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The development of dress forms in standing and sitting postures using 3D body scanning and printing

Minji Yu[1,2] and Dong-Eun Kim[1*]

*Correspondence: dekim@ewha.ac.kr

[1] Department of Fashion Industry, Ewha Womans University, #402-3, Human Ecology Building (Morris Hall), 52, Ewhayeodae-gil, Seodaemun-gu, Seoul 03760, South Korea
[2] Present Address: College of Design, University of Minnesota, St. Paul, USA

Abstract

3D body scanning and printing are attracting attention as innovative technologies for producing dress forms. While designing dress forms, the shape of the human body must be accurately reflected in the different postures. This study explored the development of dress forms as a tool to understand changes in body size and shape according to postures and reflect this information to design and fit evaluation in the apparel industry. The holistic development process of dress forms in standing and sitting postures was suggested for representing the body shape of a specific target group. The average shape of middle-aged Korean women was derived by analyzing the 6th Size Korea data. A representative participant whose dimensions were closest to the average size was selected among recruited participants for the dress form development. The body data were acquired with a portable 3D scanner and corresponding dress forms and accessories were modeled using 3D CAD software. The models were inspected and corrected through prototyping. Full-size dress forms in standing and sitting postures were printed using a fused deposition modeling (FDM) 3D printer and post-processed. Completed dress forms were body-scanned and their accuracy was evaluated through morphological similarity comparison, cross-sectional image comparison, surface area and volume comparison, and mesh deviation analysis. Although there were some minor differences caused by the modeling process, the developed dress forms reflected the main characteristics and shapes of the representative body satisfactorily.

Keywords: Dress form, Standing and sitting posture, 3D body scanning, 3D printing, 3D modeling, Human body

Introduction

The human body is dynamic. In the apparel industry, clothing is developed based on a standard standing posture, however, users wear it in daily life and perform various movements in it, such as a sitting posture. Body dimensions change with posture and, for this reason, understanding the movement of the human body is closely related to successful clothing pattern design and construction (Chi & Kennon, 2006). Previous studies have found that the fit, mobility, and appearance of clothing change according to body postures, which also affects comfort (Mert et al., 2017; Wang et al., 2019). Understanding

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how the body's surface changes in different postures is complicated as one must account for the simultaneous movements of individual anatomical components that have individual types of connective mechanisms, tissue, and muscle. The sitting posture is the most common posture in everyday human life and work. Clothing should allow for the wearer's comfort and not restrict body movement by meeting the spatial needs of the changing body shape, for example, from a sitting posture to a standing posture (Aldrich et al., 1998; Lee & Ashdown, 2005). However, few studies have explored comprehensive body shape changes from a standing to a sitting posture.

A dress form that replicates the human body can be a good tool to help understand the 3D changes of the body's surface, including body shape and measurements. A dress form is a widely used item for clothing and wearable product development in the apparel industry and research field. During the development stages of apparel products, designers place clothing samples on a dress form to evaluate the design and fit of the products. This procedure is essential for developing clothing that carries an appropriate size and design for a company's target consumer (Sterlacci & Arbuckle, 2017). A dress form must reflect the human body shape so that garment fit evaluation can be performed under consistent conditions (Yoon, 2016). As it is used as a substitute for the human body, a dress form eliminates the time and cost spent on hiring a live model. The utilization of a dress form allows for repeated fit evaluations at each stage of clothing development. To improve the fit of clothing, the apparel industry must use dress forms that accurately reflect the body shapes and dimensions of target groups. Since body shape and size vary from person to person, even within the same target group, dress forms should reflect the most representative dimensions of a target group to ensure the optimal wearability of clothing (Yang et al., 2011).

