas into reality. Fashion draping is an important part of fashion design. Draping for fashion design is the process of positioning and pinning fabric on a dress form to develop the structure of a garment design (i. Dummy for Fashion Design).

Using the i.Dummy for fashion design by modeling/draping technique, we first have a design on paper, say a sophisticated dress. We take the body measurements from our model and, with these measurements, we change the body profile of i.Dummy to match that of our model. Next, we put on cladding on i.Dummy and proceed with the muslin draping process of the required design. The muslin is taken from the i.Dummy and made into pattern pieces for cutting fabric. The cut fabrics are made into the garment and fitted on i.Dummy and model, respectively. You will see a close resemblance of the two (model and i.Dummy) in the end. (Fig. 6.16).

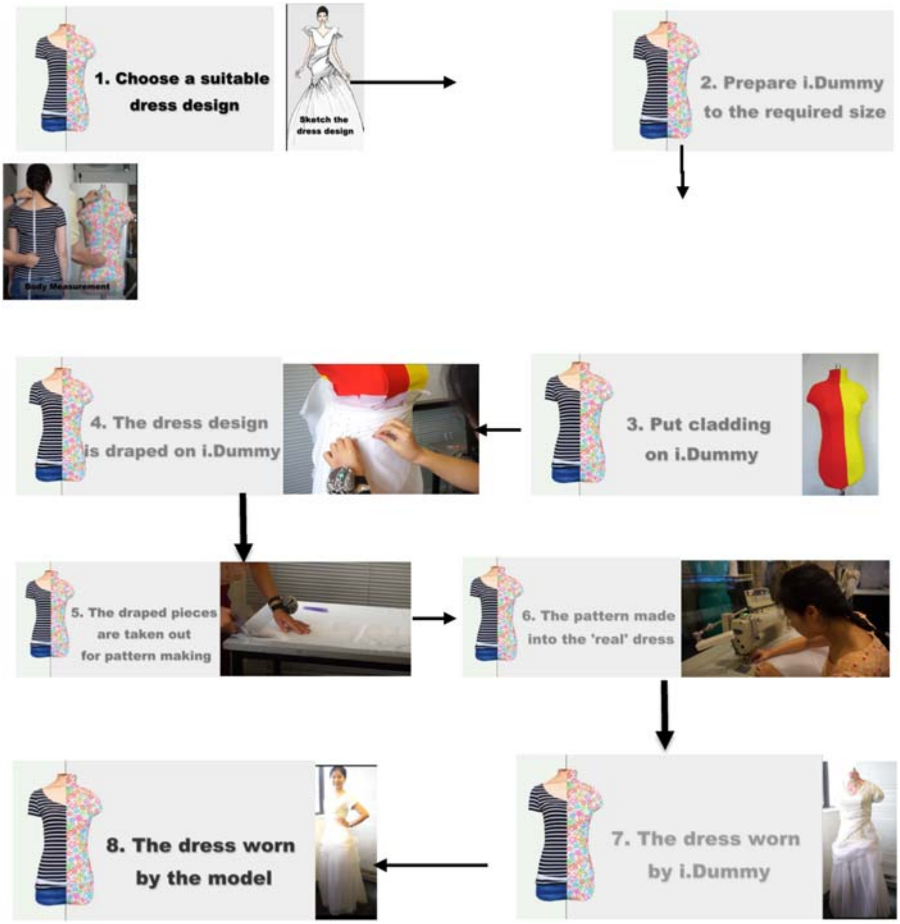


Figure 6.16 Using i.Dummy for modeling/draping a dress design.

6.7.1 Bespoke menswear

In bespoke menswear, it is very particularly needed that requirements are met with precision on the garment fit, besides the design and materials used. It is usual to call the client back to the tailor for fitting the mock to ascertain the body measurements taken initially are tallied with the fitting. Many a time, one fitting may not be enough and further fittings may be required which can be quite taxing to the "busy" client. With the i.Dummy, the client's body measurements can be entered into the customers' database list. This facilitates easy recalling out the required size when a fitting is required. Besides, when the client's physical configuration changes, it can be updated in the database and made current.

6.7.2 i.Dummy for fit assessment

As mentioned earlier in the chapter, there are many sizes in a Size Chart used in the industry. Unless one has a multiple number of dummies for each size, it is difficult to assess the fit of every garment. Adding in the probability of different markets, the amount of differing configurations of dummies will be quite high. Hence, i.Dummy through its software program can produce thousands of different physical configurations making it ideal for fit assessment of garments of any size and style.

6.7.3 i.Dummy use in technical fashion education

In many institutions offering academic or technical programs in fashion, pattern design, pattern grading, and garment making are subjects to be studied that are part of the curriculum. It can be seen that these institutions housed many dummies for fitting clothes made by the students. As most of them teach to a "Standard Size," many other sizes become unavailable for students to use. Here, i.Dummy can make it flexible to provide students with any customized body figures in three dimensions. They can be saved, recalled, and amended as necessary.

6.7.4 i.Dummy as a research tool

In several consumer product researches where body shapes are essential, i.Dummy has proved useful to these companies and research organizations as a tool to conduct accurate fit requirements so that garment fit can be attuned to different consumers in different countries.

6.7.5 i.Dummy for e-tailing platform

Understanding e-tailing in fashion is fast developing as a new mode of consumerism; however, there have been high return rates due to poor sizing and fitting of garments to the buyers. According to WAAM, it was recorded that one in three fashion products bought online will be returned to the retailer (i.Dummy for Fashion Design). One of the reasons is the ill-fitting nature of the garment vs the consumer. With i.Dummy, it is possible to receive the vital fitting body measurements of the consumer, load onto i.Dummy, and test the garment (which can be of many different brands in an online site). If it fits, the chances of the garment not fitting the consumer will be reduced.

6.8 Conclusion

i.Dummy as a sustainable tool in the fashion industry is proved. With its many models and versions, i. Dummy is fit to perform the various tasks associated with the fashion industry from design through to size-fit assessment, etc. It is left to the creative imagination of the fashion professional to make use of it to their advantage and for benefit of the industry.

6.9 Sources for further information

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3. i.Dummy smart mannequins—http://www.yinusainc.com/main/idummy-smart-mannequin
4. Robot meets mannequin—https://www.apparelnews.net/news/2016/feb/29/robot-meets-mannequin/
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10. i.Dummy, the revolutionary fitting system—https://www.youtube.com/watch?v = FDCfX_AK2I0
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Digital fashion technology: a review of online fit and sizing

7

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7.1 The evolution of online fashion-size charts

This section discusses how the sizing and sizing communication have developed from historic catalog shopping—with images and sizing information—to the online retail—with more detailed information of the product size, characteristics, and appearance made available to the consumer—and also charts a clear timeline. The online retail environment is a modern-day catalog experience with the consumers selecting garments according to images and descriptions and making selections against size charts. When clothing retail migrated online, it became necessary to provide further details than just the garment size to the consumer, and, currently, a size chart in the United Kingdom or United States contains details of the wearer's dimensions, not just the size of the garment by its size code. This increase in sizing information from sizing charts provides a unique opportunity to explore sizing, and whilst the data is a fraction of those required to develop a garment, it becomes a rich resource for the consumer, and for anyone else interested in understanding the dynamics of sizing, to understand abstruse data with a view to wise buying choices in future. Additional to size charts, many retailers offer further details to help the consumer make an informed and, hopefully, correct decision of what to purchase given returns are costly (Table 7.1).

Sizing as consumers experience it has a few distinct elements. For women's garments, there are the key dimensions of the bust, waist, and hip circumference. These are recognized by the ISO (International Organization for Standardization) standards (BSI, 2002) as the key (primary and secondary) sizing dimensions for different garment types. As well as these dimensions, there are drop values, i.e., the overall differences between these three circumferences so that a bust of 88 and waist of 72 would lead to a 16 cm drop value between the bust and the waist circumference. Drop values are illustrative of the shape characteristics of the brand of clothes sold by a retailer. Some retailers will sell clothes brands having a fixed drop value throughout their size range, whilst others may alter the drop value as it moves through the size range. Aside from the clothes' shape-related aspects of each size, there are grades (increments) which represent the key differences between the 2 parameters applied—proportionally or disproportionally—before taking the measurements for each size that dictates whether the shape is fixed or mixed for each retailer. The components of size and shape are illustrated in Fig. 7.1.

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Table 7.1 Summary table of UK womenswear retailers and summary of what consumers see when looking to purchase a dress.

Retailer	Sizing data	Product visualization	Product selection tools	Information required from the customer
ASOS	UK size range: 4–16	Model photos, product description, model catwalk video, zoom-in	Fit Assistant from Fit Analytics	• Demographic data: height, weight, age, tummy shape (flat, average, or curvy), hip shape (straight, average, curvy), bra-size • Fit Preference: loose or tight fit scale, preferred brands, and garment size
Tommy Hilfiger	US size range: XXS–XL	Model photos, product description, model catwalk video, zoom-in	Fit Finder from Fit Analytics	• Demographic data: height, weight, age, tummy shape (flat, average, or curvy), hip shape (straight, average, curvy), bra-size • Fit Preference: loose or tight fit scale
Acne Studios	US size range: XXS–L	Model photos, product description, zoom-in feature	Fit Visualiser from Virtusize	• Fit Preference: customer measure of similar garment dimensions: bust, waist, hip, and sleeve length

Diane von Furstenberg	US size range: XXS−XL	Model photos, product description, model catwalk, zoom-in	Try Me button from Style. Me	• Demographic data: height, weight, bra-size, belly shape (flat, average, curvy), body shape (hourglass, straight, pear, inverted triangle, apple) • Avatar customization: Customers can choose from the predefined face features, skin tone, hair color, and style
Marks & Spencer	UK Size Range: 8−18	Model photos, product description, zoom-in	Belcurves app. on a separate website	• Demographic data: height, bust, waist, hips, arm length
Zara	UK size range: XS−L	Model photos, product description, model catwalk, zoom-in	Embedded Fit Predictor: Prime AI	• Demographic data: height, weight, age, bra-size, select your figure, and shape form illustrations • Fit Preference: loose or tight fit scale

7.2 Predictive systems and their classification

The revenue in apparel e-commerce in 2020 was worth USD 110.6 billion and it is expected to increase to USD 153.6 billion by 2024 (Foysal et al., 2021). The huge cost of returns that cost the UK fashion industry almost £7 billion (Just Style, 2020) and the complexity of online not providing the simple direct-to-consumer service as anticipated have driven areas of development that seek to help consumers select the correct garment on the first purchase. Whilst a range of companies have been part of the development, fit analytics (http://www.fitanalytics.com) and fits me (http://www.fits.me) are currently the major players embedded in retail interfaces. These systems support consumers in assessing the fit of clothes based on body data, preference data, and experience of known brands to give predictions of consumer satisfaction with the fit of a given size. These systems have been in steady development and it’s hoped these will support retailers in reducing returns and creating a more sustainable consumer shopping experience.

7.2.1 Development of online fit systems

Virtual fit interfaces (VFIs) and sizing surveys have been developed to help customers evaluate garments by delivering information comparable to that available through direct experience with products (Kim & Forsythe, 2008). The VFI is an application that allows customers to evaluate garments through physical simulation of clothes on an animated virtual 3D avatar sized to their body measurements (Loker et al., 2004). However, the information presented to users through VFIs has a history of being abstract compared with the experience of trying on a garment in a retail store (De Coster et al., 2020). VFI lacks an understanding of what kind of information customers require to provide reliable size and fit recommendations (Januszkiewicz et al., 2017). To guide the VFI design agenda, Gill (2015) proposed to organize interfaces in three approaches: *“size recommendation,” “fit recommendation,”* and *“fit visualisation”* to achieve consistency in positioning customers

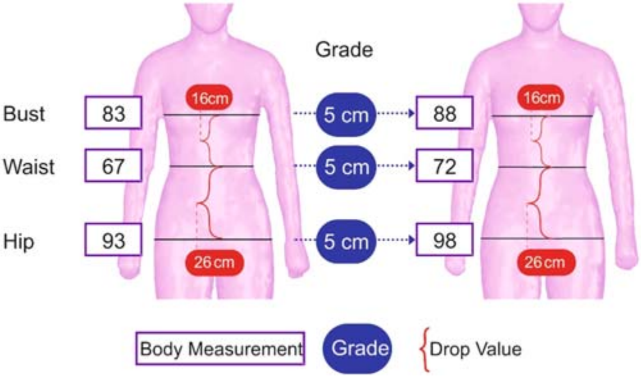


Figure 7.1 Components of size and shape.

within a context of product requirements. These approaches can be classified into three main systems:

1. Size recommendation: classifies the body within size brackets based on manufacturers' specification sheets that correspond to a specific set of body measurements, body types, and shapes. However, sizing labels attached to garments do not tell the consumer the body measurements for which the garment is designed. This inconsistency has caused VFI to predict size from often fallible data and has raised the question of how to put a highly personalized system into product development.
2. Fit visualization: lets consumers select a predetermined size garment before overlaying an image (2D or 3D) on the avatar to compare selections of garments through visual means, but does not yet illustrate the stresses and strains in the material when the customer wears the garments. Stress and strain visualizations are only used in specialized computer-aided design (CAD) tools like Lectra Modaris 3D, Optitex, and VStitcher for garment developers where expert practitioners make judgments grounded often in physical product assessment.
3. Fit recommendation: is measured by asking the consumer fit-related questions, including classifications for style preference and earlier garment purchase. This type of interface begins to consider the complexity of personal preferences having created an extensive database of garment-related information, including textiles and cloth composition (i.e., fabric, stretch, cut, and ease factors).

The three approaches provide a promising and feasible solution to achieve high garment visualization and prediction accuracy in online retail. Many interfaces being developed have sought to combine the different aspects for a more holistic overview. Thus VFI platforms consolidate multiple functions into a single app (Plotkina & Saurel, 2019). What is striking in this area is the number of companies that have evolved and those no longer trading, which suggests the issue is more complex than just matching consumers to size. The following sections discuss essential elements involved in making data reusable by ensuring that VFI developers create suitable target market information for retailers to respond to and customers to engage in the experience.

7.3 Virtual fit and size and fit-enabling technologies/online shopping for size and fit

The most effective product presentation occurs when commercial models' physical features match the consumers' (Chevalier & Lichtlé, 2012). Thus VFI focuses on amplifying the perceived resemblance between the consumer and the avatar to increase purchase intentions and confidence in apparel fit (Javornik, 2016). When designing the VFI experience, the developers assume that customers have an accurate perception of their body shape and its proportions to enter measures such as stature, mass, waist, and hip circumference (Januszkiewicz et al., 2017). However, research agrees that customers cannot define and translate their measurements into an avatar that best represents them (Plotkina & Saurel, 2019). In addition, customers' have low confidence about how well the avatar's dimensions corresponded to their body's (Linkenauger et al., 2017). Thus the existing VFI methods are prone to human error and limited by their design simplicity, which does not fully account for variations in the human body's dimensions (Alrushaydan et al., 2020). A more informed VFI design is needed to capture detailed body shapes and to realize the potential of mass customization in apparel design, size, and fit. Accuracy is needed not least because the body shape is not just about the relationships of overall dimensions, but also about the distribution of them around the body (Thelwell et al., 2020). Bodies with very similar dimensions, such as the bust circumference, may have the arcs of that dimension distributed differently as in Fig. 7.2. Body scanning illustrates the uniqueness of bodies in a way that manual

Figure 7.2 Arc distribution on populations with similar bust circumferences.

measurements did not and suggests a need for more consideration of the body in product development and selection.

7.4 Case study of My Virtual Model

The first VFI platform, created in 1997, was called *"My Virtual Model"* (MVM) and allowed users to create a 3D avatar from body measurements. MVM displayed the results in a "*virtual dressing room*" where the consumer could try on clothing, judge its look, and receive style advice from a chatbot. The platform aimed to enable customers to choose a suitable garment size and fashion experts to see value in the aggregated data for product development. According to Nantel (2004), brands that had adopted MVM noted the longer time on the site, a stronger tendency to buy, and increased average spending per customer. However, VFI has evolved slowly over the past two decades due to low consumer engagement (Hernández et al., 2019), and as a result, MVM had to be rebranded to Model My Weight, an online platform that helps customers visualize their weight loss journey. While the platform did not meet with the success desired, it has provided a first framework for consumers to create a virtual avatar and explore the assessment of garments in a virtual environment.

7.5 Case study of Metail

Metail, created in 2008, allowed female customers to design a 3D avatar from tape measure metrics: height, weight, bra-size, waist, and hips circumference. Metail aligns customer measures with a template to a proprietary scan dataset, as shown in Fig. 7.3. The Metail avatar called MeModel provides users with interactive feedback through six-angle rotating, zooming in and out, or changing the body pose. The garment is rendered on the model to show the customer how the product would look and recommend the best fitting size to buy from the retailer's available size range. However, in 2020 Metail was rebranded as Metail EcoShot and became the first virtual photo studio in partnership with Brozwear VStitcher. The interface allows fashion professionals to design garments in a CAD environment. The designer can choose a model from the Metail scan database, adjust the model's pose, and create 3D garments to judge garment style, size, and fit. This builds on some of the pure-play elements of the virtual interface that looks to hook consumers through interaction to hopefully encourage product purchase (Miell et al., 2018).

7.6 Case study of Fitbay

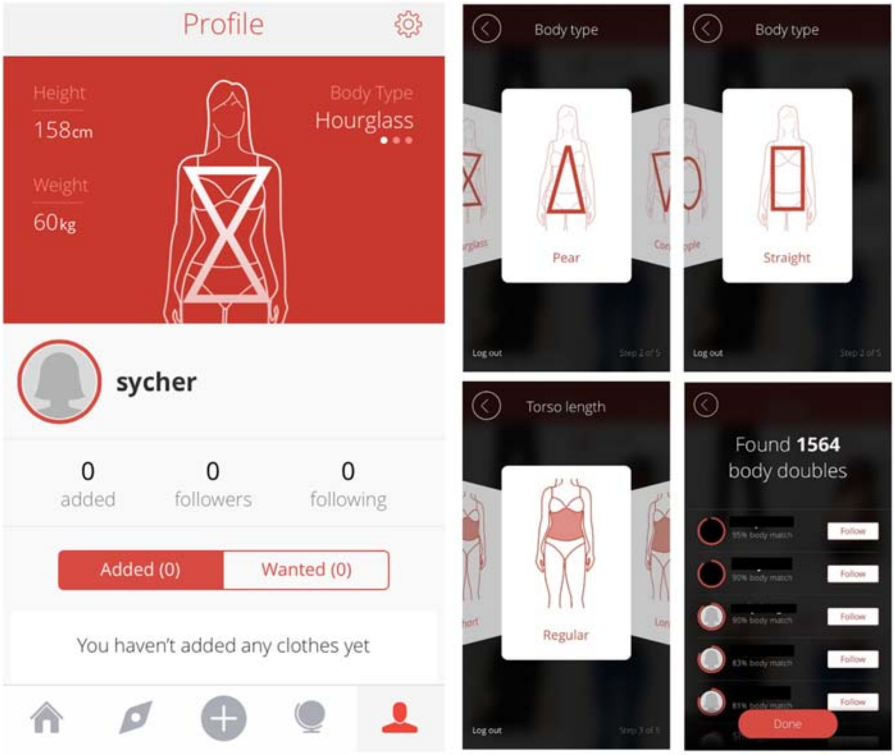
Fitbay, a company that started in 2013 and that is now no longer trading, offered a unique opportunity to manage consumers' shopping experiences. Based on a free

Figure 7.3 Metail customer journey in the house of Holland (2018) website.

mobile app, it connected consumers through shared self-reported body characteristics and fit preferences, and then used their clothing purchase reviews to make recommendations of fit to other similar users. The application required users to identify themselves against fixed criteria and used these and the users' purchase history and garment experiences to link and recommend garments. Uniquely, this system drew on peer recommendations based on shared similarities of bodies and quantitative feedback on garment experience. It sought to merge big data, peer networks, and support product recommendation, all elements that other interfaces are seeking to emulate, in a bid to ensure consumers order what they want, and as a result of which returns are reduced (Fig. 7.4).

7.7 Theory of sizing

For ready-to-wear (RTW) systems of retail to operate, sizing becomes the method of compartmentalizing segments of a population into specific groups to offer



Profile

Height 158cm

Weight 60kg

Body Type Hourglass

sycher

0 added

0 followers

0 following

You haven't added any clothes yet

Found **1564** body doubles

[redacted] 95% body match

[redacted] 90% body match

[redacted] 90% body match

[redacted] 83% body match

[redacted] 81% body match

Figure 7.4 Fitbay application.

products primarily from garment ranges. The ISO standards (BSI, 2001, 2002, 2004; ISO, 2017a, 2017b) identify the primary and secondary sizing dimensions, and these over time have become established as the principles of a sizing system. The evolution of sizing had an extensive discussion by Winks (1997), and clear explanations of how it was initially approached are documented by Kemsley (1957). Of note in the work of Kemsley (1957) and expanded on by Kunick (1967) is the requirement to keep one dimension static, say the hip, whilst waist and bust vary; this allows optimal population coverage and embeds the ides of shape into sizing systems. There is then a need to establish which of the three measurements, bust, waist, and hip, is the better dimensions to fix; it may be argued that hip is the least influenced by adiposity and age-related changes of the three. Whilst product development methodologies often have a greater number of actual measurements required (Gill, 2015), sizing is designed according to primary circumferences of the bust, waist, and hip and also to height. Based on these parameters, it is possible to map out the principles of sizing and then to consider how this operates against a population. Sizing systems are not the same as the requirements for product development, and this conflict has not been sufficiently explored and creates problems in how the consumer may experience the garment.

If we accept that sizing comprises women of bust, waist, and hips, these three variables still bring considerable complexity to any sizing system. Firstly, there are drop values which indicate the differences between each key circumference within a given size; next, there are grade increments which are the differences between key parameters applied proportionately or disproportionately in each size; these are used in grading to make garments larger or smaller from a base size. Thus with the variable of key dimensions, drop values, and increments and the possible variation of just these, sizing becomes a very complex system. The complexity also brings in the possibility of shape consideration as some systems stitch with fixed grades and fixed-shape expectations (Fig. 7.5), whilst others vary the grades and, therefore also vary the shape expectations (Fig. 7.6). Luckily, human population variation is no less complex; in fact, it's more so than even sizing variation allows. So, within these systems, the difficulty of mapping consumers to sizing exists, and the question of what predictive demographics are required to ensure a suitable match remains unanswered.

Within sizing systems, there is an issue of optimization, where size measurements are sought to be matched to an individual. The most optimal fit is achieved when a consumer's dimensions are closest to those dimensions of each size (Fig. 7.7). In reality, population shape is much more varied than the fixed sizing system and this means either the consumer makes concession of fit optimization, or garments are made which do not fit and may then be used to wear on the body for little of the garments' expected lifecycle.

When we consider a population, the shape may be illustrated by looking at how much variation may exist in the waist and hip circumference for a constant bust. Looking at the average values, as well as at the min and max differences, it is possible to map how to shape may be exhibited. Current sizing systems do not account for such differences and exclude certain shapes from achieving optimum garment fit as the retailer intended. Fig. 7.8 illustrates the variation in waist and hip that may exist in a population who share the same bust circumference, whilst there is a

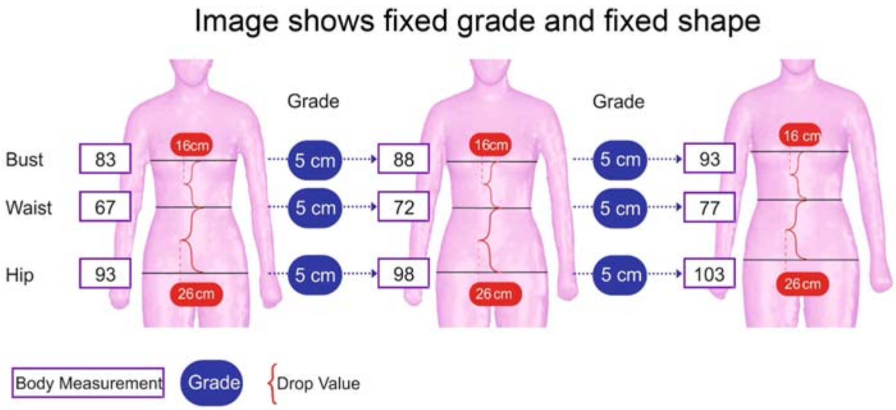


Figure 7.5 A fixed-grade increment and fixed-shape expectation.

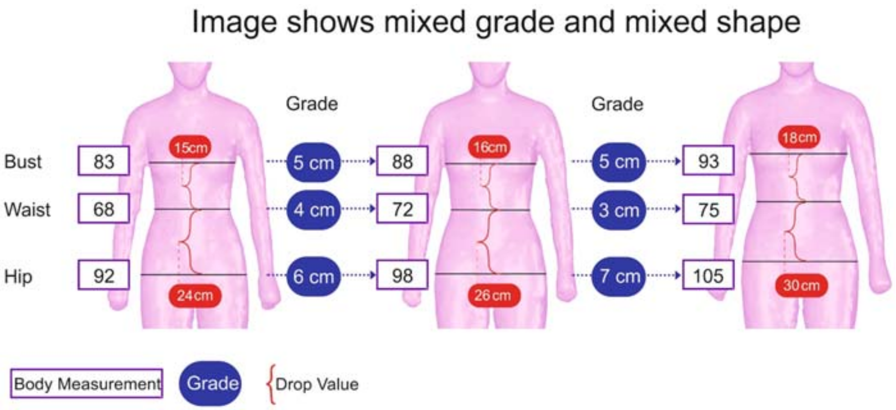


Figure 7.6 A mixed-grade increment and mixed-shape expectation.

