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An overview of current technological developments in apparel fit customization

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Abstract

Purpose – This study reviews the literature that discusses the technologies that will influence fit customization (FC). The purpose of this study is to clearly understand the current progress of such technology and the potential future development path.

Design/methodology/approach – Research papers, publications and websites of well-known apparel companies using FC are reviewed to explore the latest technological advancements in apparel FC.

Findings – Given the advances in body measurement, pattern and fit assessment technologies, FC represents a sustainable production approach for the apparel industry.

Originality/value – This review examines the state of the field, looks at possible trends in the study and highlights future directions.

Keywords Fit customization, Body measurement, 3D patten-making, Virtual fitting, Sizing system

Paper type Literature review

1. Introduction

1.1 Background

Today, product personalization and diversity have become more important, especially in the apparel industry, which has embraced the idea of producing a variety of products in small quantities (MacCarthy, 2013). In addition, online shopping has become increasingly popular with the growth of e-commerce. However, it has also been observed that customers are extremely concerned about the possibility of having to return an item (Lee and Moon, 2015; Moon and Lee, 2014). Sizing is a major issue, accounting for 64% of apparel returns, according to Body Lab research (Cilley, 2016).

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Mass customization (MC) was introduced very early to balance the variety and cost (Senanayake and Little, 2010). However, due to the complexity of body shape and the limitations of the technology, fitting is considered to be the most important issue and the most challenging work in MC for apparel (Elbrecht and Palm, 2016; Gupta, 2020; Hernández, 2018; Lang *et al.*, 2021). With the broader context of the Fourth Industrial Revolution, governments around the world are implementing plans to increase the use of digital and information technologies to modernize and expand their industrial landscapes. Until now, many works have improved upon fit through technological advancements (Li and Chen, 2018; Liu *et al.*, 2019a, 2019b; Sohn *et al.*, 2020). This review explores the ever-expanding literature on apparel fit customization (FC) and inspire scholars to advance the theoretical knowledge of shape, size and fit and its application to MC.

1.2 Related works

Some of the topics covered in this study have been reviewed in other surveys. They are addressed here to clarify their distinctions and the need for this paper.

Gill (2015) offered a thorough analysis of garment sizing, prototyping and fitting (Gill, 2015). In addition, Gupta (2020) further demonstrated the application of advanced technologies in the fields of anthropometry, size and garment fit (Gupta, 2020). These works are the most similar works to our survey. They focus on the progress of the intelligent technologies that can be used for fit, while this survey aims to offer a comprehensive overview that takes into account the ways in which the technologies handle FC and improve its application. What's more, it aims to draw attention to future perspectives based on the analysis of existing work.

Scott (2022) highlights the importance of 3D anthropometric data for improving garment fit from a sustainable perspective but does not give a profound discussion of techniques from body measurement to garment development (Scott, 2022). Gill *et al.* (2022) introduced the theory of size and the development of online fit systems, but it is just one aspect of the garment fit (Gill *et al.*, 2022).

1.3 Outline

The remainder of this study is organized as follows. Section 2 details the methodology used in this survey. Section 3 begins with the basic definitions of FC, and Section 4 reviews the state of the art in technologies supporting FC, highlighting their key similarities and differences. Section 5 provides an overview of how technologies handle fit for the apparel industry. Section 6 discusses challenges and future perspectives, and Section 7 concludes.

2. Methodology

Google Scholar, Web of Science and Scopus databases were searched using specific keywords to identify original research papers, book chapters, review articles and scientific reports for review purposes to contribute to this work. Keywords were searched individually. The Boolean operators AND, "and () were mostly used to retrieve the most relevant articles related to the search topic. Clothing, fit adjustment and MC were the first search terms used. Thirty-eight papers in all were assessed, with an emphasis on FC and MC. A secondary search was then conducted according to the relevant factors influencing garment fit. The most prevalent keywords included body measurements, fit ease and pattern-making, 3D body modeling, virtual try-on, clothing recommendation, 3D body scanning, body shape, body size, fit aesthetic, fit preference and so on. The selection criterion for studies was based on the general aspects related to FC in clothing. Due to the large amount of literature, most articles published after 2014 were included. To gain a more thorough understanding of the development of the field, the search for relevant studies was extended beyond the period 2014 to January 2024. For articles published prior to 2014, only two conditions were met:

(1) they were deemed necessary to support other studies; and

(2) their content had to be unique and noteworthy.