3D body scanning technology has begun to play an important role in apparel studies as it enables the acquisition of the human body surface and opens up new possibilities for researchers and designers to understand the complex shape of the body. The utilization of 3D body scanning allows for the acquisition of 3D information and measurements concerning the body in various postures (Choi & Ashdown, 2011), enabling the creation of dress forms in different postures. Researchers have recently attempted to develop a dress form using 3D body scanning and printing since the use of 3D technology simplifies the process of creating a product while improving the accuracy of the result (Santos et al., 2017). Previous studies (Do & Choi, 2018; Lee & Jang, 2020; Oh, 2016; Ryu & Song, 2022) have confirmed that the 3D printing method allows for the rapid prototyping of dress forms that reflect exact body shapes in a simpler manner compared to the traditional production method. However, they have mainly focused on developing dress forms in a standing posture and there have been insufficient studies on developing full-size dress forms in diverse postures using 3D technology. In addition, no study has focused on both morphological and dimensional accuracy of 3D printed dress form modeled from 3D body scan data to investigate how exactly 3D scanning and printing technology can reflect the target body.

This study explored the development of dress forms as a tool to understand the dimensional changes of the human body according to postures, focusing on standing and sitting postures which can best demonstrate comprehensive shape differences of body components. In order to verify the accuracy and appropriateness of a 3D printed dress form, the precision of implementing the human body shape in different postures using 3D printing technology was investigated with the advanced 3D mesh analyses for morphological, cross-section, surface area and volume, and mesh deviation comparisons. It proposes a new method for developing and evaluating dress forms that accurately reflect the human body in standing and sitting postures by integrating 3D body scanning and printing technology. The developed dress forms can be used for pattern design and fit evaluation in the apparel industry and help researchers understand changes in the body's surfaces from standing to sitting postures regarding both measurements and the 3D shapes. To increase the significance of this study in the apparel industry, the average size-based development method generally used for creating dress forms was adopted. It was necessary to select a target group of a specific age and ethnicity to present the complete process of developing a dress form representing a specific target consumer. According to previous studies, the bodies of middle-aged women may be distinguished from those of younger women by a decrease in metabolic function and the easy deposition of fat. However, in the apparel industry, dress forms for the checking of clothing sizes and fits have mostly been shaped after the bodies of young, fit women instead, and have therefore failed to consider the characteristics of older women's bodies (Choi et al., 2015; Goldsberry et al., 1996; Lim, 2008; Yoon & Suh, 2009). Therefore, Korean middle-aged women with normal weight were selected as a target group for dress form development. This study was divided into three main steps that included acquiring 3D body scanning data of the representative participant, using it to model dress forms in standing and sitting postures, and developing full-size dress forms through 3D printing. The three objectives of this study were as follows:

1. To understand body shape and size changes in standing and sitting postures by analyzing body dimensions according to posture.
2. To develop a method of fabricating full-size dress forms in different postures in the utilization of 3D body scanning, 3D modeling, and 3D printing technology.
3. To comprehensively evaluate the dimension and shape accuracy of developed dress forms in standing and sitting postures by comparing the contour, cross-section, area, and volume differences of the original body and model.

Literature Review

3D body scanning for body changes

3D body scanning is a technology that acquires three-dimensional shape information from a human body. It has the advantages of rapid and contactless data acquisition, high precision, and easy reproducibility (Kim & Jeong, 2015; Raux et al., 2014). Using the data obtained via a 3D body scanner, it is possible not only to quantitatively analyze human body dimensions but also to develop a product that closely resembles the human body shape by employing 3D printing alongside a reverse engineering or modeling process. Types of 3D body scanners are categorized according to their properties, e.g., laser, structured light, white light, infrared, and Moire method (Apeagyei, 2010; D'Apuzzo, 2009; Daanen & Van De Water, 1998). Traditional 3D body scanners are generally stationary and have a spatial set-up in which cameras or light source devices are installed, although, the use of portable scanners has become more common. Compared to stationary scanners, portable scanners can scan small parts for specific purposes or complete full-body scans at high speeds using a simple process (Rosicky et al., 2016).

Park and Koo (2018) reviewed research trends using 3D body scanning in apparel studies. Their findings showed that one of the most dominant research trends for 3D body scanning sought to improve the wearability and movement suitability of clothing and to design patterns by analyzing body surface changes during specific movements. Sportswear was found to be among the most prevalent targets for such research, as human body changes in dynamic postures can be usefully applied to improve function and comfort. There have also been various attempts at quantitative analysis to improve the fit of clothing and to suggest a new design or size system.