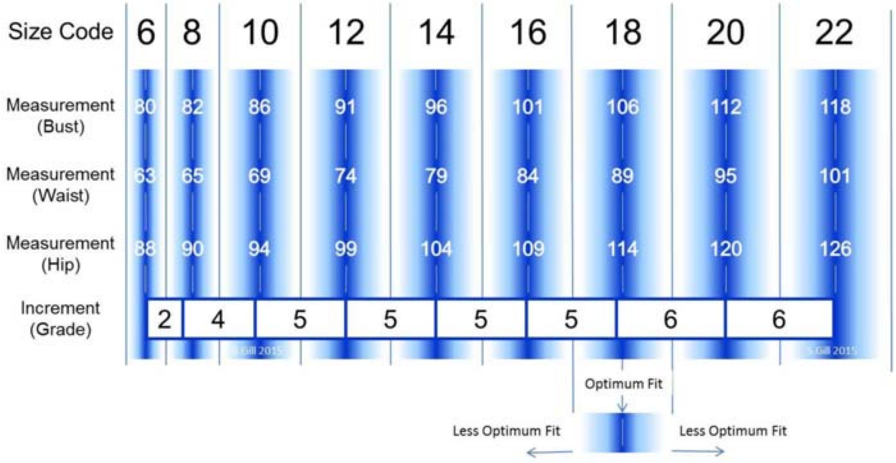


Figure 7.7 How sizing operates: outline the theories of sizing and explore what this means for a population.

range that each measurement could be different by up to 6–7 cm difference. This variation is greater than what existing sizing systems cater for. When a consumer says "I cannot wear X garment," what h = they are recognizing is that their shape is not catered for in current size offerings.

If we take a population of 100 scans (Gill et al., 2017) and just consider the interactions between the three key sizing dimensions of bust, waist, and hip circumference, it is clear that there are high degrees of variability (Fig. 7.9). Whilst some bodies conform to a notional norm in terms of drop values and shape, several bodies sit outside of this norm (Fig. 7.9A). If the same analysis is undertaken against 3

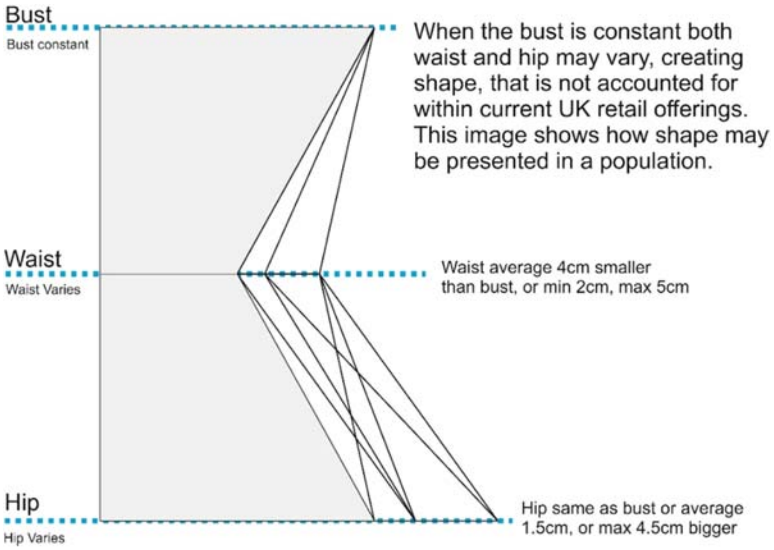


Figure 7.8 Shape variation by population waist and hip variance with a constant bust.

of UK retailers' norms, greater conformity can be seen as to how the data presents itself (Fig. 7.9B). If it is inescapable that UK retailers show greater shape conformity than can be observed within a population, then a number of consumers will struggle to achieve an optimum fit and will conclude that their bodies, rather than sizing, might be the issue. Research indicates that clothing can impact body image perceptions (Brownbridge et al., 2018; Grogan et al., 2020), and this requires careful consideration in sizing systems.

7.7.1 Key developments in theories of sizing

Whilst sizing systems remain simplistic, even in comparison to recommendations from initial population surveys (Winks, 1997), it is possible to see how retailers have tried to adjust to accommodate consumers making the most optimum choices. Unfortunately, no lasting shape categorization exists within UK retail, and each retailer often pursues a specific shape; the retailers often just alter the level of detail a consumer must provide to gain advice on size selection. Whilst the application of sizing has not progressed, it is possible to better understand the key components of sizing and to consider how these may then be addressed to lead to clothing offered in less wasteful systems.

7.7.2 Exploring proportions in product development processes

The analysis of methods produces patterns as garment shapes highlighted that proportions are an implicit part of the drafting process. Thus crotch depth/fork quantity

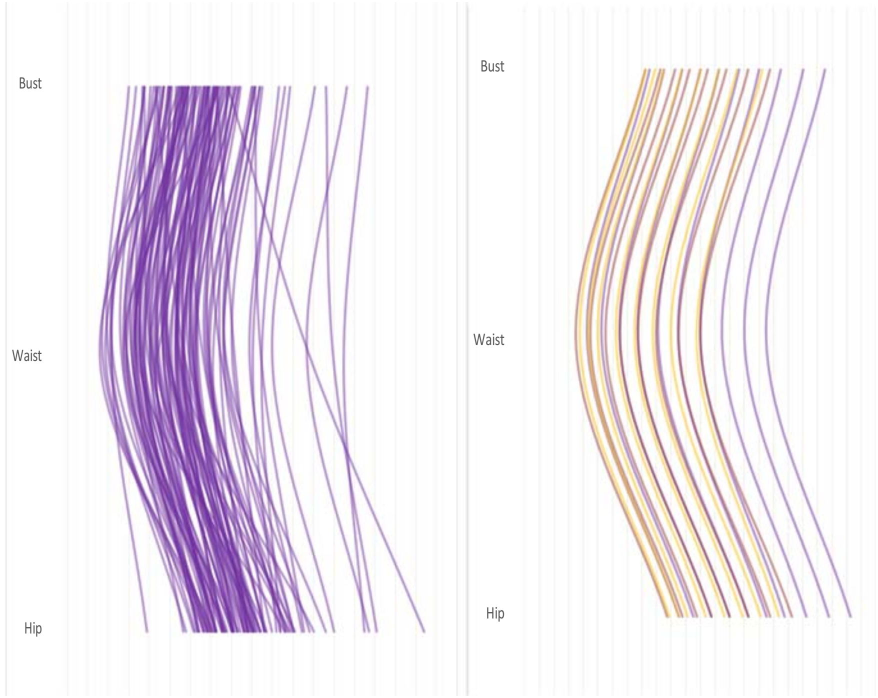


Figure 7.9 A-Left: Mapping of body shape against three main sizing dimensions 100 scans. B-Right Mapping of body shape against three main sizing dimensions three UK retailers.

can be seen in trousers to be directly derived from the hip circumferences or aspects of this (McKinney et al., 2017). The analysis also showed that proportions are used and recognized as part of product development; for example, the scye or armhole depth is often derived from other measurements, as is shown in Table 7.2. It is not uncommon for proportional rules to be applied for measurements, that are challenging to take and the existence of these methods adds further complication to the approaches for sizing in developing products.

7.7.3 Classification of the figure and proportions in sizing

According to Murtinho (2015), Leonardo da Vinci's Vitruvian Man offers a good depiction of the human proportionate system (Fig. 7.10). Vitruvian Man is said to reflect the underlying basis of the proportions of the human form and is named after Vitruvius. In essence, the illustration depicts the Renaissance idea that the human body is a symbolic microcosm at the heart of the universe. Murtinho (2015) also notes that parts of the human body were used as units of measure in ancient Greece. It is this observation upon which the Protagoras principle is grounded that humankind is the basis used to measure all objects.

Table 7.2 Proportions used to define scye (Armhole) depth.

Measurement name	Proportional assertion	Source	Application
Scye depth	Height + chest C—10.5 cm	[ASBCI Size and Fit book 2015]	
Armhole depth	21 + 3 cm ease	Beazley and Bond (2003)	Bodice pattern
Armhole depth	1/2 CB Length + 3 cm	Bergh (2006:16)	Bodice pattern
Armhole depth	Bust C/12 + 13.7	Bunka Fashion College (2009)	
Armhole depth	1/2 (1/2 Bust C + 3 cm ease) + 1 cm	Lo (2011)	
Armhole depth	1/8 chest C + ¼ back length + 2 cm	Petrak and Rogale (2001)	Shirt pattern
Scye depth	Bust/12 + 13.7 cm	Yang and Zhang (2007)	–

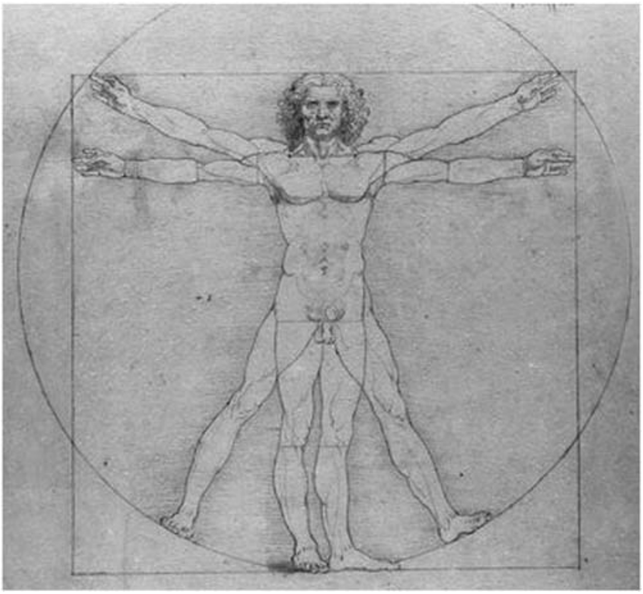


Figure 7.10 Human proportions in the manner of Vitruvius (c.1490), Gallerie dell'Accademia, Gabinetto dei Disegno e Stampe, n. 228, Venice.

These enduring proportional assumptions impact considerably on how the body is considered and how proportions are applied in product development methods like pattern drafting.

Hulme (1945), who provided a very influential text on pattern theory, claimed that the length of the head is an accepted divisional measurement of physical height. He calculated that the average height of a woman is equal to 7 3/4 heads. Four heads will be taken up by the head and torso, 3 3/4 by the legs. However, Nakamura (2016), in his study on theories of human body proportion, reported that numerous theories had been advanced relating to the proportions of the human form, and while each is different, they are all based on mathematical mechanisms. These theories are derived from the relationship between mathematics and art. Arguably, the three most widely supported models are the geometric, modulus, and fractional models (Nakamura, 2016).

The geometric construction theory concerns the structure of the human form and its outline in terms of geometric construction. For example, a triangle construction can be used to establish the location of the knees and the width of the shoulders. The modulus theory states that the height of a person is divided into separate measurements to provide the dimensions of each body part. Finally, the fractional theory states that each part of the human form is a fraction of a person's height (Nakamura, 2016). These approaches are determined by the artistic depiction rather than being grounded in actual measurements and have considerably influenced expectations of the proportions of the human body. However, when seeking to determine an average body from any population, the outcome is elusive due to the sheer variability of individuals in the population. These proportions are rarely challenged, though body scanning provides an opportunity to consider the proportions of populations and to contrast these to those used in design and product development, which can often distort the body from even the established expectations (Sanderson & Gill, 2014).

Empirical studies frequently classify body shapes to arrive at fit similarities across a sample of people (Alexander et al., 2005). This is problematic, however, because it fails to accurately reflect the breadth of differences that exist in the human form from one person to another. Indeed, previous research has established that the information about the variety of body types is so complex that there is no consistency in terms of body size and categorization. Schofield and Labat (2005) who investigated grading and sizing practices revealed that the incremental grading of pattern blocks is not correlated with the various dimensions possible across the universe of women's bodies. There are still sizing systems in use today that were initially developed in the latter half of the nineteenth century (Ashdown & Loker, 2010). Understandably, this has resulted in marked disparities between sizing systems and the dimensions of the typical woman's body, and, in turn, this has no doubt contributed to the dissatisfaction consumers have with the garments they purchase (Otieno et al., 2005). When tested, sizing systems often fail to provide an optimum fit for larger numbers of a population and can detrimentally impact how consumers feel about their bodies (Grogan, Gill, et al., 2020).

7.8 Sizing and fit

Sizing is the means to select the garments, which are then tried on to determine if they fit and, as noted previously, there are a number of decisions at earlier stages of product development that have an impact on all the later stages of the RTW process. The process often begins with the creation of a garment pattern that is the template for the materials to be cut from.

When creating garments in 2D, basic blocks are adapted to suit a specific design and produce a pattern. This process is typically performed by an expert pattern cutter. The fit of a garment is governed by numerous factors, including the body proportions, posture, and the contours and symmetry of the body. The standard approach is to create patterns for a symmetrical average body with standard proportions and posture. However, in reality, only a very small proportion of the population has body dimensions that closely match the shape and size of the standard model. For this reason, alterations must be made to the pattern to achieve a good fit. Further alterations are made to fit a dress form model before the final item of clothing is created (Fan et al., 2004).

In reality, people's bodies vary considerably in terms of proportionality, and this makes it very difficult for RTW clothing to achieve a good fit if based on a standardized sizing system. For instance, Sindicich and Black (2011) revealed several issues with the sizing and fit of business clothing for men in the United States. Applying data for 322 males aged 20−55 years in a functional design, the study revealed evidence of the problems associated with RTW sizing dimensions. Instead of relying on sizes, a large proportion of customers select garments based on their ability to accommodate their shape. As such, it is highly unlikely that a particular sizing system will be appropriate for all of the customers of a particular manufacturer. Ultimately, people's bodies vary considerably in terms of size and proportions, and any attempt to standardize clothing production will churn out what will be less than ideal products.

Notable problems are experienced by plus-size women seeking to purchase RTW garments to fit their size and proportions. A descriptive study was undertaken by Nkambule (2010) which specifically investigated the issues encountered by 249 plus-size women in Swaziland when selecting clothing of their choice to serve emotional, sensual, and functional needs. Again, it was determined that these women found it very difficult to purchase fashionable garments of an appropriate size and fit. There were also problems with proportionality when attempting to achieve a good fit, especially with regards to women's hips, buttocks, upper arms, and abdomen. The researcher also noted that the RTW clothing was typical of the wrong length. This relates to the failings of the standardized sizing system, which assumes that all people's bodies are proportional (Nakamura, 2016). People with unconventional body shapes will find it difficult to purchase well-fitted, fashionable garments if clothes are routinely designed to fit an ideal form. This is further complicated by the very limited consideration of lengths within a sizing system. Typically, retailers offer a standard height and then go up and down to tall and petite, usually by allowing a fixed-length increase, which does not account for variability that can be observed in a population. Overall, heights may not directly correspond to the proportions of segment lengths of the body, which can be seen in the below figure of scans ordered from shortest to tallest (Fig. 7.11). It is evident that whilst scans get taller, the segments' lengths

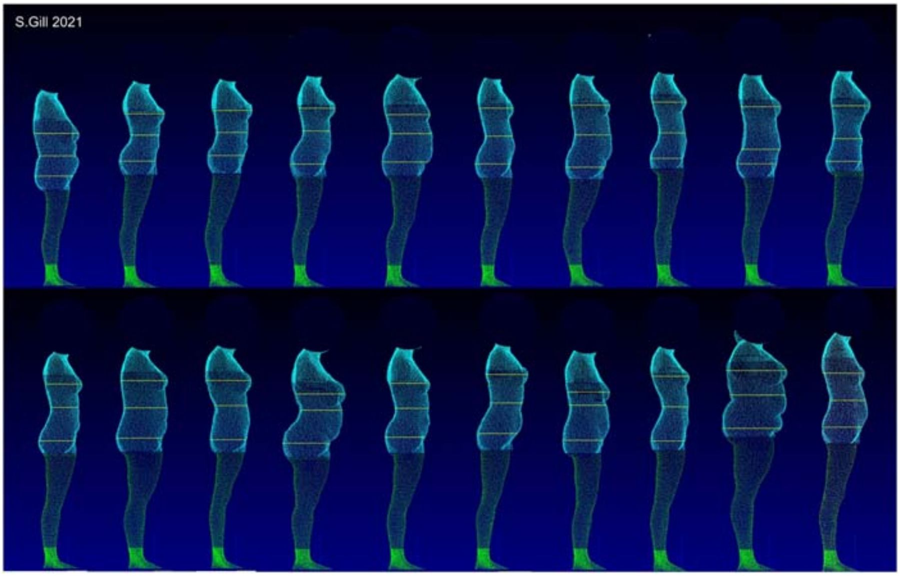


Figure 7.11 Scan population ordered from shortest to tallest, yellow lines show key circumferences of bust, waist, and hip. These allow an understanding of segment lengths between key circumferences.

between the bust, waist, and hip depicted by the yellow lines vary considerably within the population.

Clothing manufacturers face a clear quandary because they want to satisfy their customers' esthetic and functional requirements (Hernández, 2018), but this is impossible when mass manufacture demands that garments are standardized. Be that as it may, Hernández (2018) set about attempting to arrive at viable solutions including the use of a systematic model to improve the fit or the reliance on made-to-measure approaches. This revealed that the systematic model offers an effective approach to enhance the fit of an item of clothing for people with unconventional body shapes or proportions. The high degree of standardization within a population may mean that many bodies are unconventional from the narrow norms imposed in the product development and sizing processes. It is, therefore unsurprising that the current sizing systems often lead consumers to blame their bodies when they experience poor fit (Brownbridge et al., 2018; Grogan, Gill, et al., 2020; Grogan, Storey, et al., 2020).

According to Ashdown and Loker (2010), it is an objective fit evaluation that is responsible for issues regarding how well a garment fits, where these are fit tests, designer-led, and in which the consumer's notion of fit diverges from the established criteria. This highlights a difference in opinion as to whose judgment is considered as important, that of the designer/developer or that of the consumer/wearer. Designers use fit tests that are primarily concerned with how other people, usually those considered as fit experts, perceive the garment when it is being put on the body. In contrast, wear tests consider the opinion of the person who is wearing the garment in terms of how it feels and performs. Unsurprisingly, these two approaches can often give divergent results regarding how well an item of clothing "fits." Consequently, there is a need for a single universal fit system so that manufacturers, retailers, and consumers, all, have similar notions of how well a garment fits to mitigate the problems that have been identified in the empirical literature. One possibility, here, is the consideration of how the responses from actual wearers, afforded through product reviews, can temper the fit considerations of consumers.

Alexander et al. (2005) stated that clothing companies must make every effort to address how the fit of their garments relates to the various shapes and sizes of the human form. Moreover, whilst doing so, it is advised that they reflect how individual consumers perceive that garments fit. A common fit system or semantic is required so that retailers, manufacturers, and consumers are better able to communicate because this would help to address some of the difficulties identified regarding how well garments fit. To date, there is no consensus regarding a universal fit language among the research community. There is also a need for the development of scales for the assessment of fit perceptions applied in the research to be compared and allow the subjective fit to be categorized in a comparable way (Miell, 2018).

It is due to innovations, such as 3D body scanners, that anthropometric studies can be undertaken from extensive datasets. Advances continue to be made in how body scan data can be analyzed, and the result of this could be superior sizing systems. Over time, it is likely that additional countries will engage in anthropometric body scanner research, and new methods could be devised to enable information to be shared between countries on time, thereby ensuring that people around the world are able to benefit from modern sizing systems and garments that offer a better fit. Whilst the promise of mass customization has yet to be realized, technological advances continue to be made. Many manufacturers have started to offer custom-fit garments, and, in time, this may make sizing standards obsolete. Irrespective of this, by acquiring a better understanding of the many similarities and differences associated with the human form, it may be possible to agree on sizing systems for particular target markets whilst also simplifying how sizing is communicated to enhance how garments are designed and manufactured (Labat, 2007).

Gill (2015) also indicates that garment fit can be improved through technological developments, such as virtual fit innovations that can help to customize the garments for the consumers to meet their preferences. Manufacturers can incorporate these technological advances into their sizing system to eliminate the sizing issues observed in the apparel industry. Data collected through advanced technologies, such as 3D body scanning, can help manufacturers redefine the measurements and patterns for various sizes. The standard sizes obtained through proportional theories of constructing patterns should incorporate new engineering principles to ensure garment fit and to better center the actual dimensions of the wearer in the process.

It is apparent that the sizing systems applied vary from one manufacturer/retailer to another (Fig. 7.12) and also from one region of the world to another. There are associated problems with the fit of the resulting garments as well as their sizing when relying on standard sizing systems. Whilst it is expected a majority of

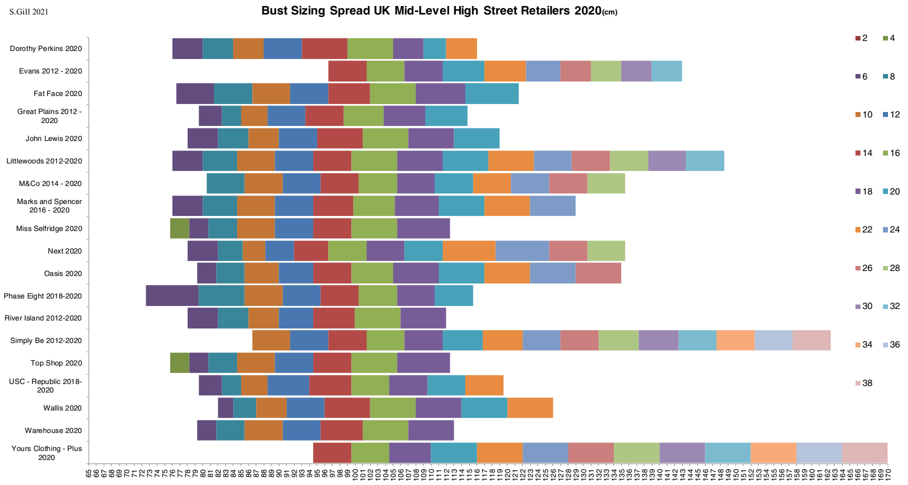


Figure 7.12 Bust sizing of UK mid-level retailers in 2020.

people's bodies comply with standard proportions and many may make concessions in fit-to-wear garments, still, there are many exceptions, and these people can experience considerable problems when attempting to purchase well-fitted RTW clothing. These people will only be truly satisfied with their purchases when steps are taken to address the problems reported regarding the sizing and proportion of RTW clothing. For instance, Gill (2015) asserts modern technology offers possible solutions to improve the fit of garments. Future advances could see advances in the efficiency of the sizing system to apply measurements that better suit the various body types that exist in terms of their size, proportion, and shape. However, these systems must be grounded in how garments relate to a population's needs and fit a population and, therefore consideration must be given to determining suitable measurements to drive product development.

7.9 Making anthropometrics accessible to the consumer

The fashion industry faces many challenges around sustainability, equity, and supply chain management (Gazzola et al., 2020) with heavy water use, pollution from toxic dyes, CO_2 emissions, soil depletion, and high textile waste (Grappi et al., 2017). In addition, the fashion industry produces twice the volume of clothing than it did in 2000 (Remy et al., 2016). However, the garment use and lifetime have decreased (Schmutz et al., 2021). This has led to surges in the amounts of textiles that have gone into landfills in the past two decades (Niinimäki et al., 2020). Historically, 25 percent of textile waste was due to "*lack of interest*" (Heath et al., 1949) which increased to 33% in 2006 (Tyler et al., 2006) and reached over 50% in 2019 (Elia, 2019). As a result, the clothing industry produces a loss of US $500bn of value in unsold merchandise (Li & Leonas, 2022). Nevertheless, avenues such as selling at throwaway prices or donating to charities cannot consume the waste generated each day. Thus in a world hungry for textiles, a more imaginative approach to designing clothes is needed (Boykoff et al., 2021).

Making anthropometrics available to customers with 3D body scanning can help to reduce waste by producing garments that customers want and which are based on their accurate body dimensions, style preferences, and demand (Freudenreich & Schaltegger, 2020). 3D body scanning produces a high-quality representation of the whole human body surface using noninvasive optical methods (Heymsfield et al., 2018). The point cloud data contain the body's surface's differential geometric properties needed to describe customers according to their shape and size, with a higher degree of precision and data complexity than manual methods can accomplish (Daanen & Ter Haar, 2013). The fashion industry can use scan data to describe, interpret, and analyze the outer body shape and dimensions for size and fit applications (Idrees et al., 2020). For example, 3D body scanning can direct a more informed process in manufacturing based on mass-customized or bespoke patterns generated through CAM software, as demonstrated by Harwood et al. (2020). The ability to gather digital anthropometric data cheaply across retail target markets means that: (1) more styles for diverse body shapes can be pursued; (2) sizing and fit metrics can be statistically validated; and (3) new brand relationships can emerge from the data that would never have been contemplated before (Januszkiewicz et al., 2019). However, 3D body scanning is struggling to develop in the fashion industry, despite growing support from researchers and garment developers who see it as a promising medium for more customized offerings . The fine-tuning issue can be reflected by ongoing attempts to diffuse on the RTW market level: My Virtual Model (1994), Levi Strauss Original-Spin (1997), Me-ality (2000), Cyberware (2001), QVIT (2009), Bodi. Me; in retail stores: New Look and Selfridges (2012), Artec Shapify Booth in Asda (2014), Bespokify (2015), or Zozo-Suit Europe (2019). Some fine-tuning issues relate to reservations regarding technology, whilst others to a desire to apply them as existing practice, rather than harness what they offer in terms of a greater depth of data to drive the product (Gill, 2015). Therefore despite the proliferation of 3D body scanning in the industry, the content aspects of the system never matured or were never developed to the extent necessary to create a platform for its users (Yan & Kuzmichev, 2020). Instead, it remained an artifact, transparent, not from being in use but through lack of use, usage, and usefulness. Lack of content options led to lack of participation, and therefore the technology can be considered only evocatively—capable of providing a base by which participants were able to comment, and project upon "if it did work" or did fulfill all it was built up to provide (Peng et al., 2012). However, past research works rarely shed light on how to implement the desired changes in the fashion industry. The "how" of achieving planned and actionable change is critical toward realizing these transformations and is what we call "transition pathways" (Hötte, 2020). Transition pathways include the necessary steps to understand technologies and their impact, desired manufacturing targets, transition costs, and identification of necessary skills and expertise for service development.