A total of 360 papers were screened to select 165 relevant scientific publications for this review. In this study, a total of 88 papers were reviewed that focused on FC. In addition, the websites of well-known apparel brands that use FC were examined to see how they handle fit online. These papers and websites provided valuable insights into the various factors influencing apparel FC.

3. Definition of fit customization

MC is one of the most promising strategies in the apparel industry. Da Silveira *et al.* (2001) came to the following conclusions: levels and the concept of MC, which aims to offer a range of products that reasonably satisfy each customer's unique needs. Information technology and flexible processes allow production systems to produce more variety at lower cost (Da Silveira *et al.*, 2001).

Senanayake and Little (2010) further elaborated on the meaning of MC. There were two other definitions for a customized apparel product. One is "consumer-customized" apparel that can be made to fit, match preferences, style and other details of a customer, and the other is "occupation-customized" apparel, such as uniforms for a specific occupation. Significantly, they suggested that the FC point is one of the key points of apparel MC (Senanayake and Little, 2010).

When it comes to personalization, fit is considered the most important factor in MC apparel and the primary determining factor (Da Silveira *et al.*, 2001; Lang *et al.*, 2021; Liu *et al.*, 2020; Xu *et al.*, 2021; Yeung *et al.*, 2010). FC is defined as the level of flexibility provided to the customer, which includes choosing not only the required measurements, the overall ease of fit and the silhouette of the garment related to the fit (Senanayake and Little, 2010; Sohn *et al.*, 2020), but also the company's fit aesthetic and the customer's fit preference (Ashdown, 2014; Hernández, 2018). Table 1 summarizes the pertinent content of FC based on the content of the literature study into three categories: body measurement, pattern and fit assessment.

4. Current development of technologies for fit customization

This study compares existing work on these elements in the context of Table 1, and discusses the technology used to handle FC and its advancements.

4.1 Body measurement

4.1.1 Body measurement techniques. The first crucial step in clothing FC is taking body measurements.

Photographic technology is a form of 2D measurement technology that captures many images of the body from different views, such as the front, sides and back (Kohlschütter and Herout, 2012). The main reasons why these methods are not widely used are their computational complexity and the challenge of regulating the crucial body model measurement, especially when the consumer subject is wearing clothing that is not appropriate and could alter the real underlying body shape. Once these issues are resolved, this method can be quickly implemented for online clothing FC because it does not require complex tools or gadgets, and the instructions are easy to understand and communicate.

Table 1. Elements in the definition of garment FC

No.	Elements		Main reference
1	Body measurement	Body measuring	Kohlschütter and Herout (2012); Ashdown (2020)
		Measurement data	Ashdown (2014); Tsoli (2014); Xia and Istook (2017); Loercher *et al.* (2018); Faust (2019);Song *et al.* (2019); Zakaria and Ruznan (2020); Lauria *et al.* (2022)
2	Pattern	Fit ease	Ashdown (2014); Liu *et al.* (2019a, 2019b); Park *et al.* (2019)
		Pattern-making	Sohn *et al.* (2020); Gupta (2020); Han *et al.* (2021); Lei and Li (2022)
3	Fit assessment	Virtual fitting	Miell (2018); Harrison *et al.* (2018); Gill *et al.* (2022)
		Fit satisfaction	Ashdown (2014); Hernández (2018); Bizuneh *et al.* (2023)

Source: Authors' own work

The use of 3D body scanners as a cutting-edge technique for quantifying human body size for custom-fitting apparel was also highlighted (Nayak *et al.*, 2015). It is considered the mainstay of anthropometric research conducted worldwide (Gupta, 2020; Pei, 2022). As 3D body scanning technology has evolved, body scanning and measurements can now be obtained not only from the static position but also the dynamic motion (Loercher *et al.*, 2018). The dynamic anthropometric data enhance the ergonomic fit of garment, particularly for workwear and sportswear.