Several studies have investigated body surface changes from standing to sitting postures using 3D scanning. Choi and Ashdown (2011) obtained human body data in active postures using a stationary-type Vitus XXL scanner and analyzed changes in the surface measurements of the lower body. Subjects were scanned in a standing posture, a knee-bend posture, a one-pace posture, and a sitting posture. Although this study was meaningful in its comparative analysis of various girth and length measurements of the lower body, it did not include angle and volume changes. Since the stationary scanner was optimized for a standing posture, there were missing data for various parts of the lower body, including the hip, crotch, thigh, and back of the calf. Distortion may occur in the process of merging and filling these with other software, and the accuracy of body data generated using this method has not been verified. Furthermore, the study included only the analysis of dimensional data while the overall shape change of the body was not explored.

Griffin et al. (2019) acquired and compared waist-hip-thigh body regions in standing and sitting postures using the VITUS Smart Full Body, Artec Eva, and Occipital Structure scanners. The researchers explored the advantages and disadvantages of 3D scanning technology for quantifying body surface changes according to posture and discussed appropriate landmarking techniques. A quadrant landmarking technique was used to analyze 1D and 2D measurements by dividing the body into sections, and volume and curve analysis was conducted by extracting the waist, hip, and pant line curves from participants' bodies in standing and sitting postures. However, this study did not analyze the change of the whole body from a standing to a sitting posture by focusing on the relatively small region related to a specific product.

Previous studies have attempted to analyze body surface changes in different postures, including sitting postures, with 3D body scanning by utilizing various data such as dimensions, volume, and curve lines. However, no study has acquired intact whole-body data and comprehensively investigated body surface changes including shape, appearance, and cross-sectional analysis.

3D printing in apparel studies

3D printing technology, also called additive manufacturing, is receiving increased attention as an innovative technology for product development. It involves the construction of 3D models, which are usually obtained through 3D scanning or created using 3D CAD software (Baronio et al., 2016). Slicing software is used to convert a 3D model to

G-code for 3D printing including various output command data such as materials, layers, supports, and fills. 3D printers can use various materials, including liquids, solids, and powders, and 3D printers are classified according to fabrication methods. Liquid-based 3D printers include photo polymerization and material jetting; powder-based 3D printers include binder jetting, powder bed fusion, and direct energy deposition. The material extrusion method using a solid material is when the material is heated at a high temperature and then extruded through a nozzle; fused deposition modeling (FDM) and fused filament fabrication (FFF) are examples of this method (Lee & Lee, 2016). Solid-based 3D printers have almost no limitations in materials such as plastics, waxes, and rubbers and can create products with complex structures.

Compared to casting and computerized numerical control, 3D printing is advantageous as it reduces material waste, is less time-consuming and expensive, and does not require the help of skilled technicians (Santos et al., 2017). The characteristics of 3D printing make it suitable for the rapid prototyping and production of single products and it is thus being increasingly used in customized product development (Kumar et al., 2019). Studies using 3D printing technology are being actively conducted in the fashion industry (Yap & Yeong, 2014). In the apparel field, several researchers have developed clothing products such as shoes, dresses, and accessories using 3D printing technology (Vanderploeg et al., 2017). Other researchers have created textile structures (Melnikova et al., 2014) using 3D printing.

Several studies have developed customized dress forms through 3D data acquisition, transformation, and printing. Vuruskan and Ashdown (2017) developed a half-scale dress form in a cycling posture through 3D body scanning and modeling. Scanned data were exported to the stereolithography (STL) format using ScanWorX software and processed into the shape of a dress form using Geomagic Studio. The half-size dress form was completed through laser cutting and gluing. Lim, Cassidy, and Cassidy (2017) developed a customized kit that can adjust a commercial dress form to a desired size and shape using 3D printing. The adjustable kit was modeled based on the six different female body types and printed using an FFF 3D printer using polylactic acid (PLA) material. Do and Choi (2018) developed an upper-body dress form for senior men using an FDM 3D printer with PLA material. In this study, the representative body type selected through the 6th Size Korea data analysis was modeled on the shape of a dress form using Design X and ZBrush software. Lee and Jang (2020) developed a half-size dress form by modifying the size of a 3D avatar in virtual fitting simulation software and 3D printing the modified avatar. Ryu and Song (2022) developed a custom-made dress form by 3D scanning one female who was within the drop measurement (hip circumference–bust circumference) range of Korean women of average weight and size and 3D printing the modeled data. However, the majority of previous studies have not explored the sitting posture—another dominant posture in daily life—to attain accurate dimensions and develop it into a dress form. In addition, they have used avatars that are different from the realistic shape of the human body or have selected representative bodies by using only a single measurement, which provides a limited representation of the targeted population and therefore cannot be used effectively in the apparel industry.