7.10 How body scanning changed online

The early scanner design was bulky, slow, expensive, and very low in resolution (Jones & Rioux, 1997). With passing time, however, scanners improved in megapixel CCD chips, which contributed to higher resolution and improved accuracy of 3D scan images (Heymsfield et al., 2018). However, the research in 3D body scanning is deeply ingrained in the technology culture that employs engineering principles with heavy reliance upon pronounced claims of improved or superior technical performance and/or specifications (Scott et al., 2019). Thus the developer's focus has been mainly on technology as a solution on its own (Daanen & Ter Haar, 2013). However, technologies by themselves are rarely transformative (Weber & Rohracher, 2012). As a result, 3D body scanners are smaller, more mobile, and faster, often imitating familiar home objects such as scale or mirrors. For example, Naked Lab utilizes a mirror and a mobile app (Grazioso et al., 2018).

3D body scanning design varies in physical characteristics, and specifications often vary between manufacturers including the number and arrangement of cameras and implementation of static or dynamic (e.g., rotating platform) components. T3D body scanning includes laser and structured light (SL) systems, millimeter-wave radar, and multi-view camera to capture information from the body's surface, thus requiring customers to wear minimal form-fitting clothing. For example, the SL scanners include Size Stream, FIT3D, Naked Labs, TC2, and Shape Scale, while Styku scanners utilize time-of-flight (ToF) technology. Systems with multiple cameras are often large and cost more than those with a single camera that includes a platform that rotates the subject 360 degrees (Bourgeois et al., 2017). One or more cameras measure deformations in the light pattern over objects (e.g., a human body) in the scene (Heymsfield & Stevens, 2017). This deformation information is used to calculate the per-pixel distance between the camera and the object and, thus creates a depth image using geometric triangulation (Remondino, 2003). Light coding is one of the most common implementations of SL developed by PrimeSense (Tel Aviv, Israel) and acquired by Apple Inc. Currently, there is a range of different scanners commercially available, with fixed scanners and mobile scanners being the main offerings (Table 7.3).

7.11 Mobile scanning interface development

Alongside the development of large scanning booths, there is also industry progress in mobile apps for engaging with clothing fit (Silva & Bonetti, 2021). Mobile solutions are finding an eager market, opening up new research opportunities, and changing the ease with which the consumer's body can engage with product development or selection. The three standard approaches to mobile scanners can be summarized as follows: 3D scanning based on photogrammetry and depth sensor, 3D reconstruction from sparse data learned from images, or measurement inserted from images (Alcacer et al., 2020). Xia et al. (2018) suggest that new mobile apps can

Table 7.3 Commercially available scanner brands.

Fixed sensor body scanners	**Rotary scanners**	**Mobile scanners**	**Entertainment**
Size stream TC2 3dMD BotSpot Vitronic Telmat Treedys	Styku Fit3D Naked Lab	Zozo-Suit Fision Netello Shapetrax Body Labs Size stream Home	Twindom

Table 7.4 Overview of mobile scanning apps.

	ZOZO	**Fision**	**Netello**	**SizeStream**	**3DLook**	**Meepl**
Measurements	Yes	Yes	Yes	Yes	Yes	Yes
2D illustration	Yes	Yes	No	No	No	Yes
3D Body	No	No	Yes	Yes	Yes	Yes
Country	Japan	Swiss	Canada	United States	United States	Swiss
Year	2015	2015	2012	2019	2016	2015

solve issues related to the high cost of large scanning systems deployment, the measurement extraction dilemma of handheld scanners, and the low-quality results from manual measuring techniques. However, more research is needed to establish how accurately and reliably mobile phone applications measure body dimensions compared with more expensive scanning booths (Idrees et al., 2020). The primary issue with scanner reliability concerns participant position and the lack of handlebars to stabilize and guide arm placement and, also, the user's underestimation of the optimal distance (Gill et al., 2016). Table 7.4 shows some of the most popular apps for body scanning and their capabilities.

7.12 Human measurement to product development

Whilst there are rapid developments in capturing the human body that are accessible to the consumer, the use of technology in enhancing product development remains limited. In part, the fact pattern block development is often limited to 2D drafting, and toile development is manually undertaken which means getting products into 3D can be problematic. This process includes methods of block creation that use limited actual body measurements and rely heavily on proportional expectations. To map measurements and bodies more clearly into the product requires clearly understanding links between body and product, which then are implemented in grading practices. This also means a break away from systems where RTW clothing imposes averages onto a population that limit

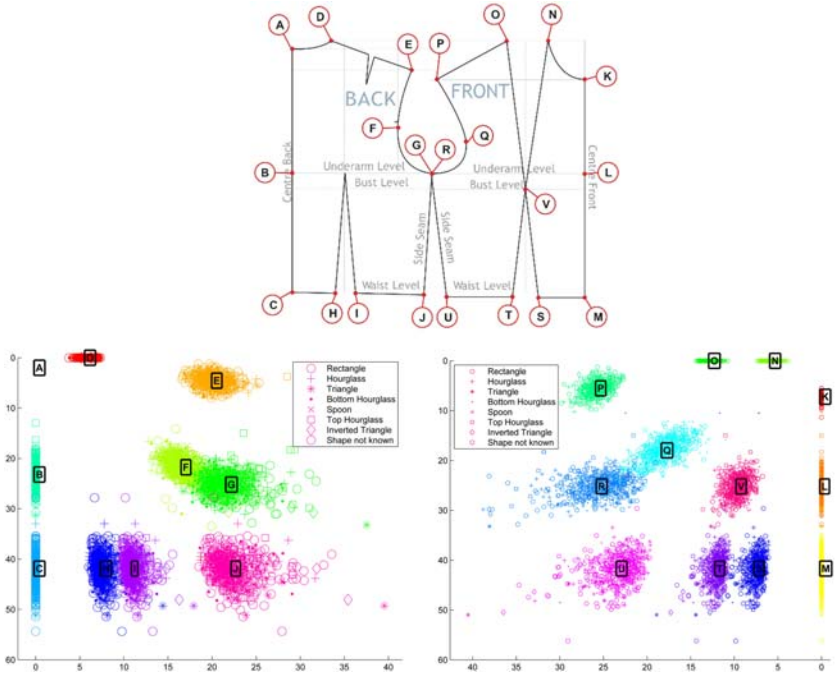


Figure 7.13 Visualizations of how a population may drive pattern development, based on women 18–35 of varied shapes. Data used to drive pattern development for a *bodice*.

consumer choice against population variation. Sizing, in general, seeks to reduce product offerings to minimize stock and manufacturing complexity, but in doing so creates considerable concession of fit optimization for the consumer. Finding ways to visualize this can be difficult (Fig. 7.13).

Consumer sizing is dictated by sizing systems which are artificial divisions based on ideals either in terms of measurement data or, more likely, selected fit models. This is further complicated by the methods of pattern drafting, which often have proportional expectations embedded within them. Sizing as a practice is generally about reducing product offerings to best suit varied populations, and whilst models exist to develop the systems, their application on populations rarely consents with how well these systems work while having implications for consumers who have to select and wear garments.

7.13 Future developments in online retail in a digital age

Whilst there remain promising developments that will improve products and help address sustainability issues within the industry, there remain some key developments that would make this more likely. Among these areas are:

1. Bespoke systems are more available to practitioners at the base level of the industry, so, it does not just empower big business.

2. Sizing systems require development to be structured to reflect even simple shape variations in a population and this may address negative impacts of highly standardized product offering on varied populations' body image.
3. More efficient means to create pattern blocks are essential to better incorporate the body into existing practices. Current manual block development is time-consuming and creates a barrier at the start of the product development process.
4. Clear theory must be developed to define the body-to-pattern relationships to aid automation and the adoption of technology. This includes establishing an appropriate theoretical basis for product development in apparel.
5. A solid theoretical basis governing the connection between fit, size, and shape should support any new techniques through theory established at the academic and industry level. This would guide the establishment of these initiatives to ensure that existing and future professionals in this field can develop a fuller understanding of this issue.
6. How clothing ease is employed is pivotal to a thriving industry given the consumer's experience of clothing ease is an essential element of customer satisfaction concerning the fit of clothing. What constitutes a suitable level of ease concerning a garment's fall on the body and style remains an open question and one that must be addressed for automation to function. Managing and guiding on ease to apply in products for different applications and using different fabrics are essential to ensure each body gets optimum fit and optimum clothing performance.

These areas of development would help to make RTW clothing more sustainable reducing waste by improving fit and decreasing the number of garments made which do not optimize fit for the population they are made for.

Product development in the clothing industry continues to be an imperfect science. Only when an appropriate theory is developed and fully verified practices are subsequently implemented will it be possible to capture the opportunities provided by emerging technologies, including everything from customer feedback via apps to virtual fit tools and scanning. The development of mobile scanning apps brings human measurement closer to the consumer, making it now all the more necessary for other parts of the digital supply chain to provide a similar benefit.

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Part 3

Anthropometric Sizing and Mass Customization Technology

Importance of sizing and fit using 3D technology

8

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8.1 Introduction

Anthropometry can be defined as the measurement of the human body. It is used for identifying and understanding the variations of human physical characteristics (Ehrampoush et al., 2016). Traditional manual techniques of collecting anthropometric data involve distances between body landmarks (often bony points, such as the acromion and patella) and the use of standardized postures. These are measured using a range of equipment including anthropometers, stadiometers, tape measurement, and sitting-height tables (Sims, Marshall, Gyi, Summerskill & Case, 2012). Body shape changes according to variations in body volume (BV) have important implications in a range of fields that currently use 1D anthropometric measurements. Such simple measurements including traditional anthropometry unable to capture body shape differences in the same detail as obtained by the 3D body scanning measurement (Daniell et al., 2014).

Before performing manual anthropometry measurements, the observer must identify landmarks for each measurement to be taken. According to International Society for the Advancement of Kinanthropometry (ISAK, 2001), landmarks are identifiable skeletal points that generally lie close to the body's surface and are the "markers" that identify the places on the body from which a soft tissue site is located, or the exact location of the measurement site to be measured. This method requires careful attention because the precise and accurate assessment of anthropometric measurements can be difficult. In measuring girths, the tape is held at right angles to the body segment or limb which is being measured. The tension of the tape must be kept constant which can be achieved by ensuring that there is no compression of the skin. However, the tape usually cannot be placed but the tape often cannot be placed without putting a pressure at the designated landmark (ISAK, 2001).

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8.2 The 3D body scanning technology

This technology is a new alternative approach for the assessment of body shape and size. With the advancement of technology and the application of 3D body scanners, techniques for obtaining anthropometric body data have become contactless, more practical, fast, and, above all, accurate. Due to ease of use, 3D body scanning is ideal for screening large populations of participants, particularly to simultaneously screen for multiple conditions (Trelevean & Wells, 2007). Wells et al. (2008) reported that for imaging external body shape, the technology of the whole-body three-dimensional surface scanning has become a novel method. The method is easily accepted by individuals and provides extremely refined information on surface topography. This technology is also low-cost and versatile. The digital nature of the results makes it compatible with longitudinal monitoring. In anthropometric surveys, this method has already been proved powerful. Automatic extraction of anthropometric measurements by 3D body scanning helps to improve the reliability of measurements and remove the operator error (Wells et al., 2008). It is a noninvasive and fast technology that can scan the human body and generate a 3D model of the body by providing precise, reproducible measurements that are accurate, including size ratio, body shapes, surface, and volumes data (Petrescu et al., 2012).

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8.2.1 Introduction to NX 16 3D body scanner

The scanner utilizes a noninvasive scanning method that projects strips of safe “white light” onto the body form and records distortions using 36 implanted nonmoving cameras inside the body scanner chamber (Fig. 8.1). The figure shows the view from outside the scan chamber (Fig. 8.1A), inside the scan chamber (Fig. 8.1B), and the implanted nonmoving camera (Fig. 8.1C). Body Measurement System software ([TC]^2 version 7.4.1) was installed in a computer connected to the NX16 3D body scanner. The software will create the initial point cloud, then, process it into a 3D body model from which customized measurements could be extracted (Simenko & Cuk, 2016). There were several measurement extraction profile (MEP) files that were used to extract body measurements, for example, Ms ISO 8559 which is the international standard used in the anthropometry field (Kim, 2016). In addition, an MEP file of Fitness Tracker specially created by the [TC]2 was used to calculate BV and torso volume.

Figure 8.1 Images of the 3D body scanner. Panel (A): Outside view; Panel (B): Inside view, and (C) camera implanted inside the scanner to capture the 3D images.

8.2.2 Calibration

For the scanner to obtain accurate and highly reliable measurements, it must be calibrated before the scanning procedure is put to perform. Before calibration, Body Measurement System software was being opened to help interface with the scanner. The tools needed for calibration were calibration balls (Fig. 8.2A) and reference cylinder (Fig. 8.2B). The reference cylinder was placed inside the scan chamber and the black curtains were closed. Upon clicking the calibrate system, the screen appeared to scan the reference cylinder. After calibration of the reference cylinder was completed, two ball strands were hung from eyehooks in the top cross brace of the scanner. The floorball was placed in between the two strands. The calibration balls were hung carefully to prevent moving capture and protect against error

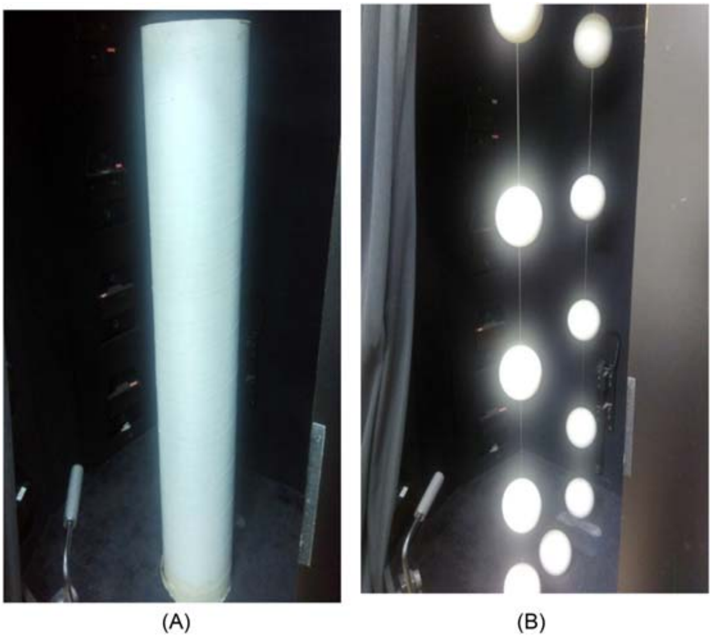


Figure 8.2 Calibration tools. (A) Calibration balls; (B) reference cylinder.

Figure 8.3 Specially designed scan wear.

results. After that, the curtain was closed again to avoid light from entering the scan chamber which would interfere with the calibration process. Fig. 8.3 shows that the calibration system was successful, with an average deviation value of less than 0.9, which is within acceptable limits (Simenko & Cuk, 2016).

A total of 300 participants were recruited for giving measurements in this study. Participants were eligible to participate in the study if they were Malaysian citizens, women, 18–54 years old, conscious, cooperative, and able to provide written informed consent. Those who were pregnant and critically ill were excluded. The mean and standard deviation of the participant age of the study population was 27.35 and 8.64 years old, respectively. Meanwhile, the mean BMI is 24.8 kg/m^2. Ethical approval for this study was obtained from the University of Malaya Research Ethics Committee (UMREC) with reference number: UM. TNC2/RC/H&E/UMREC-63. Before giving consent, all participants were informed about the purpose, protocol, and confidentiality of the information provided during this study being conducted.

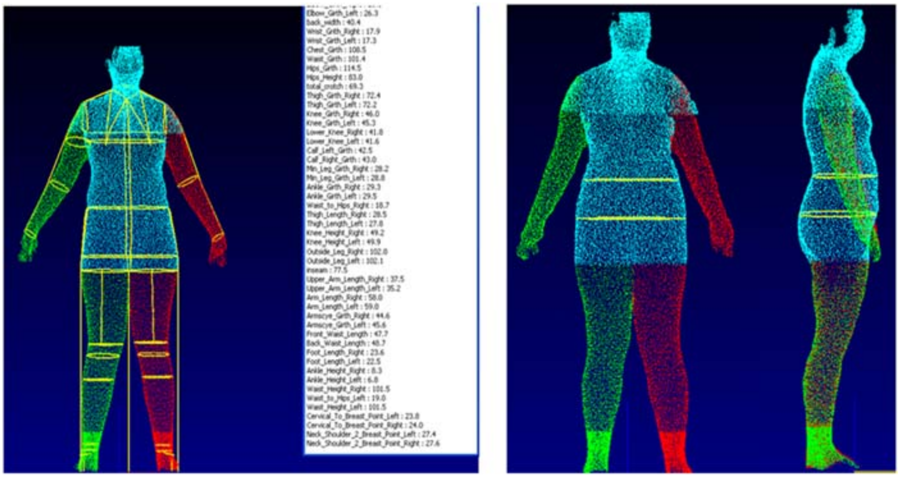
8.2.3 The 3D body scanning procedure

Participants were instructed to change the clothes into specially designed scan wear as shown in Fig. 8.3. These scanning garments were made from light brown fabric with a mixture of lycra and cotton. There were six sizes: extra-small (XS), small (S), medium (M), large (L), extra-large (XL), and double extra-large (XXL) (Japar et al., 2017). Before entering the scan chamber, participants were instructed to remove any jewelry and to tie up their hair to avoid possible errors during the scanning process. Each participant was briefed on the standard protocol of body scanning. Participants were required to stand straight, place their feet at the available footprint label imprinted on the floor of the scanner, and hold the handle using both hands.

When the scanning process started, the scanner was in an automatic operating mode and the audio instruction directed the participants through the scanning process. The participants were instructed to press the button on the right side of the handle. After that, the participant was asked to remain inside the scan chamber. The software extracted the 3D body model and all related measurements. This took approximately 8 seconds, after which the 3D body model appeared on the monitor. Then, the 3D body model was reviewed very quickly, looking primarily for correct positioning, movement, hair obscuring the back of the neck, and any other obvious anomalies. The measurement list of body measurements, as shown in Fig. 8.4A, will have appeared. After correcting for errors, the participant was scanned again to obtain better results of body measurement and to get 3D body models. The whole procedure took about two minutes to be completed. The image produced by the body scanner is shown in Fig. 8.4B, in which the virtual tape of the waist circumference (WC) and hip circumference (HC) was labeled. In this study, ISO 8559 was used for measuring WC and HCs.

8.3 Determination of reliability and accuracy of NX16 3D body scanner

A pilot study was conducted among 30 participants to obtain their waist and HC using manual and automated measurements. Each participant was subsequently



```
Elbow_Girth_Left : 26.3
back_width : 40.4
Wrist_Girth_Right : 17.9
Wrist_Girth_Left : 17.3
Chest_Girth : 108.5
Waist_Girth : 101.4
Hips_Girth : 114.5
Hips_Height : 83.0
total_crotch : 69.3
Thigh_Girth_Right : 72.4
Thigh_Girth_Left : 72.2
Knee_Girth_Right : 46.0
Knee_Girth_Left : 45.3
Lower_Knee_Right : 41.8
Lower_Knee_Left : 41.6
Calf_Left_Girth : 42.5
Calf_Right_Girth : 43.0
Min_Leg_Girth_Right : 28.2
Min_Leg_Girth_Left : 28.8
Ankle_Girth_Right : 29.3
Ankle_Girth_Left : 29.5
Waist_to_Hips_Right : 18.7
Thigh_Length_Right : 28.5
Thigh_Length_Left : 27.8
Knee_Height_Right : 49.2
Knee_Height_Left : 49.9
Outside_Leg_Right : 102.0
Outside_Leg_Left : 102.1
inseam : 77.5
Upper_Arm_Length_Right : 37.5
Upper_Arm_Length_Left : 35.2
Arm_Length_Right : 58.0
Arm_Length_Left : 59.0
Armscye_Girth_Right : 44.6
Armscye_Girth_Left : 45.6
Front_Waist_Length : 47.7
Back_Waist_Length : 48.7
Foot_Length_Right : 23.6
Foot_Length_Left : 22.5
Ankle_Height_Right : 8.3
Ankle_Height_Left : 6.8
Waist_Height_Right : 101.5
Waist_to_Hips_Left : 19.0
Waist_Height_Left : 101.5
Cervical_To_Breast_Point_Left : 23.8
Cervical_To_Breast_Point_Right : 24.0
Neck_Shoulder_2_Breast_Point_Left : 27.4
Neck_Shoulder_2_Breast_Point_Right : 27.6
```

Figure 8.4 3D body models generated by the scanner. Right panel: Virtual tape of WC and HC (Front and Side view); Left panel: Scanner output of the 3D model with extracted measurement lines and list of measurements. Note: *Yellow line* (virtual tape) shows the body measurements. *HC*, hip circumference; *WC*, waist circumference.

scanned and manually measured twice. There were two ways to determine the reliability of this machine. First, via analysis using the ICC, the correlation coefficient was used to demonstrate the strength of the relationship between two repeated measurements. The range values for the reliability coefficient start from 0 to 1. A coefficient of below zero shows “no reliability,” while >0 to <0.2 is slight reliability, 0.2 to <0.4 is fair reliability, 0.4 to <0.6 is moderate, 0.6 to <0.8 is substantial, and 0.8−1.0 is almost perfect reliability (Jamaiyah et al., 2010). The second method used the Bland-Altman plot to illustrate the spread of differences in the readings, the mean difference, and the upper and lower limit of agreement for intra-observer reliability. In Bland-Altman plots, there is no such “acceptable” range (Jamaiyah et al., 2010). As for the accuracy index, the technical error of measurement (TEM) was also calculated to determine the error margin in anthropometry. The TEM index allows anthropometrists to verify the accuracy degree when performing and repeating anthropometrical measurements. Relative TEM using value of <1.5% as the acceptable ranges for an intra-examiner beginner anthropometrist level (Jamaiyah et al., 2010). TEM was calculated using the following formula:

$$TEM = \frac{\Sigma D^2}{2N} \tag{8.1}$$

D = difference between the 1st and 2nd measurements, N = number of participants.

Next, TEM was transformed into relative TEM to obtain the error expressed as a percentage corresponding to the total average of the variable. To calculate relative TEM, the arithmetic mean of the mean between both measurements was obtained by taking the values of the first and second measurements and dividing these by two, thus generating the average value of this measurement. This procedure was performed for each one of the 30 participants. The 30 averages obtained were then summed and divided by 30 (total of participants) to generate variable average value (VAV). The relative TEM was computed using:

$$Relative\ TEM = \frac{TEM}{VAV} \times 100 \tag{8.2}$$

TEM = Technical error of measurement expressed in %, VAV = Variable average value.

Further analysis was conducted to determine the precision of the 3D body scanner measurement compared to the manual measurement. The CV is calculated to further determine the precision of both of the measurement methods. CVs of 5% and less are generally considered to allow an assumption of good method performance, whereas CVs of more than 10% are bad (Jamaiyah et al., 2010).

8.3.1 Reliability results

The results of the correlation coefficient of intra-observer analysis using ICC are shown in Table 8.1. The ICC for WC was 0.970 and for HC was 0.980, which means a strong correlation between two repeated measurements of WC and HC was obtained through the 3D body scanner. This indicates a high degree of reliability between the measurements. For visual inspection of WC measurement using the 3D body scanner, Fig. 8.5 shows that the average mean differences across all values of reading were 0.21 cm with an upper limit of +1.2 cm and a lower limit of −0.8 cm. For WC taken using MM, the average mean value is 0.17 with an upper limit of +0.9 and a lower limit of −1.2 cm. For HC, the average was −0.0067 cm, with an upper limit of +0.9 cm and a lower limit of -0.9 cm. In contrast, HC taken using MM shows more variation, in which the average mean was 0.07, the upper limit was +1.4 cm, and the lower limit was −1.3 cm.

The Bland-Altman plot (Fig. 8.5) also shows a high level of agreement for the intra-observer of each measurement in which all values in the diagram were within upper and lower boundaries. It can be seen that both Bland-Altman plots for waist and HC in automated measurement showed less deviation from the average mean value. The points were scattered close to zero, which was consistent with ICC analysis of the almost perfect agreement. As a summary, based on the repeated

Table 8.1 ICC of waist circumference and hip circumference taken using 3D body scanner.