It is critical to be able to establish a procedure for evaluating the accuracy of automatically determining landmark locations from the collected scan data for garment design (Ashdown, 2020; Kouchi, 2020). Certain international organizations and standardization initiatives, like ISO and ASTM, significantly enhance the uniform standards for ensuring the interoperability of data obtained through 3D scanning. Alvanon, Inc. created 3D avatars to assist in visualizing the posture and shape based on the standard measurements. Therefore, 3D technology-oriented functions may be recognized as the most likely future tailoring approaches for the future fit process if accuracy and compatibility are confirmed (Kooi *et al.*, 2022; Shariff *et al.*, 2022).

4.1.2 Application of body measurement data. 4.1.2.1 Body shape classification. Morphological classifications contribute to characterize body shape and improve the garment fit. Each female participant's body shape was classified by using principal component analysis and cluster analysis (Song and Ashdown, 2012), which made it possible to select fit models from the body shape group and construct the basic block designs for each body shape. In addition, a thorough classification of various shapes for men was produced through training model by using neural networks, and how each body type influences the selection of appropriate fit apparel was illustrated (Bellemare, 2014). Besides, a physical investigation of the fit evaluations of females with different body shapes was conducted to demonstrate how body shapes influence garment fit (Chrimes *et al.*, 2023).

More recent studies have used other new methods paired with 3D technology to more accurately define body morphotypes (Pandarum *et al.*, 2020). For instance, upper lateral somatotypes were classified based on directional angles of 3D space vectors (Yoon *et al.*, 2016). Han (2019) investigated the relationship between men's upper body dimensions to provide specific numerical body shape alterations based on chest girth and height, serving as a basis for grading values for men's upper body garment designs (Han, 2019). Furthermore, differences in body proportions and measurements between basketball players and an untrained group of the general population were found to examine the effect of physical variation on garment fit. (Brlobašić Šajatović *et al.*, 2019).

4.1.2.2 Sizing technique. The sizing system for MC must be developed with appropriate garment dimensions and be user-friendly so that the customer can at least easily identify his size (Ashdown, 2014; Bougourd and Treleaven, 2020). The sizing system depends on the sizing strategies as well as the body type. Sizing strategies change with fit requirements, and different sizing strategies result in different production models (Ashdown, 2014; Morlock *et al.*, 2019). The most commonly used sizing strategies may use primary or control dimensions to adjust fit. For example, key measurements, secondary dimensions and intervals were identified to develop a sizing system (Xia and Istook, 2017). The components of size range, size interval, size scale and size roll based on the ISO 8559/1989 standard were also used to create a sizing system (Zakaria and Ruznan, 2020).

Some suggestions have been made for the size system that is supposed to enhance applications. The least number of sizes used in the size system may benefit the manufacturer as well as the customer (Ashdown, 2014). Meanwhile, it would be preferable if a new standardized way of expressing size, shape and fit could be devised without the need to change the manufacturing way. In addition, size designations would be more useful if they took into account variations in height and girth measurements across age groups and ethnicities, as well as the association between ethnicity and body measurements (Faust, 2019). This suggestion is definitely worth considering that more accurate sizing techniques and guidance can be provided to serve a wide range of ages and races. It will enable global communication about fit and comfort, and also require collaboration between companies, technology developers and ethnic groups.

The importance of a motion-based sizing system is also emphasized (Jolly *et al.*, 2019; Lapkovska, 2022; Vasile *et al.*, 2021). As motion functionality has filled the gaps left by static avatars, this field of study has advanced to include soft tissue deformation to more accurately simulate changes in body shape, making it possible to convert into a new sizing system and evaluate how the body interacts with clothing and how this interaction changes with different body postures (Demirel *et al.*, 2022; Sun *et al.*, 2019; Loercher *et al.*, 2018). It is extremely useful in functional clothing design because it can realistically represent a wide range of human body shapes even in extreme postures (Gupta, 2020). This area of research promotes the development of dynamic models and improves the accuracy of the fitting process. However, measurement standard should take into account the function-oriented movement and size reference of the body in the design process.