3D printing technology provides unlimited possibilities for product development based on human-dimensional data obtained with 3D body scanning. However, there is insufficient information on how 3D human body data can be collected for the development of dress forms in various postures and no study has evaluated the applicability of 3D printing to the human body. Unlike general products that have been produced by 3D printing, the human body is a complex shape composed of curved surfaces, wrinkles, muscles, and joints; thus, using 3D printing to generate a product that accurately reflects the human body is challenging. Additionally, it is necessary to explore how to use 3D body scanning for hidden parts such as the crotch, armpits, and back of the hip in sitting posture and transform them into a form suitable for 3D printing.

Methods

Participant

A dress form in the apparel industry should be made to accurately reflect the body shape and size of a company's specific target customer. In the current study, middle-aged Korean women were set as the target group; accordingly, we analyzed the average body size of middle-aged Korean women to find a participant whose body size was the most similar to the average size of this particular group. The anthropometric data of 302 normal-weight ($18.5 \leq BMI < 25$) women in their 40 s and 50 s were extracted and analyzed from the 6th Size Korea database (Korean Agency for Technology & Standards, 2012). Following from this, 16 middle-aged women were recruited for 3D scanning and the body scan data was measured with Rhino 7 (Robert McNeel and Associates, Seattle, WA, USA) by using sectional, linear, and surface measurement tools. The acquired dimensions of the participants were analyzed to find the representative woman whose body measurements important for dress form were most similar to that of the average Korean middle-aged woman. Table 1 summarizes the size comparison results of middle-aged Korean women and the selected representative participant. The representative participant showed differences of less than 2% from the national average size in important measurements such as stature and weight, and the difference in major girth areas—including the chest (axillar level), bust (bust point level), underbust (inferior breast level), waist (lateral waist level), waist (omphalion), hip (buttock protrusion level), and thigh (gluteal fold level)—ranged from 0.17 to 1.61 cm. Considering that Alvanon, the industry-leading dress form manufacturer, set the range covered by one women's dress form size for the main circumferences (bust circumference, waist circumference, and hip circumference) as 2.5 cm to 5.75 (Alvanon, n.d.), such a difference between the selected participant and the average size demonstrates the justification for developing a dress form using this body.

3D body scanning

The Artec Eva scanner (Artec 3D, USA) was used to scan the participant's entire body in standing and sitting postures. It is a portable 3D scanner that performs 16 fps capturing with structured light and point connection processing simultaneously, resulting in highly accurate and high-resolution scanned data. It enables the capturing of a landmark and texture in full color, which is advantageous for processing body data and acquiring body dimensions. Artec Eva can be utilized for scanning the obscured areas of the human body by capturing the object from various angles, which is difficult to achieve when using static scanners (Artec 3D, n.d.)

Table 1 Comparison between the average body size of middle-aged Korean women and the representative participant