Measurements (WC/HC)	Intraclass correlation coefficient
Waist circumference (WC)	0.97
Hip circumference (HC)	0.98

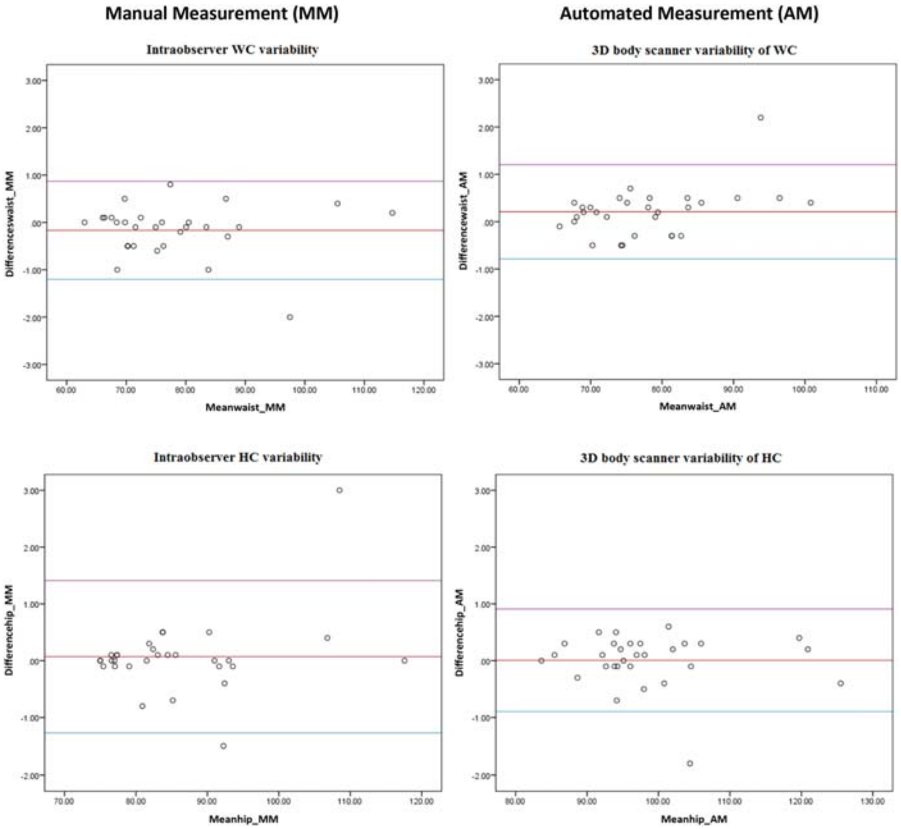


Figure 8.5 Bland-Altman plots illustrating WC and HC measured manually vs using the 3D-scanner for the entire set of participants studied. *HC*, hip circumference; *WC*, waist circumference.

measurement of WC and HC, all ICC values were >0.97 which indicates strong reliability. The ICC value suggests that the NX16 3D body scanner has relatively high internal consistency and, thus represents a reliable tool for assessing human body dimensions.

8.3.2 Accuracy results

The results for TEM are tabulated in Table 8.2. For automated measurement, the relative TEMs for intraobserver for WC and HC were 0.2% and 0.1%, respectively. As for manual measurement, the relative TEMs value of WC and HC were slightly similar for WC while HC was slightly higher. Further analysis was conducted to determine the precision of the 3D body scanner compared to its manual measurement. The CV is calculated to further determine the precision of both of the measurement methods. Variability of readings was minimal for the automated

Table 8.2 Relative technical error of measurement classification results and percentage of coefficient of variation for waist circumference and hip circumference measurements.

Type of measurements (WC/HC)	Mode of measurement (AM/MM)	TEM	%TEM	CV (%)
Waist circumference (WC)	Automated measurement (AM)	0.148	0.2	0.12
	Manual measurement (MM)	0.150	0.2	0.18
Hip circumference (HC)	AM	0.103	0.1	0.09
	MM	0.228	0.3	0.12

measurement. Percentages of CV for automated measurement of WC and HC are 0.12% and 0.09%, respectively, indicating good precision. For manual measurements, percentages of the CV of WC and HC were at 0.18% and 0.12%, respectively (See Table 8.2). AM produced slightly less value compared to MM, indicating the higher accuracy of the 3D body scanner in extracting measurement.

8.4 Comparison of 3D body shapes according to BMI categories

Further analysis was conducted to compare the 3D body models according to their body mass index categories. Three samples of 3D body models from participants were selected based on each BMI category of normal, overweight, and obese. Then, BV and torso volume (TV) were compared based on their BMI. Despite having the same rating of BMI, 3D body models are slightly different in body and TV. The 3D images give an especially clear view of the location of fat accumulation and distribution. Fig. 8.6 shows a participant in the same BMI category (BMI = 20 kg/m^2). The participant in Fig. 8.6A(ii) had a higher BV and TV compared to the other two participants. Fig. 8.6B(ii) shows a side view, with the abdomen area a bit bulging compared to the other two with a slimmer abdomen.

In the overweight category (Fig. 8.7), three samples of participants having a BMI of 25 kg/m^2 were selected. Fig. 8.7A(i) and (ii) show similar body shapes in which they have fat distributed in the lower region, especially in the thigh region. However, a participant in Fig. 8.7A(iii) had higher TV of 39.5 compared to the other two participants. As for the side view shown in Fig. 8.7B, all participants have bulging in the abdomen area had a different value of BV and TV. Fig. 8.8 shows the participant in the obese category (BMI = 30 kg/m^2). All participants showed a BV of more than 60. Interestingly, participants in Fig. 8.8A(i) and (iii) showed almost similar BV of 64.21 and 64.09, respectively. However, their fat distribution showed slight differences in which fat accumulates more in the abdomen region for the participant in Fig. 8.8A(iii). While in Fig. 8.8A(i), fat is distributed more in the thigh region.

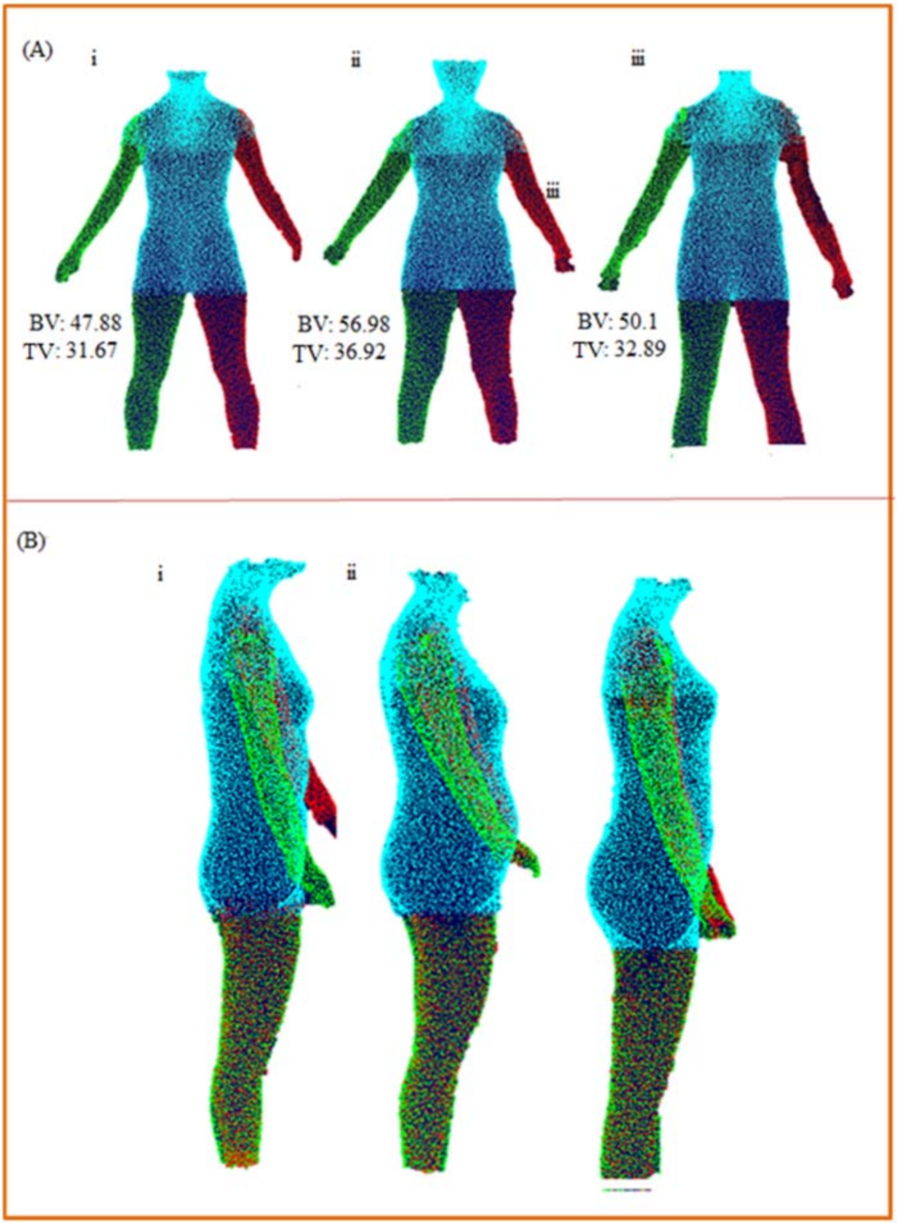


Figure 8.6 3D body models of normal BMI category (BMI = 20 kg/m^2). (A) Front view; (B) side view. Notes: BV indicates body volume and TV indicates torso volume.

The novelty of this study is the provision of a 3D body model as shown in Figs. 8.6–8.8, which compare the variability of body shapes according to BMI category. The 3D body models provided can help to distinguish individuals who have

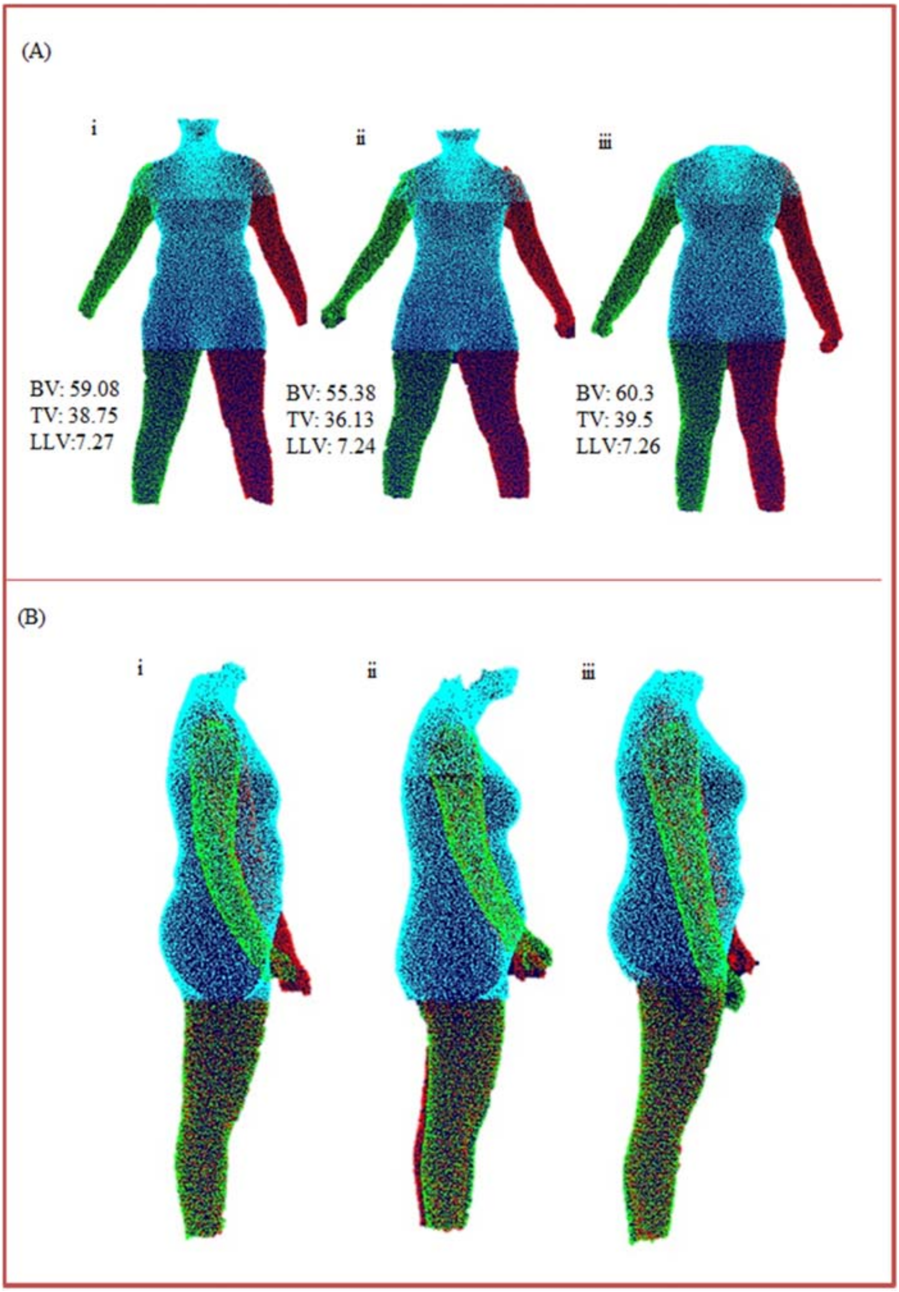


Figure 8.7 3D body models of an overweight category (BMI = 25 kg/m^2). (A) Front view; (B) side view. Notes: BV indicates body volume and TV indicates torso volume.

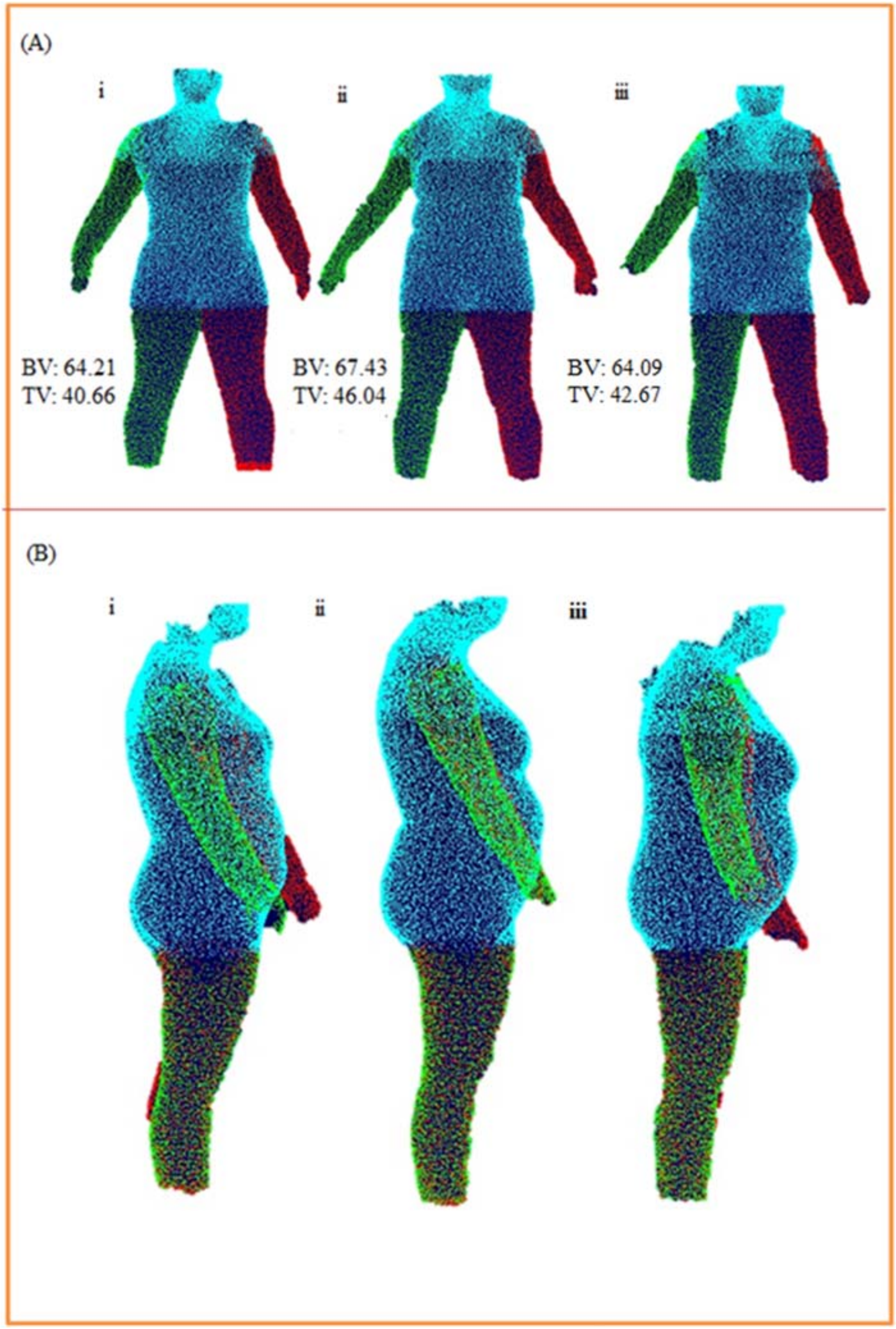


Figure 8.8 3D body models of an obese category (BMI = 30 kg/m^2). (A) Front view; (B) side view. Notes: BV indicates body volume and TV indicates torso volume.

accumulated more fat in their abdomen region. We can also use BV and TV as the reference to detect the excess amount of body fat in certain regions important to health. According to Daniell et al. (2014), the distribution of BV varies systematically with BMI. As BMI increases, the BV distribution becomes more centralized, specifically in the abdomen and pelvis regions. Similar patterns were found in our results and can be seen in Fig. 8.8. For the obese category, fat accumulates more in the abdomen and the shape is more of an android shape.

8.5 Importance of sizing and fit using 3D technology

Minimizing measurement error is of utmost importance to both manual and 3D anthropometry approaches. Anthropometric data are commonly collected manually using calipers and measuring tapes (traditional anthropometry), providing information on the static dimensions of the body in a standard position. This kind of measurement may be impractical because the observer needs to be carefully trained, the results may vary per the observer's skill level and measurement protocol, and the procedure may take longer. In contrast, when using 3D body scanning, raw data acquisition is rapid (in seconds) (Zancanaro et al., 2015). An automated 3D body scanner could potentially enhance the reliability of these anthropometric measurements since

Figure 8.9 Intellifit 3D full-body scanner room.
Source: From Warkulwiz Design Associates (n.d.), Intellifit® full-body scanner [image]. Available from: https://www.warkulwiz.com/?page = work&client = 86&filter = (Accessed on 6 June 2021).

the reproducibility of manual measurements of waist and HCs has been questioned (Medina-Inojosa et al., 2016).

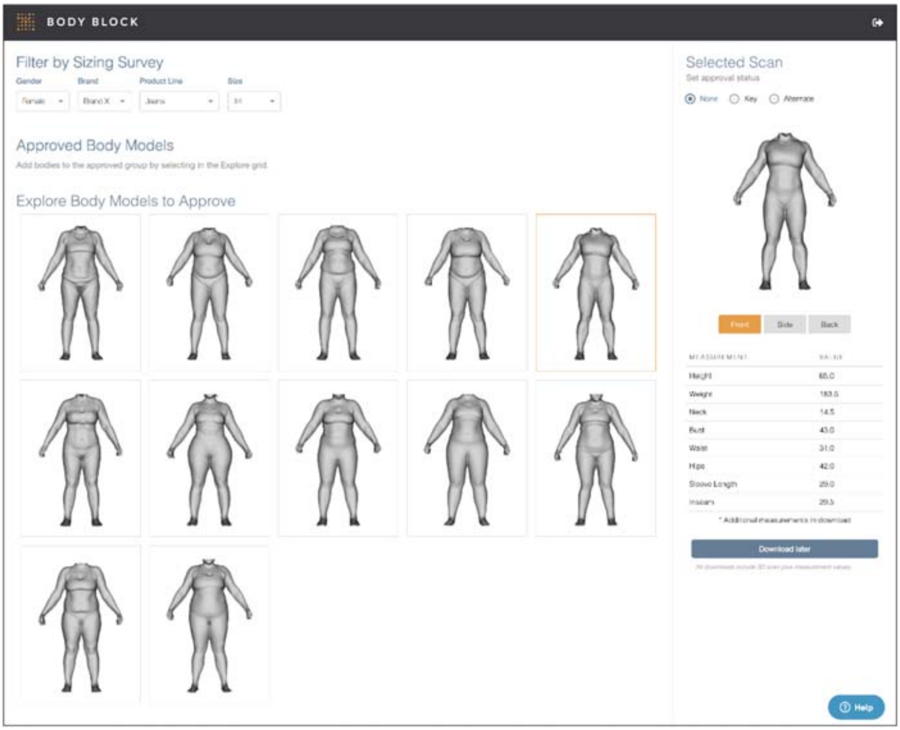
The 3D body scanner showed less variation and more precision both by numerical and graphical methods for reliability assessment, which is in agreement with the study conducted by Medina-Inojosa et al. (2016). Differences in technical issues arise when body circumference measurements obtained with a tape measure are compared with those obtained using a 3D body scanner. Measuring circumferences on a human body with a tape measure requires tension on the tape to hold the tape in a horizontal plane for the measurement; even though tension should be minimal with the tape measure, it is not tension-free compared to when measuring using the 3D body scanner (Wells et al., 2008). This study also confirms what some other studies have shown, namely, manual measurements of WC and HC may have significant variability (Jaeschke et al., 2015; Medina-Inojosa et al., 2016). Thus the NX16 3D body scanner may be considered a reliable instrument to use to obtain anthropometry measurements for sizing and fitting especially in the apparel industry.

Figure 8.10 FIT3D body scanner. *Integrated Chiropractic*.
Source: From Joseph, S. (2018). FIT3D scanner [image]. Integrated Chiropractic. Available from: https://docjoseph.com/fit-3d-now-available-at-integrated-chiropractic/2018-08-13-18-48-51/ (Accessed on 6 June 2021).

Lerch et al. (2007) research on 3D laser scanning technology for apparel states that 3D technology enables clothing to be designed by function and fit where it can be useful for protective clothing, athletic apparel, smart clothing, and thermal comfort in clothing. Subsequently, the 3D body scanner is capable of capturing body measurements and the outer layer of clothing where microclimate data can be measured; hence, functional clothing based on moisture management and climate comfort can be properly developed. Furthermore, it can be produced for both masses and the individual consumer (Lerch et al., 2007).

Fashion and health 3D body scanner room was introduced to the mass as a tool to make body measurements data available for a personalized fit, making buying clothes a lot easier and the data to be stored online for future seamless shopping experience (Horsey, 2011; Ontiveros, 2009; Belezina, 2011). Levi's is one of the brands that had been utilizing 3D scanner room technology for sizing and fitting purposes (Ontiveros, 2009) (Fig. 8.9) (Warkulwiz Design Associates, n.d.).

A study on four commercially available 3D scanners (FIT3D, Size Stream, Styku, and Naked Labs) shows reliable results on collecting anthropometric data (Tinsley et al., 2020). Although these commercial 3D scanners and systems are originally used for sports and physical health purposes, athletic apparel companies such as Adidas and Nike among others are utilizing its massive databases and the system for garment design (Arnett, 2019) (Fig. 8.10) (Joseph, 2018).



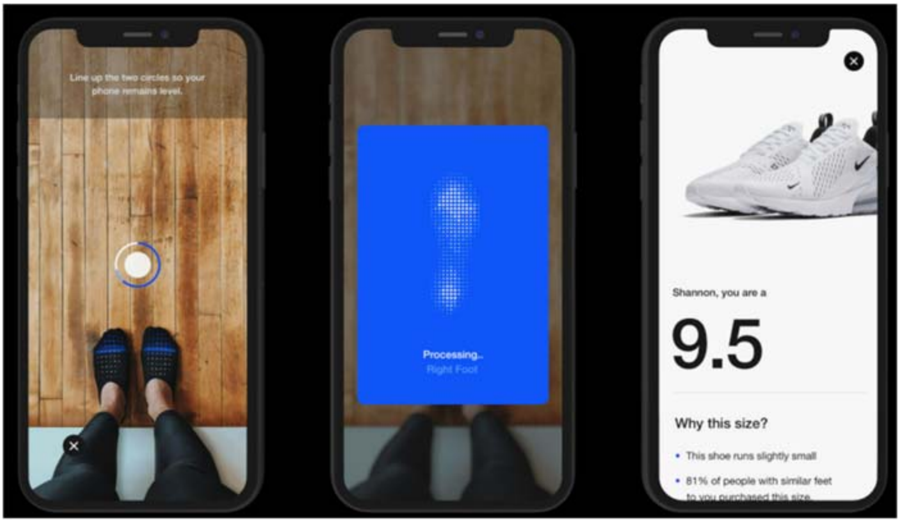
Gender: Female
Brand: Brand X
Product Line: Jeans
Size: [illegible]

● None ○ Key ○ Alternate

MEASUREMENT	VALUE
Height	65.0
Weight	183.5
Neck	14.5
Bust	43.0
Waist	31.0
Hips	42.0
Sleeve Length	29.0
Inseam	29.5

* Additional measurements in download

Figure 8.11 Human body database from BodyBlock AI by FIT3D (Shields, 2018a,b).