4.1.2.3 3D body model reconstruction. The 3D human body model created from the scanned data provides potential applications for body shape, size and fit analysis (Chan *et al.*, 2022; Yang *et al.*, 2013), as well as the succeeding stage of patterning, garment design (Alemany *et al.*, 2022; Daanen and Psikuta, 2018; Liu and Luo, 2022) and even custom avatar creation for realistic virtual fittings as part of the online marketing and consumer experience solutions (Ashdown, 2020; Chan *et al.*, 2022; Daanen and Psikuta, 2018).

The 3D body model obtained through 3D scanning must then be reconstructed and translated into correct representations for various apparel-related applications (Elbrecht and Palm, 2016). This is because the representative model of the human body must be flexible for different usages, as shown in Figure 1. The requirements or key criteria are different at each stage of the representation process, it is critical to understand and know the feature points that need to be fully or abstractly represented.

In general, polygonal, subdivision, parametric and nonuniform rational B-spline modeling are the most commonly used techniques for reconstructing 3D body models for

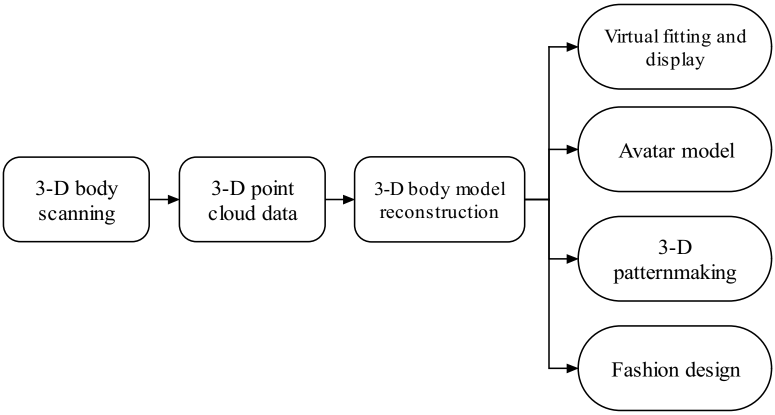

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Figure 1. Different purposes of a 3D body model

fashion applications. Table 2 compiles the important studies carried out over the past 10 years that have reconstructed 3D body models using various modeling methods to produce more accurate representations for various fit purposes.

4.2 Pattern

4.2.1 Fit ease. Clothing ease, or the estimated volume of air between the body and the garment, is important for both static and dynamic poses because it determines the movement of the user. Clothing ease and tailor knowledge such as wear comfort, product appearance and materials should be considered for fit (Bi *et al.*, 2022; Elbrecht and Palm, 2016; Kuzmichev, 2019; Wang *et al.*, 2021). The distance ease distribution of a garment is demonstrated as a critical factor in accurately achieving a garment fit (Park *et al.*, 2019). To achieve realism, it is also necessary to accurately calculate the volume of air inside the

Table 2. Summary of 3D body modeling for different fit purposes

Purpose	Modeling method	Authors
Pattern-making	Parametrization technique	Hong *et al.* (2017)
Fashion design	Shared identical topology	Xie and Zhong (2020)
Virtual display	Forward modeling, photo modeling, and reverse modeling	Liu *et al.* (2017)
Virtual fitting	Register vital body templates onto existing rigid avatars and use the finite element method to simulate	Harrison *et al.* (2018)
	A part-based semantic 3D body reshaping	Song *et al.* (2019)
Avatar model	A surface-based modeling process	Tsoli (2014)
	3D human body mesh modeling and surface reconstruction techniques	Rudolf *et al.* (2021)
	NUBRS	Lee and Song (2021)
	Structure-from-motion and machine learning techniques	Lauria *et al.* (2022)

Source: Authors' own work

clothing, as well as the total volume of the clothing relative to the naked body (Petrak *et al.*, 2018). At the same time, how the distribution of static and dynamic ease of clothing changes with motion at the chest and waist can be assessed by using a motion scanner (Liu *et al.*, 2019a, 2019b). Furthermore, the constructed 3D apparel model is then used to generate the finished garment model using predefined areas in conjunction with user preferences and previously calculated distance ease values to properly represent the intended style effect (Hidellaarachchi *et al.*, 2019).