Measurement	Average middle-aged Korean women; normal weight (A) Mean (SD)	Representative participant (B)	Difference	
			A − B	Percentage (%)*
General				
Stature (cm)	158.55 (5.43)	161.50	− 2.95	− 1.86
Weight (kg)	54.89 (5.07)	55.90	− 1.01	− 1.84
BMI (kg/m^2)	22.10 (1.72)	21.43	0.67	3.03
Length				
Shoulder length	12.43 (0.81)	11.79	0.64	5.15
Bishoulder length	38.43 (1.77)	37.51	0.92	2.39
Bust point–bust point	17.81 (1.31)	16.92	0.89	5.00
Waist front length	35.52 (1.76)	35.12	0.40	1.13
Waist front length (Omphalion)	39.57 (2.14)	39.71	− 0.14	− 0.35
Neck point to bust point to waistline	42.20 (1.92)	42.59	− 0.39	− 0.92
Waist back length	40.58 (2.23)	39.12	1.46	3.60
Waist back length (Omphalion)	44.64 (2.40)	42.60	2.04	4.57
Girth				
Neck circumference	34.29 (2.21)	34.17	0.12	0.35
Neck base circumference	38.00 (1.61)	36.87	1.13	2.97
Chest circumference	91.24 (4.29)	89.95	1.29	1.41
Bust circumference	91.18 (5.24)	89.57	1.61	1.77
Underbust circumference	79.31 (4.38)	78.98	0.33	0.42
Waist circumference	79.70 (6.01)	78.22	1.48	1.86
Waist circumference (Omphalion)	83.29 (5.41)	83.06	0.23	0.28
Abdominal circumference	86.39 (6.27)	88.81	− 2.42	− 2.80
Hip circumference	92.53 (3.83)	92.70	− 0.17	− 0.18
Thigh circumference	54.01 (2.90)	54.39	− 0.38	− 0.70
Knee circumference	35.31 (1.65)	34.57	0.74	2.10
Upper arm circumference	30.80 (1.94)	29.13	1.67	5.42
Elbow circumference	23.71 (1.21)	25.42	− 1.71	− 7.21
Width				
Neck breadth	12.07 (0.57)	11.95	0.12	0.99
Bishoulder breadth	34.70 (1.40)	36.53	− 1.83	− 5.27
Chest breadth	31.70 (1.45)	30.72	0.98	3.09
Bust breadth	29.79 (1.50)	30.19	− 0.40	− 1.34
Underbust breadth	27.65 (1.39)	28.48	− 0.83	− 3.00
Waist breadth	28.34 (1.86)	28.78	− 0.44	− 1.55
Waist breadth (Omphalion)	29.70 (1.72)	30.47	− 0.77	− 2.59
Abdominal breadth	30.72 (2.27)	32.67	− 1.95	− 6.35
Hip width	33.86 (1.45)	34.31	− 0.45	− 1.33
Depth				
Armscye depth	11.62 (1.03)	10.62	1.00	8.61
Chest depth	21.48 (1.50)	23.35	− 1.87	− 8.71
Bust depth	23.88 (1.87)	23.49	0.39	1.63
Underbust depth	21.44 (1.75)	19.76	1.68	7.84
Waist depth	21.25 (2.13)	20.38	0.87	4.09
Waist depth (Omphalion)	21.75 (1.93)	21.46	0.29	1.33
Abdominal depth	23.10 (2.01)	22.92	0.18	0.78
Hip depth	23.39 (1.45)	22.62	0.77	3.29

*Percentage (%): $100 - [(B/A) \times 100]$

Units of anthropometric measurements: cm

To acquire the 3D scanned data most similar to the actual body of the participant, it was important to ensure that the scan suit fit the participant's body well but not too tightly. Therefore, a soft, stretchable polyester bra top and underpants with a seamless design were used as a scan suit to prevent the distortion of the body caused by seam allowance.

The participant was asked to model standing and sitting postures for body scanning under natural breathing conditions, keeping shoulder ends parallel and eyes staring forward. In the standing posture, the participant stood up straight and with both feet parallel at 35 cm intervals. In the sitting posture, the legs were placed at the same location as the standing posture, the knees were straight above the feet, and the calves were perpendicular to the floor surface. For scanning in the sitting posture, a strategy to acquire complete body scan data was needed since many parts of a body, such as the underside of the thigh and back of the calf, are hidden by the chair. To avoid missing data from under the hip and thigh, we used a transparent polycarbonate chair that the structured light of the scanner could penetrate to obtain clear point cloud data. The researchers scanned the participant from various angles; these included tilting the scanner from the floor and side angles that could dig down the space between the chair legs and the calves to prevent the participants' calves from being distorted or obscured by the chair legs.

During scanning, the participant was asked to maintain a consistent posture by aligning her legs with the reference line drawn on the floor. Both arms were fixed at an angle of 40° using supports to minimize any shaking of the arm during scanning. The average scanning time for both postures was less than 3 min. Scanning was conducted twice for each posture to prevent potential data loss and point mapping errors caused by the participant's inadvertent movements.