Line up the two circles so your phone remains level.

Processing..
Right Foot

Shannon, you are a

9.5

Why this size?

- This shoe runs slightly small
- 81% of people with similar feet to you purchased this size

Figure 8.12 Nike shoe-size recommendation app using 3D and augmented reality (AR) technology (Iftikhar, 2019).

Apeagyei (2010) mentioned that other than sizing accuracy, the apparel industry can also benefit from the avatar generated by the scanner as a medium for Computer-Aided Design (CAD) purposes where existing data can be reused for mass customization and virtual fitting.

Through mindful apparel purchase, digital anthropometric data may decrease unsold clothing for its improper fit, minimizing fashion waste and also enabling consumers to save time in choosing apparel; hence, saving millions of dollars of manufacturing cost and indirectly decreasing the carbon footprints (Pena, 2018; Shields, 2018a,b) (Fig. 8.12).

8.6 Conclusion

In summary, incorporating 3D body models generated from the 3D body scanner into body shape assessment could provide better outcomes, which are more reliable and accurate. This technology also gives some important information, especially in visualization, that can give a clear understanding of body fat distribution rather than having to only rely on BMI calculation, which only provides a one-dimensional measurement. This detailed information is very important for developing sizing and fitting in the clothing industry as the manufacturer can capture data in a large body sizing database. Thus the clothing industry can maintain the production of clothes according to the sizing system provided by 3D scanning technology. Proper fit and sizing will not only revolutionize the apparel manufacturing industry but also maximize the clothing's comfort and performance for the consumers. Results from this study will be beneficial in formulating standard sizing for Malaysian women and a more sustainable practice can be implemented for the local production. As 3D body scanning technology is proved to be effective, time-saving, and sustainable, further research on other body categories should be explored. Commercial 3D scanners are readily available in the market; therefore local fashion houses and boutiques are encouraged to integrate 3D body scanning technology into their businesses for apparel customization and better customer satisfaction by getting customer size matched with the clothing available there.

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The production system of mass customization using 3D body scanning technology

9

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9.1 Introduction

Mass customization (MC) is defined as a production process or production strategy that aims to provide personalized products and services with the perspective of large-scale provisioning of customer needs (Fogliatto et al., 2012). It aims at satisfying individual consumers' needs at an affordable price, similar to the price offered by mass production (Yeung et al., 2010; Nayak et al., 2015). Specific to the apparel sector's consumers' needs, MC takes off from these two causes: (1) consumers' unmet needs in finding ready-to-wears that fit them well; and/or (2) their unmet needs in design or their pursuit of design uniqueness or the co-design experience (Satam et al., 2011; Yang et al., 2015; Yeung et al., 2010). Therefore, some researchers define apparel MC as a technology-assisted process where the consumers can get involved in the design and production process to acquire their desired design styles and fit requirements (Fralix, 2001). One classic business vision is to have consumers walk into a store, get measured through a three-dimensional (3D) body scanner, browse through the virtual 3D garment library, and try the 3D garments on in a virtual environment, and return to the store in a short period of time to pick up their "hot-off-the-assembly-line" custom-made garments (Nayak et al., 2015).

Successful implementation of MC can be beneficial for various parties in many ways. It can provide better quality and service to the consumers and, thus, increase consumer satisfaction (Yeung et al., 2010). It can help companies to retain consumers and gain brand loyalty (Yeung et al., 2010). It can reduce or avoid sale forecasting errors and, thus, reduce the inventory for the finished product and improve cash flow (Nayak et al., 2015). It can also reduce markdowns and returns, generate more profits for retailers, and help companies to increase revenue and gain a competitive advantage (Satam et al., 2011). From an environmental perspective, it can reduce waste and emissions during design and manufacturing through an on-demand production (Grimal & Guerlain, 2014). With fewer consumer returns and a lower level of unsold products due to inaccurate demand forecasting, the apparel industry can become more environmental-friendly. Since there has been more public emphasis on social responsibility and environmental sustainability in industrial practices, MC can help companies to establish good brand images (Guo et al., 2019).

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Despite its many benefits, MC has not yet been fully implemented in the apparel industry (Yang et al., 2015). This is because the successful implementation of apparel MC requires thorough industrial adjustments on the product development process, manufacturing process, communication, distribution and supply chain management, information management, etc. (Fogliatto et al., 2012). Due to the complex nature of the MC system, a successful apparel MC model requires the adoption of technologies (Yeung et al., 2010). Among all the technologies, 3D body scanning has been widely recognized as the most critical tool and an enabling technology for apparel MC (Fralix, 2001). A 3D body scan contains a set of coordinate data points that numerically describe the surface of the human body in three dimensions (Ashdown & Loker, 2010). After three decades of development, 3D body scanners have become more advanced and affordable by both retailers and consumers. 3dMD (USA/UK), Vitronic by Human Solutions (Germany), Space Vision (Japan), botspot (Germany), Elasizer (Italy), TG3D Studio (Taiwan), Hamamatsu (Japan), Fit3D (USA), Telmat (France), and [TC]^2 (USA) are manufacturers of 3D body scanning systems available in the market today, to name a few (Lansard, 2020). Moreover, smartphone-based (or tablet-based) 3D body scanning or 3D construction of the human body through photo images have developed significantly (Daanen & Psikuta, 2018): companies such as IN3D (USA), NetVirta Inc. (USA), Bodyform3D (Canada), Presize.ai (Germany), SizeYou by i-Deal (Italy), meepl (Switzerland), TechMed:3D (Canada), and QuantaCorp (Belgium) provide various solutions for the acquisition and processing of body-related data through mobile devices, while some offer built-in services such as size recommendation, and 3D virtual showroom and 3D virtual dressing room based on the acquired scan. Taking full advantage of the 3D scanning technology in apparel MC is no longer implausible.

9.2 3D body scanning in apparel mass customization production

9.2.1 Computer-aided design/computer-aided manufacturing systems

The primary tools to support MC are Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), which enable custom designs to be deployed into production quickly (Tabraz, 2017). For apparel production, CAD systems convert consumers' choices of designs into pattern pieces which will be later cut and sewn, according to consumers' body dimensions. Note that draping in 3D (on dress forms with muslin) is rarely used in the industry (Ashdown & Vuruskan, 2017); therefore, patternmaking methods discussed in this chapter all refer to flat or two-dimensional (2D) patternmaking techniques. CAM systems strategically maximize the use of a machine to automate the manufacturing process (Yeung et al., 2010). Apparel CAM systems were initially developed aiming for a smooth transition from 2D designs to 3D manufacture. Knitting, especially 3D knitting, weaving, and embroidery can particularly benefit from CAM. CAM systems are also adopted by companies nowadays to guarantee accurate cutting of the pattern pieces and used for fabric waste management (Burke & Sinclair, 2015).

Integrating 3D body scanning technology with CAD/CAM systems has received widespread attention. While traditional CAD systems focused on 2D pattern development, which still requires an iterative process of creating and shipping physical prototypes back and forth to examine product fit and style, causing tremendously longer lead time, higher costs, and increased carbon footprint; 3D CAD systems can significantly speed up the process and save on costs by eliminating/reducing the need for physical prototypes while helping companies to respond to the market faster (Lee & Park, 2017; Tabraz, 2017). A review of the technological development of 3D CAD systems can be found in Sayem et al. (2010), Song and Ashdown (2015) and Daanen and Psikuta (2018). Leading textile and apparel CAD/CAM companies such as Gerber's AccuMark system, Lectra's Modaris system, Human Solutions' Assyst system (3D Vidya), OptiTex's 3D Suite, CLO's Clo3D, Browzwear's Vstitcher, and Tukatech, all, have functions embedded that allow 3D body scans to be directly imported and to assist in the design/production process (Fig. 9.1) (Daanen & Psikuta, 2018). Moreover, these systems enable 3D garments to be virtually stitched together, adjusted based on fit or style, and visualized on virtual runways. These systems enable realistic simulation of fabric based on physical properties and most incorporate a wide variety of fabric choices in their digital libraries.

It is critical that accurate and realistic digital human models or avatars in terms of body size and shape be used to guarantee the fit and to ensure the final look of the product is what the designers and/or consumers envision (Istook et al., 2011). There are multiple ways to achieve this. The most intuitive one is to directly use

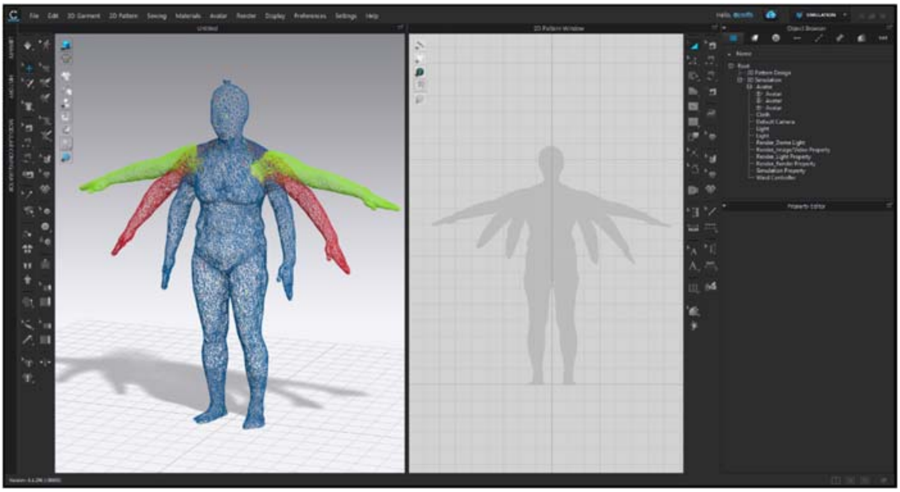

Figure 9.1 3D body scan imported into CLO and got manipulated.

the body scan of the human fit model or that of an individual consumer. As mentioned earlier, most major 3D garment simulation systems offer this function. One downside to this is that the body mesh has to be "cleaned" to remove any holes or noises to ensure that virtual garments can be fitted correctly, which means either a more advanced (and likely more expensive) body scanner with powerful algorithms to clean and patch up the scans need to be used, or an extra amount of time and effort need to be devoted to handling the scans (Istook et al., 2011). Another way is to use digital dress forms to be developed based on large-scale anthropometric surveys in which thousands of 3D body scans were acquired along with demographic information. For example, Alvanon has a professional data analytics team that works with up-to-date 3D body scan data, and it's acknowledged that their AlvaForms are one of the most highly recommended dress forms and used by many of the world's largest fashion brands and apparel manufacturers for fit testing. Alvanon also offers the digital version of their forms, The Virtual AlvaForm (Fig. 9.2), that are made compatible with 3D garment simulation systems such as CLO, Browzwear, OptiTex, and Gerber (3D, n.d.).

Using standard dress forms can still align well with apparel MC through MC sizing. Instead of producing highly personalized garments for consumers at an individual level, MC sizing is a strategy that still depends on body shape categorization to create size groups but offers exponentially more variety of sizes by including new measurements, thus creating new levels of variables for consumers to choose from (Ashdown & Loker, 2010). For example, Lands' End swimsuits included different torso lengths as a new sizing variable for their original sizes (Ashdown & Loker, 2010). Moreover, MC can be achieved solely from a design perspective and, especially, for garments from which consumers do not have high expectations on fit. For example, Threadless.com offers a wide range of artwork designs to be printed on T-shirts, hoodies, tanks, socks, and leggings and produces and sells based on

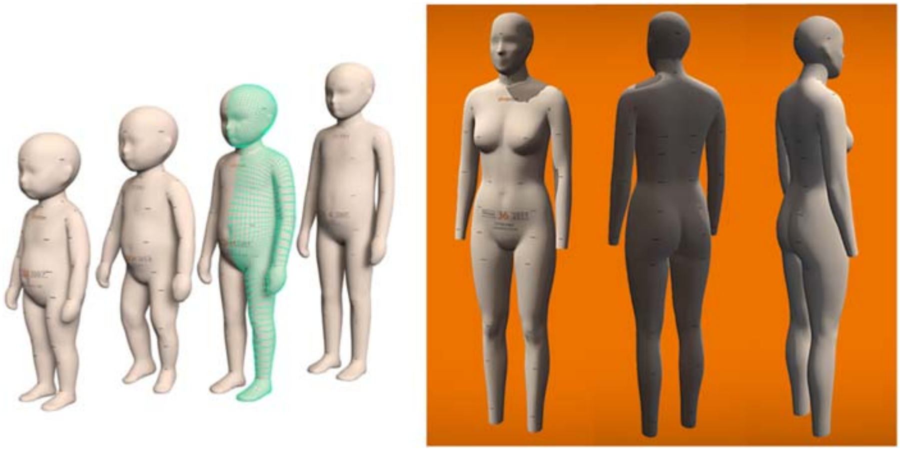

Figure 9.2 The Virtual AlvaForms (Alvanon, n.d.).

consumers' orders (Grimal & Guerlain, 2014). In this case, digital dress forms may be preferred over body scans for their higher efficiency.

A third way to build digital human model is by inputting body measurements to modify the body dimensions of a default avatar through a configurator. For the final avatar to have a realistic representation of the human body-shape, it is still necessary to train the configurator with large-scale body scan data. For example, CLO's Avatar Editor is based on thousands of body scans so that measurements not assigned by the users can be automatically adjusted to create more realistic body shapes ([Size Editor] Adjust Avatar Size, 2020). In their Avatar Editor (Fig. 9.3), there are a few default avatars with different body types that users can choose from and based on which users are allowed to input total body height, circumferential measurements for bust, waist, high hip, low hip, neck base, thigh, bicep, etc., and many other detailed measurements such as inseam height, head width, etc., to make further adjustments possible. Nevertheless, however much advanced are the training and the prediction algorithms, the edited avatars are still generic models that may not represent the complete individuality of the human body (Istook et al., 2011). In addition, these edited avatars may not represent certain uncommon body shapes, especially for those whose scan data are not included in the training data. Also, considering the fact that consumers with uncommon body shapes are more likely to

Select Avatar: FV2_Feifei

Total Body
Height: Total Height 65.500 in Inch
Width: Under Bust Circumference 29.000 in

Details: Advanced (Dressform) Inch

Neck
Neck Base Circumference 14.250

Shoulder
Across Shoulder (Curvilinear) 15.250
Shoulder Drop 1.625

CF Neck to
CF Neck to Waist 14.375

CB Neck to
CB Neck to Waist 16.125

Bust

Hip
High Hip Circumference 33.750
Height 37.000
Low Hip Circumference 38.250
Height 32.500

Leg
Inseam Height 30.500
Thigh Circumference 22.125
Height 29.372
Knee Circumference 13.750
Height 17.875
Calf Circumference 13.250
Ankle Circumference 8.875

Figure 9.3 CLO's Avatar Editor.

pursue custom-made clothing, it is better to use 3D body scans for virtual fit testing, although edited avatars may be sufficient for design purposes and can even be superior in terms of simulation speed and quality (Lee & Xu, 2020).

Experts at Assyst 3D recommend using four types of avatars based on different purposes: (1) Basic Avatar, a flexible avatar integrated in the 3D system that can adapt to different body shapes quickly, to be used during line planning and the product pre-development process; (2) Design Avatar, a nice looking avatar but without too much trivial details such as hair, together with a library of pose options, to be used during product development and virtual prototyping; (3) Fitting Avatar, an accurate avatar in terms of size and body shape which is essentially a virtual copy of a physical dress form (multiple avatars needed for different sizes), to be used during product development for fit testing; and (4) Sales Avatar, a perfect avatar that looks like a real human model as much as possible, with realistic skin texture, hair, etc. (due to the costly computation time, a pre-programed simulation with restricted user interaction may need to be adopted), to be used to showcase the final collection and for marketing, sales, and e-merchandising. Companies such as Replika specialize in creating lifelike human avatars and have been working with 3D CAD developers and apparel consulting companies.

In addition to the 3D CAD systems mentioned before, SHIMA SEIKI (Japan)'s APEXFiz 3D fabric simulation and design systems can generate high-quality virtual knit-fabric swatches and garments with realistic dimensional structures and textures (Fig. 9.4). Although woven, non-woven, and knit fabrics can, all, be simulated, the primary use of the software is for knitwear design, along with the company's WHOLEGARMENT knitting machine. SHIMA SEIKI's Yarnbank offers an extensive digital library for textile materials such as wool, cashmere, cotton, etc. Another library incorporated in the design system includes the essential and most common

Figure 9.4 Knits simulation (Photos provided by SHIMA SEIKI MFG., Ltd.).

knit constructions/patterns, such as rib, interlock, jersey, reverse jersey, rib stripe, half cardigan, full cardigan, float jacquard, rib jacquard, etc. The technological solutions offered by SHIMA SEIKI have a great potential for achieving zero-waste production in the true sense. Not only would no fabric be wasted as for example in the cutting process of conventional garment production because yarns are directly knitted into garments, but also garment overproduction and unsold inventory can be avoided through on-demand knitting and sales prediction via online pre-ordering.

Despite the advances in the development of 3D CAD systems in recent years, there still lacks a widespread application of the systems in the apparel industry. One primary reason is the steep learning curve to master the 3D software. It can take an average of two and a half months for traditional product developers to familiarize with the new system (Shin, 2015). Training pattern makers and designers to switch to 3D costs time and money. What makes it worse is the need sometimes to use several 3D systems for different purposes, as different 3D systems have different technical emphasis and advantages. A system that is superb at virtual garment rendering may be more suitable for marketing purpose. Another system that offers a wide range of exchangeable formats of pattern files that can be easily and rapidly imported to other 2D CAD and/or CAM systems, may be preferable for prototyping and pattern revisions. Taking on new technologies can be considered risky and not cost-effective, especially in the short run, by apparel companies. However, the Covid-19 pandemic in 2020 has forced many apparel companies to realize the importance and urgency of adopting 3D. To adopt 3D, companies should actively look for innovative ways to train their staff, upskill their workforce, or offer new recruiting channels to hire talents. It is also very critical that 3D CAD systems are included in fashion education, to prepare the next generation of designers and fashion workers.

Another major reason for the lack of adoption is the questionable validity of the current virtual fit testing methods. 3D CAD systems offer various solutions that attempt to visualize fit. CLO includes a "stress map" function in their system to show the external stress that causes garment distortion per unit area of the fabric; a "strain map" function to show the distortion rate in percentage; and a "fit map" function to show the tightness of the 3D garment (Garment Fit Maps, n.d.). OptiTex includes the "tension map" feature to allow users to inspect the amounts of stretching and tension at different areas of the virtual garment, and also the distance between the fabric and the avatar (Tension Map, n.d.). Nine different colored maps can be generated via functions named: "Distance (cm)," "Tension XY (fg/cm)," "Tension X (fg/cm)," "Tension Y (fg/cm)," "Stretch XY (%)," "Stretch X (%)," "Stretch Y (%)," "Normal Collision Pressure," and "Tangent Collision Pressure." However, the overwhelmingly large number of options can be very confusing to users in terms of how to interpret the colors and which map(s) they should base their decisions on. In addition, whether the maps, alone or combined, can faithfully represent fit and replace the fit tests on physical samples is highly questionable. Moreover, while fit test on physical garments relies on the directions and the number of wrinkles that appeared on the garment, still the fact remains that whether the virtual simulation is capable of generating wrinkles and visuals that are true to life is also questionable (Kim & LaBat, 2013;

Porterfield & Lamar, 2017). Research has been done to visually examine the difference between real and virtual fits of garments. Even for skirts, the results were not satisfactory, let alone for pants, the most challenging garment item for a good fit (Koo & Suh, 2009; Lee & Park, 2017; Song & Ashdown, 2015).

Other hindrances for 3D adoption include: (1) the complex and manual workflows in 3D systems, which require the development of automated functions and again the training of staff; (2) the inconsistent quality and results in the simulations, which require further improvement of the technology and the establishment of virtual testing standards; (3) the large volumes of data, which require better data management and storage solutions; (4) the disconnection of the product team from the revenue team (responsible for marketing, sales, e-commerce, etc.), which requires enhancing communications and extending training; and (5) the high costs in establishing a 3D pipeline. It can take 18−24 months to build the pipeline and maintaining it can still be a recurring cost center. One bottleneck is the difficulty in scaling real-life 3D rendering. For example, to have the virtual garment viewed in 3D, each design needs a turntable rendering where a series of 2D images at different perspectives of the garment need to be generated. It could take 1 or 2 hours for a single garment and 10 hours of rendering for all its colorways. Fortunately, companies such as FNX specialize in speeding up the rendering process to generate fast and realistic-looking images for e-commerce. 3D CAD developers and apparel companies should work closely with experts from the animation industry and the film industry in this aspect to make virtual technology more acceptable and accessible.

Progress has been made on the 2D CAD systems for MC pattern development as well, with 3D body scanning as a most crucial technological foundation. Services such as Bespokify (Singapore) and Tailornova (USA), and software such as Clone Block (Canada) aim at creating custom-fit or Made-to-Measure (MTM) patterns based on body measurement data extracted from 3D scans. 3D scanning technology has enormously increased the potential of MTM patternmaking, due to a scanner's ability to extract measurements rapidly, much more efficiently than manual measurement techniques can (Istook et al., 2011). In addition, body measurements that are not so easily obtained through manual techniques, such as angles, depths, etc. can be rapidly and consistently extracted from 3D body scans (Istook et al., 2011). 2D CAD systems such as Tukatech's TUKAcad Tailor Edition system, Gerber's AccuMark MTM system, and InvenTex MTM, online patternmaking platforms such as BootstrapFashion.com and PatternLab, prompt users to import or input body measurement data to: (1) find patterns that match; or (2) make modifications to certain "master" patterns to incorporate customized fit features.

Most of the methods to create MTM patterns, however, do not truly provide custom-fit patterns for consumers at an individual level (Miracle or Myth? MTM, 2015). In order to achieve fully personalized MTM, the following issues need to be addressed and improvements made for the 2D CAD systems: (1) given it is difficult to collect body measurement data correctly and reliably from consumers (Gribbin, 2014), it therefore follows that it is better to avoid input prompts and rely on 3D body scanning technology; (2) given traditional body measurements are not sufficient to describe many detailed body shape attributes, it therefore follows that new measurements ought to be added or new methods adopted to alter "master" patterns; (3) given many of the master pattern pieces were derived from empirical data which do not reflect the full range of the variation of body shapes and postures of consumers, it therefore follows that updated anthropometric data ought to be collected and new "master" patterns ought to be developed specifically for the "non-typical" body shapes; and (4) while measurement extraction relies on the accurate placement of body landmarks, still automatic detection of landmarks on body scans is not sufficiently reliable nor consistent (Istook et al., 2011; Nayak et al., 2015), with existing auto-detection algorithms based heavily on body shape assumptions (and again, excluding non-typical body shapes). On the other hand, manual placement of body landmarks is extremely time-consuming, counteracting the benefits of the fast body scanning process. This can also bring challenges when new measurements are added to alter patterns (in terms of cost effectiveness and consistency across scans/consumers). Therefore, new technological approaches or solutions ought to be developed to automate the landmark detection process.

CAD and CAM are usually brought up together in the apparel industry (Ashdown, 2014; Burke & Sinclair, 2015; Istook et al., 2011). Given most CAD systems (OptiTex, Gerber, Tukatech, Lectra, Assyst, VetiGraph, etc.) also have production management functions such as marker making incorporated, it therefore follows that these systems can also be considered as CAM systems. Marker making is the process of arranging pattern pieces to be cut on a rectangular area where the fabric will lie. Most software not only offers automatic marker making, but also reports the marker efficiency (the area ratio of the marker used in a garment to the total marker), a critical parameter for fabric waste management. In addition, these CAD/CAM systems automatically generate order information reports, including size and measurement information, material and style information, and even bar code information, to facilitate automatic manufacturing (Customize Excel Report, n.d.). Collaborative tools have also been added to the systems for communication with other parties in the supply chain. For example, CLO has a function that allows annotations to be added anywhere on the pattern pieces to inform other parties (Pattern Annotation, n.d.). Moreover, new functions have been developed specifically to facilitate MC. For example, OptiTex provides a "Print & Cut" function that allows graphics created via Adobe Illustrator to be aligned on the patterns and kept for marker making, so that together with a digital fabric printer, the product can be printed and cut on-demand (Print & Cut, n.d.). AccuMark MTM system offers information management tools for querying orders by customer name or any other order detail. Lastly, 3D simulation systems are highly interconnected with CAM (Burke & Sinclair, 2015). Most 3D systems also offer digital pattern library, digital fabric library, avatar library, and other data management solutions. Companies such as Carmel Clothing have been using 3D technologies to collaborate with partners across the supply chain.

Earlier reports claim that the 3D virtual simulation technology can cut down on time for designing and prototyping by an estimated 50% and can reduce the number of samples needed from an average of 3–5 to just 2 (Song & Ashdown, 2015). It can also facilitate decision-making at various stages of the design and production process (Porterfield & Lamar, 2017). At the 2020 3D Tech Festival organized by Alvanon, Assyst reported that their industrial customers were able to achieve a 15%–50% reduction in product pre-development time, a 30%–60% reduction in workload and oversampling, and a 5%–15% decrease in communication efforts. Gerber reported that with 3D implementation, the number of prototypes can be reduced to 2–3 from 8–10, and a 1.5–2-week shorter turns on average can be expected. Carmel Clothing reported a 53% decrease in physical sampling on average, a 29% decrease in the number of fits per style, and a 38% increase in overall productivity, after adopting OptiTex 3D. For designers and product developers, the ability to check the final looks of their designs in real-time through virtual means and then send their designs directly to the machines can significantly reduce efforts spent on communication and enable a seamless production process (Lee & Park, 2017). On the other hand, for consumers, the ability to preview the design they chose or co-created on a virtual version of themselves can be extremely helpful in making purchase decisions (Istook et al., 2011). Current CAD/CAM systems have become better at integrating all areas of the production and merchandising processes, connecting all parties along the way, including buyers, designers, suppliers, manufacturers, retailers, etc. They make it possible for companies to reduce cost and lead time, to achieve economies of scale while maintaining individual-level customization for design and fit (Burke & Sinclair, 2015).