4.2.2 Pattern-making technique. Basic blocks are critical and created by using empirical principles and "size charts" or averaged body measurement data (Gupta, 2020). Because base block patterns in computer-aided design (CAD) systems can be developed for multiple figure types rather than just one standard pattern, they can significantly enhance the fit of the pattern and offer a feasible and quick way to implement efficient and effective apparel MC (Han *et al.*, 2021). The quality of the block patterns and the grading rules have a direct impact on the fit of the garment.

While the flat-pattern method remains popular, techniques for converting 3D designs to 2D patterns have made it possible to produce 2D pattern pieces directly from a 3D design (Abtew *et al.*, 2018; Kulińska *et al.*, 2022). As shown in Figure 2, a 3D modeling approach was used to create an upper garment model for 3D pattern-making (Zhang *et al.*, 2015). Besides, patterns can be captured on the mannequin or body directly from key points on the fabric in a 3D shape (Lei and Li, 2022).

In addition to producing 2D patterns from the 3D body model, the process of converting flat 2D pattern data into a 3D simulation is complicated by the variable and unpredictable nature of the fabric. Some software programs, such as the Optitex CAD system, can use 2D patterns to visualize fit in 3D. Their ability to be used for garment design and simulation, as well as the ability to change patterns simultaneously, has shown significant advances (Špelic, 2020).

Most importantly, however, is the ability to organically integrate the scanned 3D body data into the CAD applications. After the garment specifications have been defined to fit the patterns, the CAD technology is expected to handle the garment assembly by following the specific pattern-making rules and evaluating the quality of fit on 3D human models (Nayak *et al.*, 2015).

Thus, it is noted that fit problems can now be solved thanks to advances in CAD technologies. The primary cause of the current problem is the incompatibility of legacy systems. For example, 3D shape data cannot be used directly in the fit simulation or pattern-making process (Gupta, 2020; Scott and Sayem, 2018). As a result, the future looks bright, as

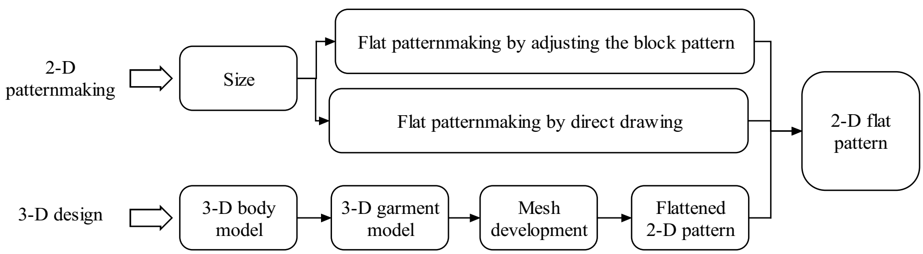

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Figure 2. 2-D and 3D design pattern-making processes

cutting-edge technologies will be able to address the shortcomings and inconsistencies of traditional pattern-making methods used to customize apparel fit.

4.3 Fit assessment

4.3.1 Virtual fitting. Virtual fitting techniques based on body scanning are gradually making their way into the public. As shown in Figure 3, the model demonstrated the method of collecting body measurements and also presented a virtual fitting system to resolve fit issues (Ashdown, 2014; Kouchi, 2020; Miell, 2018). A virtual try-on provides a computer-generated visual representation of how a garment will look on the wearer and improves the fitting result. A generic automatic method was proposed to correct 3D wearable items from a reference body mesh to a target body mesh (Hu *et al.*, 2020). A landmark guided virtual try-on method was also used for clothes to solve the problem of clothing trials on e-commerce websites (Roy *et al.*, 2022). Furthermore, to address the problem of difficult to warp clothes