Data processing

The data obtained via 3D body scanning at the initial stage were not in the form of a perfect human body shape but were a collection of multiple partial images and point clouds. Therefore, post-processing was necessary to generate a 3D model. Post-processing was performed with the collected point cloud and texture images using Artec Studio 14 Professional (Artec 3D, USA) software. The Artec Studio program provides an Autopilot function that enables optimal algorithm setting to create a 3D model with high accuracy. The Autopilot function proceeds as per the following four steps:

1. Responses to some simple questions regarding the characteristics of the scanned object are required to construct the most appropriate algorithm.
2. Superfluous portions of the scan data are deleted using the edit function.
3. The scattered scan data are aligned to prevent fusion errors.
4. Model creation is performed automatically. This step consists of fine registration, global registration, outlier removal, fusion, small-object filtering, mesh simplification, texturing, and texture optimization (Artec 3D, 2019).

Through post-processing, the multi-scan data were fused into a single human body shape and the texture images were accurately restored to obtain a realistic 3D human model. Before exporting the data, the 3D model was properly aligned for dress form modeling by using the object movement and rotation tools.

Dress form development

The 3D body scan data of the representative participant in the standing and sitting postures were converted into STL format for dress form modeling. Meshmixer 3.5 (Autodesk, USA) and Rhino 6 (Robert McNeel & Associates, USA) software were used to model them into the shape of a dress form. Before producing the full-size dress forms, prototypes were 3D printed to check for any errors or scope for improvement. The dress forms were printed at a 15% scale and accessories were printed at full scale. Meshes were rendered and converted to G-code using the slicing program, Cubicreator v4.2.3 (Cubicon, Korea). Cubicon Single Plus (Cubicon, Korea), an FFF-type printer, was used for prototyping with acrylonitrile butadiene styrene (ABS) material. ABS was chosen as it is considered suitable for dress form production due to its good strength, impact resistance, and processability.

Full-size dress forms in standing and sitting postures were printed using Stratasys Fortus 250MC, an FDM-type 3D printer. This printer was deemed appropriate for producing full-size dress forms that precisely reflect the body shape of middle-aged Korean women due to its relatively large output size of up to $254 \times 254 \times 305$ mm with an achievable accuracy of ± 0.241 mm. Ivory-colored ABSplus-P430 material was used for modeling and a supporter was created with a breakable structure to obtain a clean surface on the dress form after removing the supporter.

The accuracy of the completed dress forms was evaluated to validate the utilization of 3D technologies for fabricating a human body model in various postures. The dress forms were 3D scanned and both qualitative and quantitative analysis methods were employed for systematic and comprehensive assessments: morphological similarity comparison, cross-sectional image comparison, surface area and volume comparison, and mesh deviation analysis. In this accuracy evaluation process, differences between comparison groups 1 (dress form and modeling) and 2 (dress form and representative body) were analyzed. Group 1 was used to investigate the modeling implementation accuracy of 3D printing technology and group 2 was used to verify the utilization of developing a dress form using 3D human body scan data.

Results and Discussion

Comparison of body dimensions in standing and sitting postures

Through 3D body scanning and post-processing, complete body data were acquired, including those for detailed parts such as the armpits, crotch, underbust, and underarm areas. Furthermore, the underside of the thigh and back of the calf in the sitting posture were captured successfully, which is critical for developing a dress form with accurate dimensions in the sitting posture.

To investigate changes in body dimensions according to posture, measurements in the standing and sitting postures of the representative participants were compared (Table 2). Most length measurements did not have many differences regarding posture but waist front length and waist front length (omphalion) were 3.45% and 3.60%

Table 2 Dimensional changes in the standing and sitting postures of the representative body