9.2.2 Modular design

Modularity is an efficient design practice that decomposes complex assemblies or processes into simpler but standardizable units, or modules, each of which can be created and modified independently and also replaced by other modules of a similar nature/function (Chen & Lapolla, 2020; Grimal & Guerlain, 2014). A spread collar, a straight-point collar, a button-down collar, a club collar, etc., can be all considered as modules of a similar nature/function for an MC shirt design and production system. Modules of distinctive functions can be combined and assembled into a variety of designs. For example, a spread collar module can be configured with an angled chest pocket module, and a straight-point collar module with a rounded flap pocket module. Modifying the patterns for the collar module will not impact the pocket module. Moreover, if there are three choices for each of the two module variables, there will only be $3 + 3 = 6$ modules while achieving $3 \times 3 = 9$ design options. Adding sleeve modules as another module variable, with long-sleeve and short-sleeve as choices, for instance, will increase the number of design options to $3 \times 3 \times 2 = 18$ but increase the number of modules by 2. Therefore, one main goal of a modular system is to achieve a wide range of outputs in the final products by changing the way a small variety of parts combine to give a final product (Chen & Lapolla, 2020). From the perspective of project management, modularity can be viewed as grouping relevant processes and components into standard units/modules for effective production and management, and the modules can be produced in the same fashion of mass production. It allows efficient and economical production of individualized small-scale products; therefore, it is considered a fundamental strategy for MC (Yeung et al., 2010).

Fashion companies such as JC Penney, Levi Strauss, Nike By You (previously called Nike ID), Adidas, Brook Brothers, Converse, Burberry, and Ralph Lauren adopted modular customization by offering their consumers a variety of modules to choose from to create individualized products (Nayak et al., 2015). However, only a limited number of styles from a much larger style library, owned by the company for ready-to-wears, are offered to consumers for MC. Moreover, to reduce cost, patterns are usually first created based on standard body shapes and later adjusted to meet individual consumers' fit requirements (Yeung et al., 2010). Ralph Lauren's "Create Your Own" men's polo shirts include sleeve modules (short-sleeve and long-sleeve), fit modules (classic, custom slim, big & tall, and golf), fabric choices (cotton mesh, weathered mesh, etc.), color choices, a variety of logos and monograms to be embroidered onto the shirt combined with a variety of thread color choices, or a variety of graphic to be printed onto the shirt. Women's polo shirts have slightly more styles to start with but have similar within-style modules. It is worthwhile mentioning that certain module choices may not be offered to combine with other modules; therefore, the final design options can be fewer. For example, four fit choices are offered for women's polo shirts: classic, slim, relaxed, and cropped; however, for short-sleeves, only classic, fit and relaxed fits are available, whereas for long-sleeves, only slim and cropped fits are available. Lastly, a ready-to-wear sizing technique was adopted for these polo shirts, where men's sizes range from XS to XXL and women's from XXS to XL. No adjustment is offered to fit individual consumers.

Taking the example of Levi Strauss, today's Levi Strauss's "Tailor Shop" emphasizes customization more on design rather than on fit. For a selected pair of jeans style, consumers can choose from a variety of modules for fabric wash color, overdye color, graphical pattern (e.g., floral, galactic, brush, leopard, etc.), distress level (none, worn, damaged, and destructed), and back patch color and pattern (e.g., rainbow, tan and copper foil, fluo pink, etc.). Although a wide range of sizes is offered based on waist circumference and jeans length, it is still based on a sizing technique for mass-produced garments. However, Levi Strauss's mass-customized blue jeans in the 1980s and 1990s had an emphasis on fit. Levi Strauss's launched the "Personal Pair" program in 1994 and later renamed the program the "Original Spin." Prototype jeans in every possible combination of waist, hip, and crotch length were provided in-store for try-ons. Jeans were individually manufactured for each consumer after pattern alterations were made (Ashdown & Loker, 2010; Yeung et al., 2010). This strategy increased the number of jeans sizes from 40 to about 4000, two orders of magnitude. However, the program was considered low in efficiency and, sometimes, annoying to consumers, as consumers had to visit the store, get measured, and try on multiple pairs of prototype jeans (Zeleny, 1996). In 2004, Levi's stopped the "Original Spin" program. The discontinuation can be a result of the following reasons: the closure of Levi's last domestic production facility; the use of MC as merely a marketing strategy while failing to generate additional values for consumers; neglect of deepening relationship with consumers and collecting consumer feedback; and neglect of improving the shopping experience for consumers (Ashdown & Loker, 2010). Later on, although Levi's started to set up body scanning for their consumers, measurement data obtained from the scanners were used only to identify the best-fitting jeans in stock, rather than for customization (Yeung et al., 2010).

Online fashion design software/services such as Tailornova and PatternLab attempt to achieve MTM patternmaking by modularity. Tailornova offers users the benefits as follows: (1) given modules for silhouettes, sleeves, necklines, straps, back closures, ruffles, pockets, waist bands (pants), etc., users get to preview the technical sketch of the final look of their design and export the flat pattern set in a. dxf format which is compatible with most CAD systems; (2) users are allowed to switch their choices for any module at any time and view the updated technical sketch instantly; and (3) the fit can be modified based on an input of body measurements at any time, including any time after the module selection and configuration. PatternLab provides a slightly different user experience: (1) users are prompted to select a general pattern block from a limited set of choices (usually 1−3) of block modules. For example, there are three blocks for skirts to choose from, namely a basic skirt block, a semi-circle skirt block, and a full-circle skirt block. (2) Users are then guided to the next step to determine the garment fit by choosing either pre-defined garment ease settings or custom settings. If the pre-defined fit is based on industrial standards and body measurements (e.g., bust ease = 9% of bust circumference), then the custom fit requires users to input their preferred bust ease, waist ease, and hip ease in centimeters. (3) Other module features are introduced later via the step-by-step guidance, including modules with higher degrees of design details (e.g., the waistband modules). While users cannot switch to another choice offered by an earlier set of modules in the patternmaking process without retracing to the earlier steps where the module was introduced, the fact remains that instead of merely offering choices, PatternLab enables users inputs for many other steps as well. For example, users can input their preferred skirt length in centimeters by choosing from thigh-length, knee-length, and floor-length skirts.

Moreover, Tailornova allows instant 3D visualization of the selected module patterns for design preview. Digital human models are built by modifying the body dimensions of default avatars using the same set of body measurements input by users to modify the flat patterns. Therefore, it is critical that the body measurements are correctly measured. Since 3D body scanning technology has been considered the most reliable way of acquiring body dimension data, the technology can play an essential role in modular patternmaking and design. An upload of their body scans into the system/platform can save users the trouble of manually inputting data which is also error-prone. Avatars built directly from body scans can look more realistic and, therefore, deemed more trustworthy by users to make design and fit decisions. In addition, the use of digital design libraries can greatly benefit modular design. Libraries incorporated in 3D CAD systems are essentially modules. They provide the solution for easy maintenance and update of the modular design choices. New fabrics can always be tested and added to the fabric library, and new graphics to the graphic library. Switching to another modular choice and previewing the final look in 3D can be more easily achieved in real-time with preloaded libraries, making it possible to create an interactive co-design experience for consumers who do not possess any technical design skills.

In addition to applying modularity in products, modularity in the production process is applied such that the products can be assembled efficiently via the configuration of independent modules (Yeung et al., 2010). Process modularity enables a flexible production process. It is based on three critical factors: (1) process postponement, which is the deliberate delay to wait for customization demands; (2) process re-sequencing, which is the reorganization of the production process sequence; and (3) process standardization, which is specifically for early-on production steps (Yeung et al., 2010). Postponement, in particular, is an essential strategy for enabling MC. It allows products to be stored in a semi-finished state, so that the final assembly can be processed after consumers' requests are known (Guo et al., 2019). It also allows companies to outsource production activities and/or materials to reduce cost and further enhance flexibility and responsiveness in the production process (Yeung et al., 2010).

Modularity and postponement can save time because early-on standard production steps need not wait for consumers' inputs. However, MC garments are bound to have a longer lead time than ready-to-wears, and time is still an essential concern. Unlike Ralph Lauren's polo shirts which have predefined sizes, MC garments with highly personalized fits which require adjustments of patterns for individual consumers can have an earlier decoupling point (or order penetration point, referring to the stage where consumers' requests may influence the production of the customized products). For this type of apparel MC, technologies and high processing speed computers can be very important for the postponement policy to be successfully implemented (Guo et al., 2019). 3D simulation technologies and MTM systems can be especially helpful. Lastly, the postponement policy also relies heavily on a reliable MC system (Guo et al., 2019). Since 3D scanning is more reliable in acquiring body measurements, it further proves its importance and usefulness.

One downside of modular design is that it may limit the design variety for consumers (Yang et al., 2015), especially for consumers who pursue unique products and co-design experiences (Grimal & Guerlain, 2014). However, other researchers found that too many design choices may bring confusion and frustration to consumers (Ashdown & Loker, 2010). Therefore, identifying the right level of modularity and the right number of modular choices can be critical, not only for the sake of consumer satisfaction, but also for inventory and production management.

9.2.3 Modular production system, unit production system, and flexible manufacturing system

In general, there are five types of garment assembly/production systems adopted by factories: Bundle System, Progressive Bundle System (PBS), Modular Production System (MPS), Unit Production System (UPS), and Flexible Manufacturing System

(FMS) (Ashdown et al., 2007; Kincade et al., 2013; Moin et al., 2013). Note that MPS is a different concept from "modularity" or "modular design" (described in the previous section). The Bundle System, or Conventional Bundle System, is a dedicated system in which work units, i.e., pieces of multiple garments, are tied into bundles and assembled at the same time. Due to limitations in equipment and operator training, factories using Bundle System can only make one category of garments (shirts, jackets, etc.) (Kincade et al., 2013). Similar to a Bundle System, in a PBS, garment pieces are assembled in bundles. PBS is also called a "straight-line system" or "assembly line system," in which workers in a sequential line do their assigned single tasks on each work unit within the bundle and pass on the work unit to the next operator using a tray, a cart, a conveyor, or some other automated transfer device (Kincade et al., 2013). Bundle System and PBS are traditional systems that have been used worldwide for several decades, mainly due to their ability to produce ready-to-wears in large volume at low unit costs. However, they lose their cost benefits when the degree and the frequency of style change increase and when low volume productions, as in the case of MC, are expected (Moin et al., 2013).

The MPS is also called a Team System or Cellular System, in which 5–17 operators work as a team or module to produce one finished garment at a time (Ashdown et al., 2007; Kincade et al., 2013). In a team or module, each operator is trained, sometimes cross-trained with other team members, for three or more tasks. Operators in a team help one another to finish the garment fast and also help to correct their team's work throughout the process to ensure the quality of the work (Ashdown et al., 2007). Levi Strauss used this production system to manufacture their custom-fit jeans in the 1980s and 1990s (Ashdown & Loker, 2010). More factories nowadays are converting to MPS from PBS for agile and flexible manufacturing (Moin et al., 2013).

The UPS, also called an Overhead System or Hanger System, is a computerized system that processes garment products by individual units (Ashdown & Loker, 2010). All pieces for one garment are transported via a computer-controlled overhead transporter and sent to the appropriate operation stations where operators perform the tasks without removing the pieces from the transporter. Operators are often cross-trained for multiple tasks so that they can switch to a different task to avoid bottle-necks in the production process (Ashdown et al., 2007). One downside for UPS is that it requires heavy capital investment for the installation of the overhead transporter (Moin et al., 2013). Nonetheless, UPS can be very efficient and beneficial with regard to small-lot production and MC production (Satam et al., 2011).

Lastly, the FMS is a system made up of various manufacturing techniques and optimized program modules (Guo et al., 2019). It can be achieved by the combined use of information systems, materials handling systems, and computer-controlled manufacturing equipment such as CNC (computer numerical control) systems (Dean et al., 2009). For example, the same automated transporter used in UPS can be installed for PBS and MPS (Moin et al., 2013). Adopting FMS in dedicated flow lines such as those in a PBS can achieve economies of scale while attaining a certain level of customization (Dean et al., 2009). Flexible manufacturing via flexible machinery (the core of a UPS), flexible operators and operational structures (as in an MPS) enables companies to compete on economies of scope (instead of economies of scale), ensuring high efficiency and quality for products with high variants (Squire et al., 2006). FMS can also be especially efficient to reduce inventory management costs introduced by the high level of modularity in MC (Guo et al., 2019). Other flexible machinery and manufacturing techniques for mass-customized apparel FMS include digital printers, single-ply cutters, tension-free spreading machines, automated cutting machines, digital sewing machines, and so forth (Nayak et al., 2015; Satam et al., 2011). 3D body scanning systems, virtual fitting systems, CAD/CAM systems, computer-aided process planning systems (which serve as the link between CAD and CAM) can all be critical information systems to implement apparel MC via FMS.

9.2.4 Additive manufacturing/3D printing

Additive manufacturing, commonly known as 3D printing, is the process of joining materials, usually layer by layer, to create parts from 3D digital data as opposed to subtractive and formative manufacturing methods (Lee et al., 2017). Other names for 3D printing are "solid freeform fabrication," "direct manufacturing" and "rapid prototyping" (Eyers & Dotchev, 2010). 3D printing enables the quick fabrication of complex designs and customized products (Choong et al., 2020). It can shorten the product development cycle for customized designs significantly without generating too much additional cost (Kwok et al., 2017). It can be especially economical for low-volume production as it eliminates the fixed costs for tooling or molds to create products (Eyers & Dotchev, 2010). It enables high level of responsiveness and flexibility in the production process. For example, during disruptions in supply chains caused by unexpected events such as the Covid-19 pandemic, critical parts can still be fabricated on-demand by a 3D printing facility and via online sharing of 3D data (Choong et al., 2020). Recent developments in machine, material, and process have allowed 3D printing to broaden its usage from prototyping to end-use product manufacturing (Kwok et al., 2017). In fact, a wide range of 3D-printed applications was used to fight against Covid-19, including personal protective equipment (PPE), personal accessories, medical devices, testing devices, and emergency dwellings (Choong et al., 2020). Combined with 3D scanning, 3D printing has been widely used to implement customization or MC for prosthesis, and dental and hearing aid applications (Deradjat & Minshall, 2017; Kwok et al., 2017; Miclaus et al., 2017).

In the apparel sector, 3D printing has been used for the development of accessories such as jewelry and bags (Watkin, 2017; Daviy, n.d.). RhinoGold, 3Design, and Gildform are several examples of 3D modeling CAD systems or online design platforms for jewelry design (Burke & Sinclair, 2015). Jewelry is created either by direct 3D printing or by lost-wax casting, where metal (e.g., sterling silver) is poured into a 3D-printed casting mold made from wax. Shapeways is one of the many 3D printing service companies that offer customized production of jewelry products (Power Your Jewelry Business, n.d.). Moreover, many 3D-printed garments have been featured on the fashion runway in fashion shows (notable fashion designers are Iris van Herpen, Catherine Wales, Francis Bitonti, Noa Raviv, Ganet Goldstein, Melinda Looi, etc.; notable fashion brands are Chanel, Victoria's Secret, Pringle of Scotland, etc.). Fashion designers such as Danit Peleg and Stéphanie Santos have created 3D-printed garments for sale (3D Printed Jacket, n.d.; Stephanie Santos Couture, n.d.) (Fig. 9.5). A few 3D-printed art pieces were built based on 3D body scans (Greder et al., 2020; Shark, 2018).

Footwear is another fashion sector where most innovations and successful adoptions of 3D printing take place. Companies such as Materialise fabricated highly fashionable 3D-printed shoes for fashion catwalks (Burke & Sinclair, 2015). Nike has produced 3D-printed textile "upper" (referring to the part of a shoe that wraps around the top of the foot) for performance sneakers using their "Flyprint" technology and materials. Adidas has manufactured a 3D-printed midsole (located between the upper and the outsole) for performance sneakers to achieve precise control over support and cushioning. Bauer have used 3D foot scanners and 3D printing to create shoe lasts for individual consumers for custom skates. Indeed, together with 3D scanning, 3D printing has great potential for tailored fit products (Kwok et al., 2017).

Despite the great potential of 3D printing, there are several fundamental drawbacks of its current implementations in a fashion that needs to be addressed by future researchers and designers. Firstly, many of the amazing 3D printed fashion items on the fashion runway shows barely provide any wearing comfort or functionality as "wears." The materials (especially PLA, i.e., polylactic acid plastic) are

Figure 9.5 3D-printed garments for sale (Designer: Stéphanie Santos).
Source: Available from: https://www.stephaniesantos.store/clothes.

usually rigid, stiff, and easy to break down or shatter (Jacobson, 2017). While advanced printing materials for apparel applications are being developed in research labs (Melnikova et al., 2014), the filament choices available in the market are still limited and not flexible enough (Daviy, 2019; Perry, 2018). Even with flexible and durable new materials, the printed garment can create the sensation of fake leather or rubber which sticks to the wearer's skin, causing great discomfort (Jacobson, 2017). The washability of the 3D-printed garments is also questionable (Valtas & Sun, 2016). Although there has been research reporting that PLA appliqués could endure a 45-min detergent-free, delicate wash cycle, the same researchers speculated that a tougher washing cycle (higher water temperature, with detergents added, etc.) may cause PLA breakdown (Samuels & Flowers, 2015). Consumer interviews also showed that clothes's wearing comfort, wearer mobility, garment durability, and compatibility with daily life were the major concerns with regard to 3D-printed garments (McCormick et al., 2020; Perry, 2018).

Secondly, it costs tremendously to 3D-print a garment, mainly due to the printing time. threeASFOUR's Pangolin Dress for their Fall 2016 Biomimicry collection took ten printers 500 hours working at the same time to finish, followed by another time-consuming process of assembly (Jacobson, 2017; McCormick et al., 2020). It took Iris van Herpen, a pioneering 3D-printing fashion designer, 260 hours to 3D-print and an additional 60 hours of handwork to assemble the 3D-printed patches to create one of the dresses in her Ludi Naturae collection (Mendoza, 2018). Designer and then-student Danit Peleg created five 3D-printed garments for her graduate collection, and the project took her 2000 hours, an average of 400 hours per garment piece (Logan, 2015). Designer Charne Esterhuizen's 3D-printed butterfly dress took more than 800 hours to print using six printers (Sibthorpe, 2017). Designer Zac Posen's 3D-printed rose dress took over 1100 hours to print and assemble (Epstein, 2019), each of the 21 petals from the rose dress costs over $3,000 to manufacture (Lazaro, 2019). It took 150 hours for designer Julia Daviy to print one dress with geometrical shapes for her show during 2018 New York Fashion Week (Daviy, 2019). The designer also reported that even for a skirt with a simple style, it can take her printer, a most advanced printer, some 18 hours to print (Daviy, 2019). To make things worse, most commercially available 3D printers only have limited printing area (Valtas & Sun, 2016) and, therefore, a bigger and often more expensive printer is needed, which not only can take up a lot of space but can also be far beyond affordable for consumers to print at home. Otherwise, garment printing has to be done in parts rather than in one sitting, losing a certain degree of automaticity. Moreover, assembling the parts is very likely to require manual work, especially if the advanced materials resemble fabrics. For the same reason, garment sewing is still done manually in factories rather than automatically by computers and robots; handling flexible 3D-printed materials cannot be done automatically without adding tremendous costs.

Thirdly, while sustainability is one primary reason driving designers to pursue 3D printing, what people fail to realize is that when printing in 3D, often a base and a series of supports need to be printed together with the desired piece to avoid any overhangs from collapsing and prevent unwanted deformations (Pasricha & Greeninger, 2018). If the fashion piece is hollow, it can cost more in material for supports than for the piece itself, making the process not sustainable. Printing the supports can exacerbate the excessive printing time and printing cost. Moreover, the support materials, which are usually soluble (e.g., Hydrofill filament), have to be removed, usually by soaking in hot water for a few hours. The soaking process also adds to the printing time and costs water and energy consumption (the water needs to be constantly heated). To avoid or reduce the need for printing supports (also to reduce printing cost and time), many designers have switched to the technique which is essentially "2D printing" instead of "3D printing," where pattern panels of a garment were printed on a flat surface by a 3D printer and later had to be assembled to form a 3D structure (Kang & Kim, 2019; Spahiu et al., 2020; Valtas & Sun, 2016; Peleg, n.d.). Even Nike's Flyprint uppers were firstly printed on a flat surface. Sometimes even for flat-surface-printing, supports are unavoidable in order to achieve the desired functional textile-like (woven/knit) inner structures (Melnikova et al., 2014) (Fig. 9.6). Therefore, the 3D printing process is not as "zero-waste" as most people imagine. In addition, this practice would not benefit the fit issue for customization or MC. Because the 2D patterns cannot provide a good fit for non-typical body shapes, changing the material from cotton or polymer to plastic would certainly not help. Furthermore, although the commonly used printing material PLA is biodegradable, it still takes a long time to degrade and requires a decomposing facility (Daviy, 2019). Also, due to its non-flexible nature, many designers are forced to choose less eco-friendly materials for wearability (Daviy, 2019). This issue, however, is rather minor compared with the others and can be resolved through new inventions of sustainable, flexible, and durable materials.

Lastly, there is a steep learning curve for 3D modeling, even for experienced fashion designers (Pasricha & Greeninger, 2018; Valtas & Sun, 2016). As 3D printing was not invented primarily for fashion design, the current commercial software (Solidworks, AutoCAD, 3D Studio Max, PTC Creo, Rhinoceros, etc.) are not apparel-specific, making the design process more challenging to master (Valtas & Sun, 2016). The technical barriers hinder many designers to realize their design ideas (Daviy, 2019). Without fashion-designer-friendly CAD systems for 3D modeling and with very few designers well trained to use the systems, it would be extremely difficult to

Figure 9.6 Support material used (and dissolved) to achieve knit structure (Melnikova et al., 2014).

push forward 3D printing in garment production (Kang & Kim, 2019). Furthermore, although many consumers believe that 3D printing makes the fashion design process simpler, or that it even enables them to co-design or create unique design items all by themselves (Perry, 2018), unless more intuitive design software/apps are developed, it is not likely that the design-it-yourself or co-design business models are user-friendly to be implemented, let alone open to being popularized.

Nevertheless, there is one feasible and promising use of 3D printing technology for apparel MC. In addition to digital human models for virtual fit tests, often physical dress forms are still necessary for further validation of fit. Rapid and accurate creation of customized dress forms via 3D printing may expedite the design process and shorten the lead time (Bauer's use of a foot scanner and 3D-printed lasts is one successful example). However, printing a human body, or just the torso section, in full scale can be extremely costly. One solution to save printing materials and printing time is to create adjustable 3D-printed padding kits to place on standard dress forms at the bust, hip, side hip, waist, and shoulder areas so that local shapes can be modified to achieve the custom body shape (Lim et al., 2017) (Fig. 9.7).

Another solution to reduce 3D-printing costs is using scaled-down dress forms (e.g., half-scale forms). With the help of a pattern digitizer and CAD software (e.g., OptiTex, Adobe Illustrator, etc.), pattern pieces can be easily scaled down (to be tested and adjusted) and scaled up (to reflect the adjustments in full scale). Research on the effectiveness and validity of scale-down forms on apparel design and production has shown promising results (Ashdown & Vuruskan, 2017; Phoenix, 2018).

Commercially available half-scale forms such as Alvanon's Half-Scale AlvaForm have been in the market since 2007 (Ashdown & Vuruskan, 2017). These half-scale forms are built based on 3D body scans and can be very accurate in depicting body shape variations. Although they have not yet been widely adopted by the industry, school projects show that they can be effectively used to develop apparel products ranging from lingerie to outerwear, from casual wear to evening gowns (Ashdown & Vuruskan, 2017). Custom half-scale forms can also be made by stacking up layer by

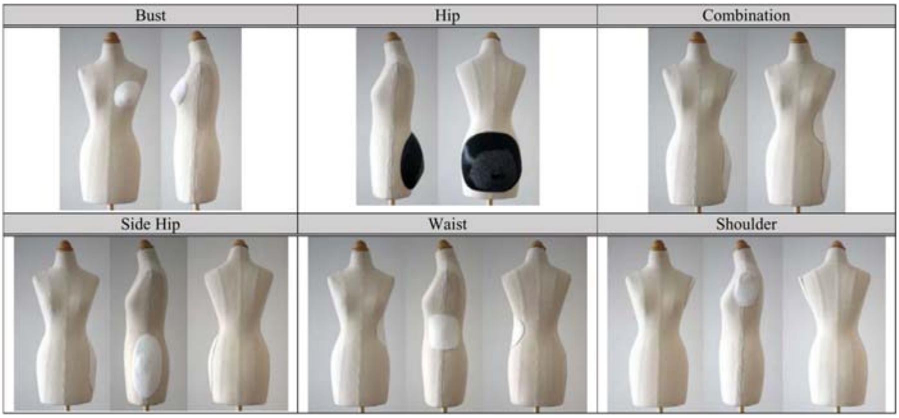

Figure 9.7 3D-printed padding kits placed on a full-scale dress form Lim et al. (2017).