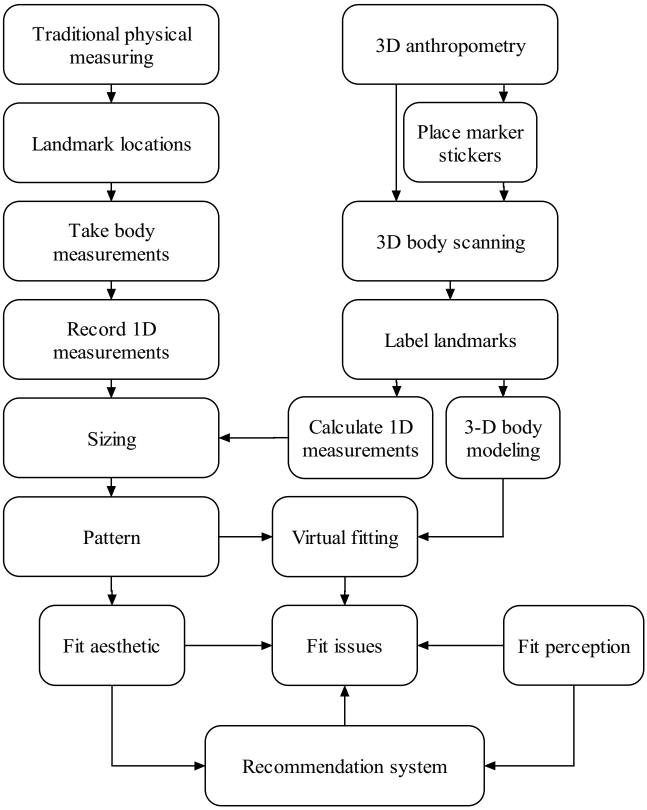

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Figure 3. The solution to fit issues

to align with the new body, the clothes warping module and cross-domain fusion module was used to generate the composition mask and composite the final try-on result (Hu *et al.*, 2022).

However, the virtual try-on fit is only an approximation of the visual effect, not the actual manufacture, due to the complexity of the fabric and the way the body and garment collide (Gill *et al.*, 2022). Some studies have focused on the appearance of a tight-fitting virtual garment in terms of the mechanical properties of textile materials (Ancutiene *et al.*, 2014), geometric shape of the basic pattern according to the key poses of the skating sport (Xiao *et al.*, 2024), pattern simulation in the 3D virtual sewing and fitting system (Zhu and Song, 2020) and the basic block pattern modification according to the fabric used and the mismatch between 2D and 3D measurement lines at the bust, waist and hip girths when the ease allowance is changed uniformly (Lagė and Ancutienė, 2019). Once the fabric and body virtual fitting problem is solved, other functionalities such as sizing or fit assessment can be added to virtual try-ons to benefit custom manufacturing.

4.3.2 Fit satisfaction. It is clear that precise measurement, body shapes, patterns and careful consideration of the material's mechanical and physical properties all contribute to a well-fitting garment (Bizuneh *et al.*, 2023; Gupta, 2020). Besides, customer value, which includes service, price, quality and emotions, also has important effects on their satisfaction. Therefore, customer fit preferences should be investigated extensively, not only from the customer's body shape, lifestyle, age, culture, previous purchases and returns (de Barros Costa *et al.*, 2017; Qian *et al.*, 2014), but also customer psychological aspects (Lang *et al.*, 2021).

Customer fit satisfaction helps to reduce return rates for clothing manufacturers and decrease textile wastes for environment. To improve fit satisfaction, clothing manufacturers need to place emphasis on both fit aesthetics and the technology application. The fit aesthetics can guide the innovation and development of technology, such as recommendation system, which provides recommendations on which style will fit the customer. However, prediction accuracy is the most critical and difficult point, as it is influenced by user's fit preferences and expert fit aesthetics in addition to recommendation algorithms (Shani and Gunawardana, 2011; Yu-Chu *et al.*, 2012; Zhou *et al.*, 2017).

5. Practices of apparel fit customization

Some large apparel industries, such as Brooks Brothers Inc., have already implemented the FC strategy. As digital technology advances, more and more apparel industries offer sizing or fitting assistance on their websites to customize the fit. For example, Indochino Inc. (www.indochino.com) uses size prediction to recommend sizes using intelligent algorithms. Bonobos Inc. (https://bonobos.com) uses fit models that represent a variety of body shapes and offers a wide range of sizes to fit different body types, from athletic to regular to slender. Proper Cloth Inc. (https://propercloth.com/about) has developed an algorithm that asks users a series of questions about their body type to help them calculate their measurements for men's shirts that can be tailored online.