Measurement	Standing posture (A)	Sitting posture (B)	Difference	
			A − B	Percentage (%)*
Length				
Shoulder length	11.79	11.79	0.00	0.00
Bishoulder length	37.51	37.51	0.00	0.00
Bust point–bust point	16.92	16.92	0.00	0.00
Waist front length	35.12	36.33	− 1.21	− 3.45
Waist front length (Omphalion)	39.71	41.14	− 1.43	− 3.60
Neck point to bust point to waistline	42.59	44.87	− 2.28	− 5.35
Waist back length	39.12	39.35	− 0.23	− 0.59
Waist back length (Omphalion)	42.60	43.83	− 1.23	− 2.89
Girth				
Neck circumference	34.17	35.15	− 0.98	− 2.87
Neck base circumference	36.87	37.67	− 0.80	− 2.17
Chest circumference	89.95	89.78	0.17	0.19
Bust circumference	89.57	88.58	0.99	1.11
Underbust circumference	78.98	78.98	0.00	0.00
Waist circumference	78.22	82.36	− 4.14	− 5.29
Waist circumference (Omphalion)	83.06	87.18	− 4.12	− 4.96
Abdominal circumference	88.81	92.55	− 3.74	− 4.21
Hip circumference	92.70	104.45	− 11.75	− 12.68
Thigh circumference	54.39	60.44	− 6.05	− 11.12
Knee circumference	34.57	39.97	− 5.40	− 15.62
Upper arm circumference	29.13	29.13	0.00	0.00
Elbow circumference	25.42	25.42	0.00	0.00
Width				
Neck breadth	11.95	11.95	0.00	0.00
Bishoulder breadth	36.53	36.33	0.20	0.55
Chest breadth	30.72	30.63	0.09	0.29
Bust breadth	30.19	30.10	0.09	0.30
Underbust breadth	28.48	27.87	0.61	2.14
Waist breadth	28.78	29.07	− 0.29	− 1.01
Waist breadth (Omphalion)	30.47	31.30	− 0.83	− 2.72
Abdominal breadth	32.67	32.82	− 0.15	− 0.46
Hip width	34.31	36.77	− 2.46	− 7.17
Depth				
Armscye depth	10.62	10.72	− 0.10	− 0.94
Chest depth	23.35	22.68	0.67	2.87
Bust depth	23.49	23.06	0.43	1.83
Underbust depth	19.76	20.36	− 0.60	− 3.04
Waist depth	20.38	21.94	− 1.56	− 7.65
Waist depth (Omphalion)	21.46	23.34	− 1.88	− 8.76
Abdominal depth	22.92	24.83	− 1.91	− 8.33
Hip depth	22.62	23.90	− 1.28	− 5.66
Drop value				
Drop 1 (bust circumference–waist circumference)	11.35	6.22	5.13	45.20
Drop 2 (hip circumference–waist circumference)	14.48	22.09	− 7.61	− 52.56
Drop 3 (hip circumference–bust circumference)	3.13	15.87	− 12.74	− 407.03

Table 2 (continued)

Measurement	Standing posture (A)	Sitting posture (B)	Difference	
			A − B	Percentage (%)*
Drop 4 (bust circumference–underbust circumference)	10.59	9.60	0.99	9.35
Flatness ratio				
Bust flatness ratio (bust depth/bust breadth)	0.78	0.77	0.01	1.28
Waist flatness ratio (waist depth/waist breadth)	0.71	0.75	− 0.04	− 5.63
Hip flatness ratio (hip depth/hip width)	0.66	0.65	0.01	1.52

*Percentage (%): 100 − [(B/A) × 100]

Units of anthropometric measurements: cm

longer in the sitting posture, respectively; these changes were related to the intensified protrusion of abdominal fat in the sitting posture.

Many circumference, width, and depth measurements had noticeable differences between postures. While the upper body area, including the neck, shoulder, chest, and bust, showed little or no change regarding posture, the large dimensional changes between the two postures began from the waist. In the sitting posture, waist and abdomen circumferences increased by 4% to 5%, and hip, thigh, and knee circumferences increased by 12.68%, 11.12%, and 15.62%, respectively, having the largest change rate among all measured dimensions. The knee circumference was increased in the sitting posture where it was bent at a 90° angle.

The width changes were mostly small compared to circumference and depth changes, although the hip area spread to the side in the sitting posture with a 7.17% increment. The depth of the waist, waist (omphalion), abdomen, and hip was larger in the sitting posture with 7.65%, 8.76%, 8.33%, and 5.66% increments, respectively. The body depth increased further along the lower abdomen due to the protrusion of fat and then slightly decreased from there as the width increased in the hip.