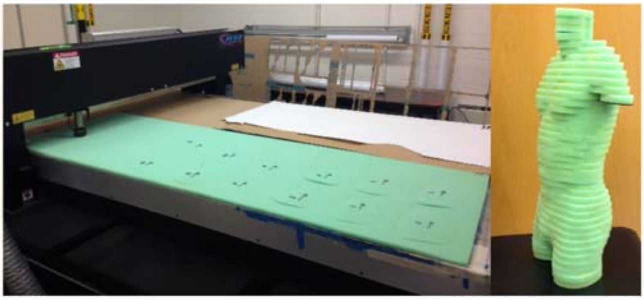

Figure 9.8 Custom half-scale forms created by stacking of foam slices (Ashdown & Vuruskan, 2017).

layer the cross-sections of the body laser-cut from a foam sheet, a procedure similar to 3D printing (Fig. 9.8). Typically, the stacked foam layers are then covered by a knit fabric and have style lines added. In fact, DittoForm uses a similar technique to create full-scale custom dress forms from 3D body scans. Compared with 3D printing, this method can save cost in materials, but may require more time and manual handling (Vuruskan & Ashdown, 2015). Furthermore, robot mannequins (e.g., Euveka) that can change into a wide range of body shapes are competitive alternatives for traditional dress forms. Whether 3D printed forms can outcompete foam forms or robot mannequins, with regard to cost and efficiency, remains to be tested.

9.3 Future directions

3D CAD systems have great potential to speed up the MC product development process, help companies save on costs by eliminating/reducing the need for physical prototypes, respond to the market faster, and reduce carbon emissions caused by shipping back and forth physical prototypes. To flatten the steep learning curve of 3D software, companies should look for innovative ways to train their staff. Fashion education should include the training of 3D CAD software to prepare the next generation of designers and fashion workers. CAD systems should incorporate more automated functions to reduce manual workflows. To increase the validity and effectiveness of virtual fit testing, 3D CAD developers and apparel companies should work closely with experts from the animation and film industries to generate more realistic virtual images. The establishment of virtual testing standards is also highly necessary. In addition, the choice of virtual fit models is critical for virtual fit tests. While body-dimension editable avatars may be superior in simulation speed and quality and are easier to animate, they may not be able to represent all the diversity of body types for consumers seeking MC. It is more promising to rely on the future developments of powerful body-scan processing algorithms to clean and patch up scans and convert scans into digital models suitable for fit tests. Moreover, many of the current 2D MTM CAD systems do not actually provide custom-fit patterns for consumers at an individual level. To achieve fully personalized MTM, updated anthropometric data that include non-typical body types should be used to develop generic master patterns, and new methods to measure the body need to be adopted to modify master patterns for individual fit. New technological solutions to automatically detect body landmarks on scans (that work for all types of body shapes) should be developed. Lastly, to avoid input errors, it is recommended to stop requesting body measurement information from consumers and rely fully on body scanning instead.

Modular design allows for an economic production of individualized small-scale products, and it is an effective practice for apparel MC. While one downside of modular design is that it may limit the design variety for consumers, the fact remains that too many design choices may bring frustration to consumers. Therefore, identifying the right level of modularity and the right number of modular choices can be critical, not only for the sake of consumer satisfaction but also for inventory and production management. Given modular design also allows pattern modules to be independently adjusted based on data acquired from body scanning, it follows that the introduction of new or improved methods that facilitate this practice should be encouraged. Furthermore, MPS, UPS, and FMS are effective garment assembly systems that companies should switch to. Digital printers, single-ply cutters, tension-free spreading machines, automated cutting machines, and digital sewing machines are other helpful machinery for MC manufacturing. These systems and technologies should be used along with the 3D body scanning technology to make apparel MC truly possible.

Additive manufacturing (i.e., 3D printing), however, is not yet ready for apparel MC. Nor is it a promising future direction unless technological developments can significantly reduce the tremendous cost and time for printing and, significantly, improve the wearability, washability, and other functionality of the printing materials to match with conventional fabrics. It is neither a “zero waste” nor sustainable practice for apparel production. Nevertheless, rapid and accurate creation of customized half-scale dress forms via 3D printing may be a potential use of the technology. However, whether it can outcompete foam forms or robot mannequins, about cost and efficiency, remains to be tested.

9.4 Sources for further information

Website links for all the tech companies mentioned in this chapter can be found at the end of Chapter 10.

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The effective communication system using 3D scanning for mass customized design

10

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10.1 Introduction

Consumer satisfaction has a direct impact on the consumer's future purchase behavior and on a company's reputation, both associated with the profitability and competitiveness of the company (Carpenter & Fairhurst, 2005). High satisfaction leads to brand loyalty, a higher chance for consumers to repurchase, to share positive reviews about the product/service, and to recommend it to others (Carpenter & Fairhurst, 2005). Brand loyalty and consumer retention can be achieved by establishing consumer relationships where effective and recurrent communication is a must. Effective communication is also key to the sustainability of the fashion industry, as poor communication can lead to tremendous returns, especially for e-commerce. Not only does the return shipping leave a great deal of carbon footprint, many of the returned products cannot be put back to storage in time and, as a result, end up directly in the landfill. If size and fit are correctly communicated, there will be a huge reduction in returns because size/fit-related issues are the primary cause for returns.

Communication is a two-way process (Fiore, 2008). Apparel companies need to receive information to understand the demands of their consumers, especially if the company tries to adopt MC which requires their relationships with individual consumers to reach a personal and intimate level (Anderson-Connell et al., 2002). On the other hand, apparel companies need to deliver information about the style and design, fit and size of their products to their consumers effectively to reduce frustration and misunderstanding. In a retail store, the role of a salesperson cannot be stressed more (Nikhashemi et al., 2019). Salespeople can help deliver product information and, in the case of MC, help consumers to configure personalized products (Yeung et al., 2010). A well-trained salesperson can gain the consumers' trust and increase consumers' confidence to purchase an MC product. However, the apparel retail industry often has a high turnover rate of salespeople (Yeung et al., 2010) and, therefore, it is not always possible to invest hugely in the training of salespeople. Also, in the absence of salespeople in e-commerce, other effective communication means need to be implemented.

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Design and style can be easily delivered to consumers via visuals such as photographs, physical or virtual runway shows, etc. Usually, consumers can directly see and touch the garments exhibited in a retail store, on mannequins, or racks. In terms of size and fit, size designation is one traditional method to deliver size information. It has been widely used for ready-to-wears, but also used for MC garments (e.g., Ralph Lauren's "Create Your Own" polo shirts, Levi Strauss's "Tailor Shop" jeans, etc.). Size designations are typically expressed in three ways, namely, by body measurements, by letters (e.g., S, M, and L), or by size numbers (e.g., 6, 8, and 10) that are linked to a measurement chart (Ashdown & Loker, 2010). The latter two (letters and numbers) are less informative and vulnerable to vanity sizing (Ashdown & Loker, 2010), where garments are intentionally labeled with smaller than actual sizes to flatter consumers (Chun, 2007). Fit information is typically communicated (sometimes as part of the garment style) via photographs, displays on mannequins, sketches, or by descriptive words such as "relaxed fit" and "slim fit."

Typically apparel companies acquire size information: (1) by requesting body measurement data from consumers via input prompts on an e-commerce website (e.g., Lands' End); (2) by body scanning the consumers (e.g., Acustom Apparel); or (3) by asking consumers to try on multiple prototype garments (e.g., Levi's "Personal Pair" in the 1990s) (Yeung et al., 2010). Among these methods, 3D body scanning can be the most accurate and efficient method to help consumers identify their correct sizes, which could be done automatically: (1) by comparing the extracted measurement data of an individual consumer with those of the available sizes; or (2) by comparing the individual scan with the scans of fit models of the available sizes (Ashdown & Loker, 2010; Pei et al., 2020). Body scanning can also provide consumers with a unique shopping experience that can add value to the products (Fiore, 2008; Yeung et al., 2010). Moreover, measurement data extracted from a body scan are not limited to the primary measurements such as bust, waist, and hip commonly seen in a size chart and, therefore, they can be more informative for product development. For custom-fit apparel MC, nothing compares to body scanning in communication efficiency.

10.2 Body scanning methods in commercial settings

In general, there are three common ways to take body scans in today's settings:

(1) In-store kiosks or scanners have been set up, mainly by footwear brands such as Adidas, New Balance, ANTA, Lotte, Nordstrom, Bauer, Fleet Feet, ecco, etc., using a 3D foot scanning platform called Volumental. Brooks Brothers was the first apparel brand to implement whole-body scanning in their New York City store in the 1990s; however, no updated information of their using body scanners can be found online. Brooks Brothers' website has no mention of the technology, not even for their MTM tailored garments (Made to Measure, n.d.). Acustom Apparel is currently using whole-body scanning to create custom suits and other menswear. Consumers can make appointments online to get scanned in their store located at New York City SoHo (Acustom Experience, n.d.).

(2) Non-branded scanner booths have been set up in shopping malls, business centers and fitness centers. For example, Shapify currently has ten booths worldwide, four in the U.S (https://www.shapify.me/scanning-point); Fit3D has set up hundreds of scanners at fitness centers around the world (https://fit3d.com/location). [TC]^2 launched the ImageTwin Data Sharing Network in 2008 and used to have more than 20 body scanning sites (ImageTwin 3D Scan Data Network Launched, 2018) and, yet again, no updated information can be found.

(3) Smartphone-based body scanning apps allow consumers to scan themselves at home and take total control of their scans. The Nike Fit app allows consumers to scan their feet and obtain shoe size recommendations (What is Nike Fit?, 2019). FIT:MATCH launched with Savage X Fenty to have their Fit Xperience app available in stores which allows consumers to be scanned and receive bra size recommendations across styles ("FIT: MATCH Partners with Savage X Fenty (FIT:MATCH Partners with Savage X Fenty, 2022). RedThread also relies on a mobile app to create custom-fit garments for women (available items are several pants, a jacket, a tee, and a dress), where two photos are taken for each consumer to generate measurement data. Each consumer also has to take a short fit quiz before placing the order.

Most mobile apps (e.g., Sizer, MTailor, meepl, i-Deal SizeYou, Presize.ai, etc.) rely on phone cameras to take photos of the user at multiple perspectives (or a video of the user spinning around 360° which is essentially still a series of photos), and then construct the 3D model from the photos. Many companies have utilized Apple's Face ID-enabling TrueDepth camera to generate accurate 3D face/body scans (e.g., Scandy Pro, Heges, IN3D, Bellus3D, etc.). Moreover, LiDAR, short for "Light Detection And Ranging," has become a mature technology and has gained attention for its body scanning potential (Zohdi, 2020). Apple has added LiDAR sensors to their Pro models of iPad and iPhone12, and beyond (Gallagher, 2021), increasing the ability to take body scans in a highly accurate and efficient way. FIT:MATCH is one of the first companies that adopted LiDAR technology for accurate torso scanning.

MySizeID uses smartphone sensors (rather than cameras) to measure body dimensions. Body measurements are captured via the user moving their smartphone over their body at a certain location (e.g., span over the chest to obtain chest measurement). Users can also type in their measurement data, such as body height and body weight. Another smartphone-based body-measuring app that had a successful marketing and received wide-spread attention from the public is Zozosuit. Zozosuits are skin-tight spandex bodysuits which are overall black but covered in white dots. They were sent to consumers initially for free. Wearing the bodysuit, a consumer can get scanned using Zozo's mobile app. 12 photos were taken when the user was asked to turn clockwise for the full 360° for the construction of the 3D model (Ryan, 2018). Eighteen body measurements can then be extracted. However, the Zozosuit experiment ended up a failure, mainly due to consumers' lack of enthusiasm to use the bodysuit to make garment purchases while the company was swamped with the huge cost of distributing the bodysuits (Bain, 2019; Reuters, 2019). Nevertheless, Zozo's failure does not undermine the market needs for body scanning apps. With recent developments in smartphone scanning technologies, a bodysuit is no longer necessary.

10.3 Effective e-commerce communication using 3D technologies

Communication between consumers and apparel companies, nowadays, is mainly accomplished by e-commerce (Fogliatto et al., 2012). The internet has become the foundation of many innovative communication technologies. It provides a low-cost and effective communication infrastructure that is not restricted by time and distance. Many companies used to invest a large amount of money in carrying out projects to collect and analyze consumer data (Helms et al., 2008). E-commerce makes the process much easier and less costly: basic personal information can be collected through consumer registration to the site; product preference information can be collected from consumer feedback and purchasing habits; and consumer interests can be analyzed and predicted from electronic interactions such as browsing records and site navigation patterns (Helms et al., 2008). It benefits greatly for both the demand and the supply sides (Fiore, 2008; Helms et al., 2008). With orders taken online and directly sent to the company which sells the product, the company no longer needs to depend on any intermediaries. For the demand side, it allows companies to provide cheaper (and sometimes better) products or services while bringing maximum convenience to their consumers, as the purchase activities and service requests can all be made at home from a computer. E-tailers can, often, provide better consumer service than traditional retailers due to the increased efficiency in communication (Helms et al., 2008). E-commerce can enhance economic efficiency by matching the demand and the supply sides. For example, many platforms enables recommendation algorithms to provide products to consumers based on their specific requirements or preferences (Helms et al., 2008), which is MC in a sense. The matching algorithms also allow companies to target their marketing efforts to specific groups, another approach to reduce cost. The rising impacts of social media provides new opportunities for companies to interact with and thus understand their consumers better, to provide one-of-a-kind products (Goh et al., 2013). In short, e-commerce helps companies to be more flexible, responsive, and efficient and, therefore, it has become a critical enabling means to support MC (Helms et al., 2008). For the rest of this chapter, MC communication technologies will be discussed solely from an e-commerce perspective.

There are mainly two types of motivation that drives consumers to shop: utilitarian (task-oriented) and hedonic (pleasure-seeking) (Brown, 2016). Although it was found that e-commerce is considered to be more of a utilitarian retail channel (compared with physical retail stores) by consumers (Kim & Eastin, 2011; Liu & Forsythe, 2010), it is also important for e-tailers to make full use of the internet and increase the ease-of-navigation and esthetics of their websites to satisfy hedonic consumers. In the age of information explosion, consumers' attention is more likely to be drawn to websites with the merits of innovation and uniqueness (Helms et al., 2008). In addition, many of the hedonic consumers enjoy exploring information online, seeking engagement and entertainment (Brown, 2016). Therefore, it is recommended to include features that encourage lingering on the websites to engage and entertain hedonic consumers (Kim & Eastin, 2011) while keeping the functional or utilitarian features as is, such as lower prices, increased product variety, and improved check-out convenience.

Many apparel e-commerce websites incorporate "live chat" features that connect consumers with salespeople to provide digital consumer service, such as style, wardrobe, and sometimes size recommendations (e.g., Levi's, Adidas, Cartier, Victoria's Secret, Gap, Fendi, etc.), while others incorporate "virtual shop assistant" powered by AI to answer simple questions (e.g., Uniqlo, H&M, Louis Vuitton, Calvin Klein, etc.). Most chatbots/virtual assistants can direct consumers to salespeople should the questions be answered not to the satisfaction of the consumer. Emails and telephone calls are still major means for e-tail communications and are offered by almost all e-commerce websites. Consumers of Lululemon can also schedule 15-minute or 30-minute video chats with salespeople to get help on product style, sizing, and fit (Virtual personal shopping is here, n.d.). Hemster, launched in 2016, provides an on-demand tailoring service online that helps consumers to modify their garments for improved fit. Consumers only need to schedule video chats (via Zoom or Google Meet) and ship their garments without leaving home to get the work done. Many of the e-commerce websites also invite consumers to leave their feedback regarding their online experience and/or the products (e.g., Cartier, Uniqlo, Lululemon, etc.). These simple internet tools can contribute to the two-way communication process and may especially benefit MC products. As explained earlier, apparel MC relies heavily on technologies. Since not all consumers are "tech-savvy" or patient with instruction tutorials, it is recommended to have salespeople or highly sophisticated AI to stand by to help consumers handle technical challenges and foster a personalized shopping experience.

While the "live chat" or "chatbot" mainly functions as a utilitarian feature and makes it easier for consumers to acquire product information, to cancel orders, change the order information, and get a refund, etc., 3D scanning, 3D modeling, virtual try-on, and codesign features can be considered promising recreational and hedonic features (Brown, 2016). In the following subsections, online product configurator, online fit quiz /size recommendation, and virtual try-on will be specifically discussed.

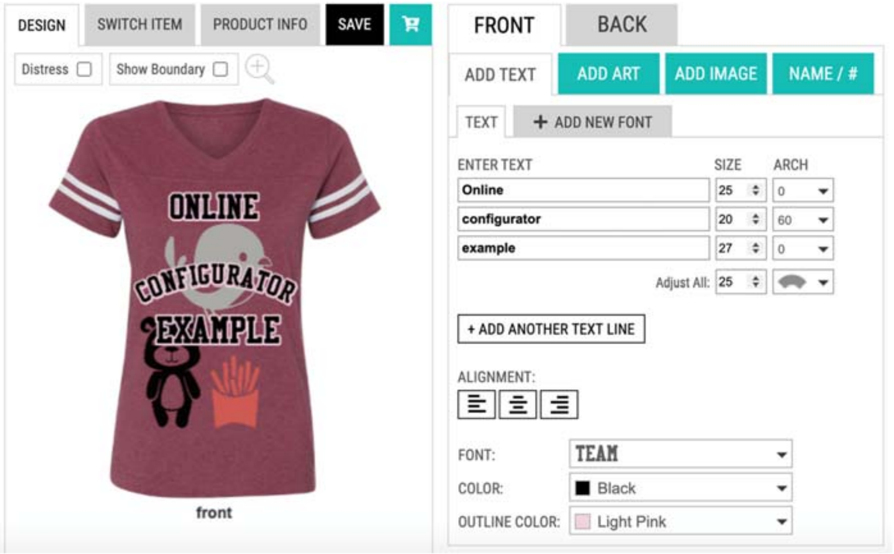
10.3.1 Online product configurators and codesign

Online product configurators are useful e-tail tools, especially MC products (Ashdown & Loker, 2010). They allow consumers to select style features, fabric features, color features, etc. and input measurement data to personalize their apparel products. With preview of the final product instantly presented on the screen, consumers can directly participate in the design process by choosing and combining different components until they achieve their personal favorites. A sophisticated configurator can incorporate 3D visualization functions (e.g., Tailornova) to allow consumers to upload their body scans or create virtual avatars that reflect their body shapes (Ashdown & Loker, 2010). The body scans/avatars can further be animated to perform virtual runway shows as one way of virtual try-on. Other means of virtual try-on, including interactive ones, can also be added to the configurator. Step-by-step instruction can be added to guide consumers throughout the configuration process to reduce the technical threshold. Previous research has shown consumers' willingness and even enthusiasm for product configurators (Ashdown & Loker, 2010; Fiore et al., 2001; Kamali & Loker, 2002; Lee et al., 2002). A well-designed configurator plays a key role in enabling and facilitating codesign (Yeung et al., 2010). It can also directly transmit MC orders for production, removing intermediaries to save time and cost (Yeung et al., 2010).

Product configurators are already implemented on quite a few apparel e-commerce websites. Ralph Lauren's "Create Your Own" polo shirts and Levi Strauss's "Tailor Shop" jeans both have instant preview of the final product with the selected style, color, fabric, and other design components. Another example is Nike's custom shoe website, "Nike By You" (previously called Nike ID), which allows consumers to choose their own preferred "Base" (a large variety of color options are offered), "Swoosh/Flywire," referring to Nike's classic logo (color and placement options are offered), "Laces," "Midsole," "Midsole treatment," "Outsole," etc. Consumers can also put their initials or other personal details on the shoes. Different shoe types have different components available for customization. For example, soccer shoes may have color options for "Ankle Cuff" and functional options such as "Traction" that running shoes lack. (Two options for "Traction" are offered, namely, "Firm Ground" and "Artificial Grass," referring to the optimal ground type that the shoes are designed to play soccer on). Instead of letting consumers design from scratch, multiple general design templates are offered, each of which has its design components that can be modified. Any change to a design component is instantly reflected on a series of photos, which include multiple perspectives of the shoes (top view, side view, etc.). The finalized design can be previewed in 3D where the consumer can rotate the 3D model to examine the design from any other perspectives not presented by the photos. The 3D shoe models are very realistic looking. In addition to Nike, Timbuk2 has a very similar configurator for custom backpacks and messenger bags, except that a 3D preview option is not available.

Threadless.com provides another feasible solution for codesign. It collects artworks to print on clothing (T-shirts, hoodies, dresses, etc.) from its online community, where professional designers/artists and consumers can all contribute (Grimal & Guerlain, 2014). Among the garment types, T-shirts have the highest flexibility for customization. Consumers can choose the base color of the T-shirt (a large variety of colors are offered), a fit preference with options such as "fitted," "regular unisex," "extra soft," "heavyweight unisex," "tri-blend," etc. (the material property affects the fit and, therefore, several material options are regarded as fit options) and a size (letter sizing is used). Other garment types (hoodies, leggings, tanks, sweatshirts, etc.) have limited or no base color choice, and limited or no fit choice. Just as the configurators of Ralph Lauren and Levi Strauss, the instant preview of the garment with the selected options is enabled, and achieved via photos. Another garment codesign website, Customizedgirl.com, has a slightly more interactive configurator, where multiple lines of custom texts can be placed and visualized on top of a laid-flat blank garment, either a T-shirt, a tank, or a long-sleeve tee (Fig. 10.1). A variety of base colors are offered. The font color, font outline color, font style, and font size of the custom text can be edited separately for each line. Each line of the text can also follow a curved path that has a different arch degree. In addition, new layers of texts, as well as graphics, can be added. Custom graphics can be selected from the website's online library or uploaded by the consumers at will. The locations for the texts and graphics can be modified via drag-and-drop.

Instead of focusing on graphics personalization, eShakti's configurator emphasizes the garment pattern variations and fit customization (Fig. 10.2). Consumers

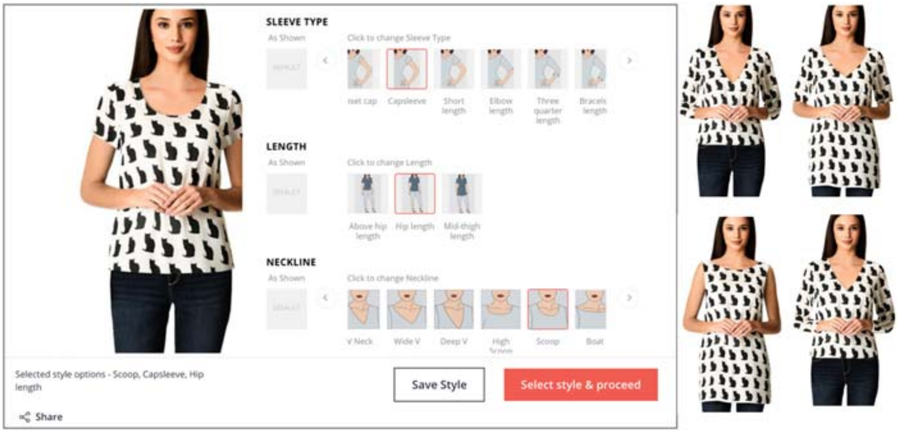


ENTER TEXT	SIZE	ARCH
Online	25	0
configurator	20	60
example	27	0

Adjust All: 25

FONT: TEAM
COLOR: Black
OUTLINE COLOR: Light Pink

Figure 10.1 The online configurator of customizedgirl.com.



Selected style options - Scoop, Capsleeve, Hip length

Figure 10.2 The online configurator of eShakti.com.

can select their preferred collar/neckline, sleeve length, and garment length for a template style (Fig. 10.2). Collar styles may include “Peter Pan,” “Round Collar,” “Mandarin Collar,” “Shawl Collar,” etc., while neckline styles may include “Jewel,” “Scoop,” “U Neck,” “Deep V,” “Split Scoop,” “Boat,” etc. Sleeve types may include “Sleeveless,” “Inset Cap,” “Cap Sleeve,” “Short Length,” “Elbow Length,” “Three Quarter Length,” “Bracelet Length,” etc. Skirt/dress lengths may include “Mini,” “Above Knee,” “Knee Length,” “Below Knee,” etc., while length options for a top may include “Above Hip Length,” “Hip Length,” “Mid-thigh Length,” etc. A template style does not necessarily offer a full combination of all the design component options. Some have more options for sleeve types, others, more for neckline styles. A style change to a component is instantly reflected on the garment worn by the human model. This is much more effective in terms of communication than merely displaying the croquis (i.e., the technical drawings) of the garment. Moreover, not only are standard sizes offered by the website, consumers can also input their measurement data (seven requested measurements and three optional measurements) to opt for custom sizes. Detailed instruction with photo illustrations is provided to guide consumers to take measurements.

In addition to eShakti, Sene is another MTM brand that adopts a similar concept. For denim jeans or pants, consumers can select their preferred rise (four options are offered: “High Rise,” “Medium Rise,” “Low Rise,” and “custom rise” where consumers can input a value in inches), and their preferred length (again, four options: “Full Length,” “Ankle,” “Cropped”, and “custom length”). For blazers, consumers can select their preferred fit (“Very Slim,” “Tailored,” “Straight”), and their preferred length (“Long,” “Modern,” “Short,” “custom length”). These choices will have a direct impact on the garment patterns. Such classic configurators used by eShakti and Sene are similar to the ones used by Tailornova and PatternLab. However, eShakti and Sene directly face consumers and sell the final assembled garments, whereas Tailornova and PatternLab mainly target fashion designers and the production side and have garment patterns as their final products.