Redcollar Inc. (www.redcollar.com.cn) has successfully attained FC after more than a decade of arduous struggle and substantial financial investment. Customers can obtain a range of personalized products at a reasonable price thanks to an internet-based platform that fully integrates customer data into the production process. For apparel of the same quality, users only pay 20% to 50% of the industry average. The company's net profit grew by about 46% year over year in the first three quarters of 2022, a sign of economic progress. This illustrates that while implementing new technologies takes time and money, the return on investment can be significant once a strong ecological model is formed.

Furthermore, an analysis of consumer feedback on their actual experiences with clothing FC platforms of Sumissura was identified the primary advantage of FC is its functional value, followed by ease of use and emotional value (Lang *et al.*, 2021). Functional value is predominantly characterized by comfort, the quality of tailoring and materials, and the fit of the products. Three main cost-related concerns were unsatisfactory service, disappointing product performance (e.g. poor fit) and financial risk (e.g. a mismatch between price and perceived quality). Consequently, ensuring high satisfaction with product performance emerges as the foremost benefit consumers seek from FC. In addition, user-friendly interfaces, exceptional service and aesthetic appeal are critical considerations for enhancing the overall consumer experience.

6. Discussion and implication

The three main applications of the technology currently used in FC are body measuring, pattern technique and fit evaluation. Technological innovations in these areas aim to better meet customer personalized fit demands, to improve cost control and increase profitability for apparel manufacturers and to reduce textile waste and pollution for environment. To drive technological advancements in these three domains effectively, it is essential to comprehensively understand the theory of consumer value, fit aesthetics and sustainable development. These theoretical foundations can guide technological innovations in measurement, pattern-making and fit assessments, enhancing the efficiency of technology application, minimizing technological waste and providing support for establishing an ecological model of FC.

The challenges of future studies on plausible technologies for apparel FC is likely to include the following.

The first is the availability of garment measurement data obtained through body measurement. Much research has been done to find methods or develop algorithms that can accurately identify landmarks directly from 3D scanned data of the human body, as well as 3D body modeling techniques. The real problem, however, is that it is unclear how to effectively apply the relationships between body data and garment dimensions. The difficulty of application is compounded by the differences in measurement methods used by different manufacturers. Since some measurements may not be appropriate for apparel production, it is sometimes necessary to consult customer fit preferences to validate the accuracy of the measurements. As a result, there is currently no industry-accepted technique for locating, labeling and tracking landmarks on 3D bodies in relation to garment dimensions.

It is imperative that the technical compatibility of body measurement data should be carefully considered to increase the general availability, ease of integration and affordability of these technologies. Manufacturers of apparel CAD manufacturing systems need to align themselves with an appropriate or set of standards for exchanging 3D body data to effectively combine fit patterns, virtual garment simulation, fit assessment, style modification and garment suggestions. The availability of standards will also help improve communication and promote more consistent representations of the various body types needed for CAD/CAM.

The guidelines or standards for categorizing the body morphotype must be made available to the sizing system. It is essential to determine the body morphotype according to age and ethnicity because the clothing fit is greatly influenced by the size, shape and posture of the body. Further research should be done on the body shape changes to build a comprehensive motion-related sizing system for some professional or competitive clothing.

3D pattern-making is a sustainable digital production method and a challenge for the future. There is still room for improvement in 3D body modeling technology when it comes to pattern generation for actual production. All relevant elements that influence the pattern, such as the fabric and the sewing technique, should be taken into consideration. Therefore, further research should be done to find the relationship between the fabric performance, clothing ease and body model to accurately and effectively construct the 3D garment model that is available in actual production. This has the potential to significantly advance the CAD/CAM-driven apparel fit modification process if it can be done accurately and consistently in the near future.

The flexibility and accuracy of virtual fitting in real-world production should be improved. Most virtual try-ons based on samples are widely used to show effects, but are rarely used in actual manufacturing due to accuracy issues. Besides, the virtual fitting online need to improve the ease of use, such as user-friendly interfaces and easy navigational structures. In addition, fit aesthetics and customer value are important factors for fit assessment and should be studied further to enhance customer fit satisfaction.

7. Conclusions

FC offers the apparel industry a sustainable way of production and can be improved as technologies evolve. A thorough comparison and analysis of current research has also been given in this review. In general, the aspects that affect garment fit, such as body measurements, patterns and garment fit relationships, must work together in an integrated manner to truly achieve computer-aided garment fit.

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