Suit Kits is an MTM brand for women’s custom suits. Their online configurator “Suit Builder” is powered by 3D virtual imaging technology (just like “Nike By You” and Timbuk2), while also allowing minor modifications on the garment patterns (just like eShakti and Sene). A variety of fabric and lining options are available and changes are instantly synced on the virtual garment. For a blazer, consumers can choose whether they prefer single-breasted or double-breasted. They can choose their preferred lapel style (“Regular Peak Lapel” or “Wide Peak Lapel”), jacket button placement (“One Button” or “Two Buttons”), button (from a variety of button pictures), cuff button placement (“Spaced” or “Kissing”), pocket style (“Flat,” “Slanted” or “Faux”), blazer length (“Long,” “Median,” or “Short”), etc. The websites have multiple suit/blazer templates, and each has distinctive components for configuration. Consumers are also offered matching suit bottoms (skirt or pants) made with the same fabric of their choice that they can add to their purchase. Other add-ons may include a matching vest, matching sweat guards (for armpits), and more bottoms. Consumers can also opt for a personalized monogram with their preferred font style and color. The personalized monogram, however, does not get synced on the virtual garment (as Nike By You, n.d., Ralph Lauren "Create Your Own" and customizedgirl.com make possible). Finally, some preexisting, industrial-standard patterns of the suits will be altered based on consumers' body measurements. Consumers need to make appointments with tailors located in big cities (New York, Chicago, Boston, Los Angeles, etc.) to get their measurements taken.

10.3.2 Fit quiz/size recommendation

In addition to the traditional way of communicating sizing information using size charts, many e-commerce websites implement fit quizzes and/or algorithms to facilitate size recommendations. These fit quizzes can be a supplement for body scans (acquired via scanner booths or mobile apps) or body measurement inputs. The "Smart Fit" quiz of Sene is made up of questions about body height, body weight, and typical sizes worn (for tops, bottoms, bras, etc.). It also includes a series of picture-choice questions regarding self-perceived body shape, including shoulder shape, shoulder slope, lower body shape, buttock shape, etc. Some of the body shape questions can be skipped if consumers are not confident with their answers. Suit Kits also incorporated a similar but short-version fit quiz along with its "Suit Builder" configurator. Consumers are asked to choose sizes that they normally wear for tops and bottoms, and to check any fit issues they typically encounter with ready-to-wears from the following list: "Different sizes on top & bottom," "Sleeve or pant length too long or short," "Jacket buttons pull/gape," "Skirts "ride" up or "twist" and "No petite sizes/No plus sizes."

Similarly, the fit quizzes of RedThread include questions about typical sizes worn, and picture-choice questions ask for fit issues encountered with ready-to-wears. For the issue with pants length, consumers are offered three options to choose from: "Too long," "Too short" and "Length is just right." Pants fit issues have the following options: "Gap at waist in the back," "Too tight in thighs," "Too loose in thighs and legs," "Pulling at the front crotch (whiskers)," "Crotch is too baggy," "Too tight in the butt," "Too baggy in the butt," "Muffin-top spillage over waist band" and "Fit just right." Each option is accompanied with a hand-drawn illustration. Consumers can choose as many options as they desire. The final question for pants prompts consumers to report the body area(s) where ready-to-wear pants are too tight for them. Options include "Waist," "Hips," "Butt," "Thighs" and "Calves." Moreover, instead of a generic quiz (such as the one used by Sene), RedThread sets up one fit quiz per garment type. One drawback is that only a limited number of garment types can be provided. In addition to pants, a separate fit quiz is set up for jackets. Consumers are prompted for their typical sizes for tops (number sizing) and also for bras (number sizing for band, letter sizing for cup, e.g., 34C). Issues with jacket fit include "Too tight in the chest," "Too tight in the shoulders," "Too loose in the shoulders," "Too tight at hip bone," "Sleeves too long," "Sleeves too short" and "Fits just right." Body area options where tight-fit occur include "Neck," "Shoulders," "Chest," "Waistline", and "Hip/Butt (for longer jackets)." The last fit quiz is for tees where letter sizing is used for "typical size worn."

Such fit quizzes collect helpful information to facilitate MC. However, some flaws cannot be ignored: (1) Giving consumers an option to skip fit quiz questions can reduce the chance that a random thus false answer is selected when the consumer is not certain with their answer, but it also risks losing critical information which can eventually lead to fit problems. (2) Without objective evaluation criteria, consumers' self-perceived body shapes may be biased by their subjective standards. This can result in consumers' answers being different from the answers judged by pattern developers or designers. Moreover, the limited choices (usually 3–4) in body shape illustrations may exclude certain non-typical body shapes, yet too many choices may confuse consumers. (3) Due to "vanity sizing" and fashion brands each having their sizing methods, many consumers may not know their sizes. Other consumers may unintentionally report wrong sizes, judged by industrial standards. (Even the industrial standards are not always consistent). To base the product development on sizes reported by consumers can cause major fit problems. (4) In order to adjust garment patterns, the qualitative (rather than quantitative) descriptions of the fit issues consumers typically encounter are not informative enough. For example, exactly how much additional ease should be added to the pant patterns if the "thigh area" is "too tight"? An arbitrary guesswork can end up with the pants still being "too tight" at thighs or making them "too loose." Nevertheless, these fit quizzes can serve their purpose much better if they are accompanied by objective assessment functions enabled by body scanning (RedThread is a good example). With body scans, body shapes can be evaluated objectively by measurements extracted from the scans; sizes (and therefore base patterns) can also be determined objectively through measurements; while ease, minus ease, or other pattern adjustment parameters can be determined with quantitative references.

The fit quizzes mentioned above help the e-tailors themselves to make improvements on their own MTM products. Alternatively, companies such as Fit Analytics and meepl provide size/fit recommendation services to independent fashion brands. Fit Analytics' "Fit Finder" matches consumer data, such as age, body height (in cm), body weight (in kg), self-perceived belly shape and hip shape (chosen from a set of shape illustrations), fit preference for a specific type of garment, etc., with product data of a specific brand (e.g., The North Face). "Fit Finder" has both a webpage version and mobile app versions (for both Android and iOS systems). Another mobile app with similar functions is meepl. Its "Quick Size" function relies on 3D body avatars constructed from 2 photos and additional user information, namely age, body height, body weight, and gender, to recommend a size or to facilitate the development of MTM garments (by feeding measurement data to a pattern grading CAD system). 45 body measurements can be extracted from a body avatar. FIT:MATCH is another B2B (Business to Business) size recommendation platform. Instead of relying on size surveys or fit quizzes submitted by consumers, their solution is solely based on the 3D shape captured through LiDAR scanning, where details such as an overhanging necklace and the asymmetricity of the breasts are truthfully reflected. Also unlike most other matching solutions which are based on body measurements extracted from the scan/avatar, their patented algorithm matches the 3D surface of the scan to the closest 3D surface of an existing avatar from an extensive database. The database consists of avatars of human wear testers and their size data collected through actual fittings of the products. By finding the digital "fit twin" with the same body shape who has tried on all the products in advance, the consumer can find their size without the need to try on the products themselves ("FIT:MATCH Partners with Savage X Fenty, 2022).

Other fit/size recommendation platforms include Size Advice, Easysize, MySizeID, Sizer, Presize.ai, Bodi.Me, Fitle, AstraFit, True Fit, visualook, etc. Many body scanning mobile apps have size recommendation functions. Common features for these apps or webpage services (including FIT:MATCH, Fit Analytics, and meepl) are the use of machine learning or other AI techniques and that of API (Application Programming Interface), which enables information exchange among multiple software intermediaries (webpages, apps, etc.). In addition to the methods mentioned before, API facilitates the development of a different type of size recommendation that is based on consumers' previous shopping experience. Consumers are asked for the information of a previously bought product that fits them well, and sometimes this information is the only reference to determine the size for a new product to be bought (e.g., Zappo). Despite their undoubted usefulness, these apps/webpages that solicit user information can share the common drawbacks in regard to the validity of user input (e.g., whether consumers can assess their body shapes, remember their sizes, and/or input their measurements correctly). Although body scanning can make the measurement acquisition process objective, whether the landmark detection algorithms (e.g., the determination of the waist plane and thus of the waist circumference) for non-typical body shapes (e.g., plus-size populations) are reliable enough remains to be tested. For example, algorithms that work for Missy Size 6 may not work for Size 16. Moreover, many algorithms rely on the size charts provided by brands. While it may bring convenience to consumers as they no longer need to study the size charts themselves, the fact remains that fundamental flaws in sizing, should there be any, can still cause fit issues. Consumers with non-typical body shapes, who may have high hopes in these apps, can still end up disappointed.

10.3.3 Virtual try-on

Virtual fitting rooms have gained increased attention in recent years. Adding Virtual try-on functions to an apparel product configurator can enhance its performance and attractiveness to hedonic consumers (Ashdown & Loker, 2010; Brown, 2016; Lee & Xu, 2020). However, virtual try-ons have not been widely adopted by e-tailers. This is mainly due to consumers' concern for the accuracy of the simulations (Lee & Xu, 2020). Although consumers may find the experience amusing, they find it difficult to trust the simulated results regarding fit (Calhoun et al., 2009). The advantages and technological hindrance of virtual try-ons have been partially discussed in the chapter before. Companies such as Gerber, Human Solutions, OptiTex, CLO, Browzwear, Tukatech, Shima Seiki, etc., all, have advanced garment simulation technologies available. Other companies that provide virtual try-on solutions specifically for e-commerce are Metail, triMirror, nettelo, FittingBox, Zugara, FXMirror, visualook, Acep Trylive, MemoMi, 3D-A-Porter, Zeekit, style. me, etc.

Some solutions rely on body scanning, but the majority rely on 3D avatars, where the skin tone, hairstyle, etc., can be modified in addition to avatars modeled by body measurements (some allow the upload of facial images to be mapped onto the avatar's face). Although 3D avatars are less accurate in terms of body dimensions (because only limited number of measurements are usually used to adjust avatar size), they are easier to manipulate and animate, thus better at offering interactive experiences that hedonic consumers may enjoy. Most solutions also implement mix-and-match functions that give consumers more freedom in browsing the styles that they like. My Virtual Model Inc. (MVM) was one of the earliest that provided virtual try-on services using avatars (from the late 1990s to the early 2010s). Many fashion brands (e.g., Land's end) incorporated MVM on their e-commerce websites (Lee & Xu, 2020). However, no updated information can be found, and the company's website (http://myvirtualmodel.com/) is no longer accessible. Another early attempt is Fits. me, a start-up company in the early 2010s that tried virtual fitting room solutions. Consumers were required to enter their body measurements to modify the dimensions of the avatars. Fits. me was later purchased by Rakuten (Lunden & Lomas, 2015). However, Rakuten announced the discontinuance of the Fits.me business after July 27, 2018 (https://fits.me/). Fitiquette, brought by Myntra (an Indian apparel e-commerce company) in 2013 (Lunden, 2013), is another example adopting a similar solution. Yet again, no updated information can be found of the further use of their virtual fitting room solution. triMirror provides an integrated solution of virtual try-on for e-commerce that is also based on avatars. triMirror's system enables tension maps to show the tightness/looseness of the virtual garments and implements runway animations for avatars with garments on. Their website is up-to-date (https://www.trimirror.com/).

One last example (for virtual try-on based on avatars) is Metail's "MeModel," which offered virtual try-on plug-ins to apparel e-tailers in the mid-2010s. However, Metail went onto a different path (no updated information regarding MeModel can be found, even on Metail's website). Currently Metail provides a different solution for virtual garment demonstration, called "EcoShot." EcoShot generates life-like 2D images translated from pre-loaded 3D avatars (Fig. 10.3). Its library includes a variety of virtual fit models, accompanied by their corresponding 3D avatars. Users of Browzwear's VStitcher CAD software can install the EcoShot plug-in, choose an EcoShot avatar, design and fit the virtual garment on the avatar, and generate the life-like images as a final step. To switch to a new fit model, the new 3D avatar (for that human model) needs to be selected, and the virtual fitting process needs to be redone before the new EcoShot images can be generated. Although virtual garments can only be visualized on selected fit models instead of on individual consumers, EcoShot's technology offers a promising future direction to help consumers embrace virtual try-ons.

Another major type of virtual fitting rooms is achieved by AR technologies along with computer vision technologies, which allows consumers to view their augmented selves on web-browsers, in-store kiosks, or smartphone apps with

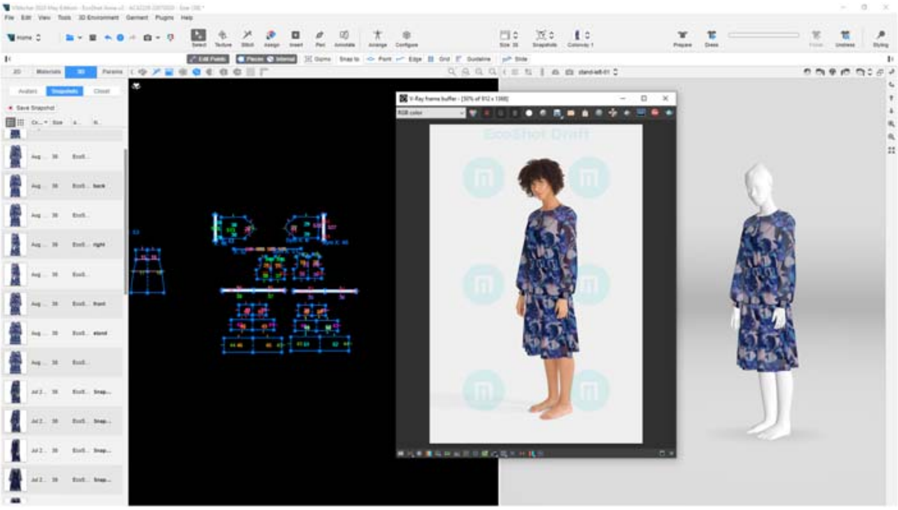


Figure 10.3 Metail's EcoShot incorporated in Browzwear's CAD system (Smith, 2020).

product images superimposed on top. The motion of the consumer is captured and tracked the whole time, and the product images move along with the consumer. FittingBox and Acep Trylive adopt the technologies and enable consumers to try on glasses/sunglasses virtually via webcams. "The Sampler" by Converse is a mobile app that adopts AR for virtual try-ons of shoes (https://www.rga.com/work/case-studies/converse-the-sampler-3). Zugara allows the capture of the full body and the superimposition of various types of garments. It has two primary products: "Virtual Style Sense" for in-store retail and "Webcam Social Shopper" for e-commerce. In 2012, Uniqlo introduced its "Magic Mirror" which used AR to achieve virtual color change of the garment (among four of Uniqlo's selected jacket products) the consumer wore standing in front of the Mirror (Millar, 2012). Other attempts of full-body AR try-ons are offered by Fitnect (https://www.fitnect.com/), Fitting Reality (website no longer in use: http://fittingreality.com/), "Imagine That" online virtual fitting room (website has not been updated since 2011: https://www.imaginethat-technologies.com/), MemoMi's "Memory Mirror" (https://memorymirror.com/), etc.

One last example (for full-body try-on based on AR) is FXMirror which provides in-store kiosks for consumers to try on garments within the shop inventory. Consumers can use a hand gesture to browse through garments on the kiosk's screen, or they can tap on a tablet connected to the kiosk. A QR code (Quick Response code) is generated after a consumer finishes a try-on, storing information of the garment products and the virtual avatar (a video-recording of the consumer in front of the kiosk during try-on) in a database. The consumer only needs to scan the QR code to make the purchase and re-access the avatar for future try-ons on FXMirror's mobile app "FIT'N SHOP." New garments can be added to the kiosks or e-tail platforms by taking two pictures (front and back views) of any physical garment and using FXMirror's "Cloth Authoring Tool" to convert the photos into a

3D image of the garment (it takes roughly 10 minutes to render one 3D garment). The AR technologies enable consumers to see how the garments look on themselves without having to physically put on the garments. Although AR try-ons provide little information on how the garments would fit, they are still promising technologies for MC, especially for the implementation of modular design and online configurators. Moreover, fit assessment can be done via other means in addition to AR try-on. For this reason, FXMirror has a second option for virtual try-on, i.e., via 3D avatars (resized according to consumers' body measurements). A consumer can directly build and use the 3D avatar on the mobile app without using the in-store kiosks, but the kiosks are also able to capture the consumer's facial features and expressions, and map the facial images onto the avatar in real-time.

10.4 Conclusion and future directions

Effective communication leads to high consumer satisfaction, which leads to repurchase, brand loyalty, and positive reviews of the products. It also leads to fewer returns, reducing the carbon emissions caused by shipping, and less landfill of unsold inventory. Therefore, it is the key to a sustainable fashion industry. Online product configurators are important enabling tools for facilitating codesign and, therefore, they should be implemented for MC products, especially on e-commerce platforms. 3D body scanning can be the most efficient method to communicate size information, with smartphone scanning as the most promising technological foundation. Size recommendation functions are the key features for MC products which give an emphasis on personalized design features (as opposed to on personalized fit). Sizing systems are still used instead of creating patterns for every individual consumer. Nevertheless, the fit issue should not be ignored. Most size recommendation apps base their algorithms on the comparison of the extracted measurement data of an individual consumer with those of the available sizes (provided by brands). Should fundamental flaws exist in sizing or in landmark accuracy for nontypical body shapes, the effectiveness of these algorithms can be diminished. Therefore, a more promising way to help consumers identify their sizes is by comparing the body scan of an individual consumer with the scans of fit models of the available sizes. Fit quizzes can be a good supplement for body scans taken in scanner booths or via mobile apps, but it is not recommended to use the fit quizzes alone to develop products, because consumers' answers about their body shapes can be biased by their own subjective standards; by vanity sizing and inconsistent sizing among brands, basing the product development on the typical sizes consumers wear causing major fit problems; and lastly, by qualitative descriptions of the fit issues consumers previously encounter not being informative enough to make corrections to garment patterns.

Virtual try-on or the virtual fitting room is a promising feature that can entertain hedonic consumers, although consumers may find it difficult to trust the simulated results regarding fit. Compared with 3D CAD systems, it is more critical for virtual fitting rooms to adopt realistic looking virtual models that are true to the body shapes of the consumers. Virtual models developed directly from body scans are still superior to body-dimension-editable avatars. Advanced algorithms that can rapidly process body scans and convert them to an animated version of 3D models are essential. Moreover, advanced rendering technologies that can rapidly and truthfully map the skin's texture to the surface of the 3D model (especially for the face) can be beneficial. Finally, AR and computer vision are promising technologies to enable consumers to browse and choose their preferred design and style, and these technologies should keep focusing on design and style alone, leaving the fit issue to be solved by pattern development technologies, 3D body scanning, and other technologies.

Major technological improvements have been achieved since the concept of apparel MC was brought up several decades ago. The successful implementation of apparel MC by taking full advantage of the 3D scanning technology is bound to happen and probably not before long.

10.5 Sources of further information

All the companies mentioned in this and the previous chapters are listed below. These companies embrace the most up-to-date technologies.

Company websites:

3D-A-Porter: https://3d-a-porter.com/
3D Body Cloud: https://3dbodycloud.com/
3dMD: https://3dmd.com/
3D Measure Up: https://3dmeasureup.com/
Acep Trylive: https://www.aceptrylive.com/
Acustom Apparel: https://acustom.com/
Adidas: https://www.adidas.com/us
Alvanon: https://alvanon.com/
AlvaForms (Alvanon): https://alvanon.com/resources/alvaform-manual/
APEXFiz (Shima Seiki): https://www.shimaseiki.com/product/design/software/
Assyst: https://www.assyst.de/en/index.html
AstraFit: https://www.astrafit.com/
Bauer: https://www.bauer.com/en-US/homepage
Bellus3D: https://www.bellus3d.com/
Bespokify: https://bespokify.com/
Bodi.Me: https://www.bodi.me/
botspot: https://botspot.de/en/
Bodyform3D: https://www.bodyform3d.com/
BootstrapFashion.com: https://patterns.bootstrapfashion.com/
Brook Brothers: https://www.brooksbrothers.com/
Browzwear: https://browzwear.com/
Carmel Clothing: https://carmelclothing.global/
CLO: https://www.clo3d.com/
Clone Block: https://fashionshouldempower.ca/

Customizedgirl.com: https://www.customizedgirl.com/
DittoForm: http://www.dittoform.com/
Easysize: https://www.easysize.me/
Elasizer: http://www.elasizer.com/
Euveka: https://www.euveka.com/en/
eShakti: https://www.eshakti.com/
Fit3D: https://fit3d.com/
Fit Analytics: https://www.fitanalytics.com/
Fitle: https://fitle.com/en/
FIT:MATCH: https://www.fitmatch.ai/
FittingBox: https://www.fittingbox.com/en/
FNX: https://www.fnx.tech/
FXMirror: http://www.fxmirror.net/en/main
Geomagic: https://www.3dsystems.com/software
Gerber: https://www.gerbertechnology.com/
Gildform: https://www.gildform.com/
Heges: https://hege.sh/
Hemster: https://www.hemster.co/
Human Solutions: https://www.thehumansolution.com/
IN3D: https://in3d.io/
InvenTex: http://www.inventex.eu/en/
Lectra: https://www.lectra.com/en
Levi Strauss: https://www.levistrauss.com/
Lululemon: https://shop.lululemon.com/
Materialise: https://www.materialise.com/en
meepl: https://www.meepl.com/
MemoMi: https://memorymirror.com/
Metail: https://metail.com/
MTailor: https://www.mtailor.com/
MySizeID: https://mysizeid.com/
nettelo: http://nettelo.com/
NetVirta: https://www.netvirta.com/
Nike By You: https://www.nike.com/nike-by-you
OptiTex: https://optitex.com/
PatternLab: https://patternlab.london/home/
Perfect Fit: http://perfectfit.net/
Presize.ai: https://www.presize.ai/
QuantaCorp: https://www.quantacorp.io/
Ralph Lauren: https://www.ralphlauren.com/
RedThread: https://redthreadcollection.com/
Replika: https://replika.ai/
Scandy Pro: https://www.scandy.co/apps/scandy-pro
Sene: https://senestudio.com/
Shapeways: https://www.shapeways.com/
Shapify: https://www.shapify.me/
Shima Seiki: https://www.shimaseiki.com/
Size Advice: https://sizeadvice.com/
Sizer: https://sizer.me/
SizeYou (i-Deal): https://www.sizeyou.it/en

Space Vision: https://www.space-vision.jp/
style.me: https://style.me/
Suit Kits: https://suitkits.com/
Tailornova: https://tailornova.com/
[TC]^2: https://www.tc2.com/
TG3D Studio: https://www.tg3ds.com/
Timbuk2: https://www.timbuk2.com/
TechMed:3D: https://techmed3d.com/
triMirror: https://www.trimirror.com/
True Fit: https://www.truefit.com/Home
Tukatech: https://tukatech.com/
VetiGraph: https://www.vetigraph.com/en/
visualook: http://visualook.com/en/
Volumental: https://www.volumental.com/
Zappo: https://www.zappos.com/
Zeekit: https://zeekit.me/
Zozo: https://corp.zozo.com/en/
Zugara: http://zugara.com/

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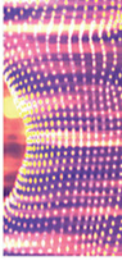
Note: Page numbers followed by "*f*" and "*t*" refer to figures and tables, respectively.



THE TEXTILE INSTITUTE BOOK SERIES

Digital Manufacturing Technology for Sustainable Anthropometric Apparel

Edited by Norsaadah Zakaria

Digital Manufacturing Technology for Sustainable Anthropometric Apparel is a thorough and practical examination of the state of the art in anthropometric apparel manufacturing technology.

The scale of the textile industry, in economic as well as environmental terms, is so significant that new technologies and techniques that deliver improvements are of great interest globally. Consumer preferences as well as government regulations are causing apparel manufacturers to prioritize sustainable practices, and at the time of unprecedented technological evolution and competitive pressure, integrating these measures with other priorities is a key challenge.

By combining the expertise of contributors from the world of technology change management and technical textile engineering, this book provides a unique interdisciplinary resource for organizational as well as technical implementation. Newly developed Industry 4.0 technologies are addressed, along with the latest data collection and analysis methods. A strong awareness of the importance of sustainable practice is maintained throughout the book, helping the readers to understand these new technological advances in those terms as well.

Key Features

- Provides practical technical instructions for the implementation of new technologies for 3D body scanning, and anthropometric design and sizing
- Explains the latest technical methods for the collection of anthropometric data, and also examines related ethical issues
- Shows how to integrate the anthropometric design methodologies into a full smart manufacturing system

About the Editor

Norsaadah Zakaria is a chartered clothing associateship and an academic research fellow at Taylor's University, Subang, Malaysia. She is also the founder of Clotech Atelier Academy—Telestia Malaysia.

Her main research interests include TVET education for sustainable practices in the clothing industry, traditional and 3D body scanning anthropometric surveys, data modeling for clothing sizes, shape analysis based on anthropometric data and sizing system optimization, and validation using data mining. She is also offering professional programs accredited by The Textile Institute—United Kingdom.

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