Among the calculated values, drops 2 (hip circumference–waist circumference) and 3 (hip circumference–bust circumference) increased by 52.56% and 407.03%, respectively, in the sitting posture; this was because the hip circumference increased at the largest rate in the sitting posture. Drop 1 (bust circumference–waist circumference) increased by 45.20% in the standing posture because the difference between the two circumferences decreased as the waist circumference became larger in the sitting posture. The waist flatness ratio (waist depth/waist breadth) was higher by 5.63% in the sitting posture, implying an increase in the degree of protrusion of the waist.

The hip was the part most affected by the posture change from standing to sitting, which was thought to be because it had direct contact with the surface of the chair. The thighs also widened horizontally in the sitting posture. Thus, there were significant changes in body dimensions between the postures. This shows the necessity of practice to consider the dynamic body in clothing product development and the need to consider clothing fit in different postures.

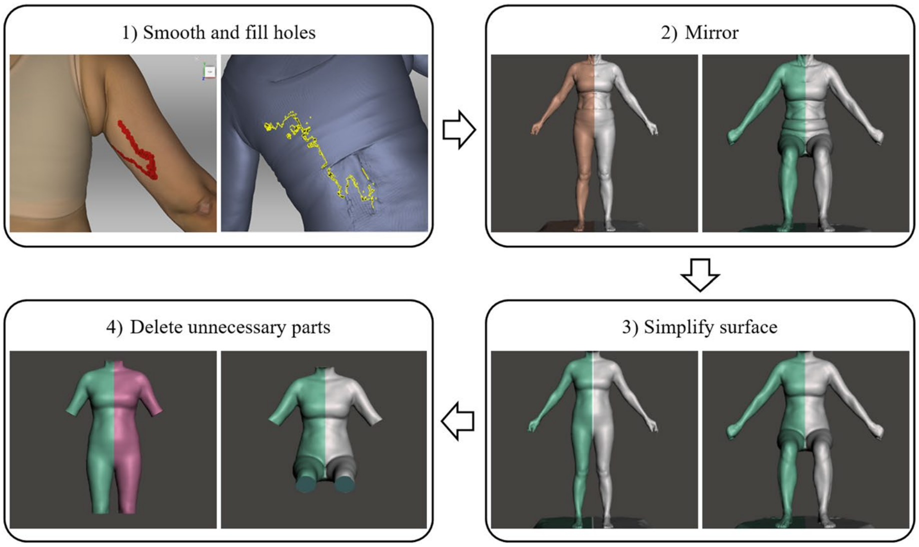


Fig. 1 A process for modeling the basic shape of a dress form

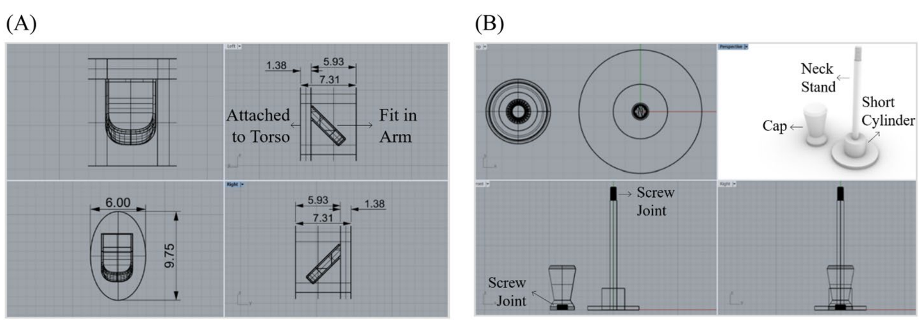


Fig. 2 Arm hook modeling (**A**) and neck stand and cap modeling (**B**)

Dress form modeling

Basic shape

The basic modeling process of the dress form is shown in Fig. 1. First, a hole-filling procedure was conducted to prevent modeling errors. The chair used for the sitting posture was deleted. Next, the left side of the body was mirrored to make the dress form symmetrical. Third, 3D sculpting tools in Meshmixer were used to smooth and remove irregularities from the body surface, such as the wrinkles from the scan suit and the belly button. This process was carefully conducted to avoid distorting the main dimensions and shape of the body. Finally, the face, arms, and legs were removed for the development of the torso-type dress form. The face was deleted based on the virtual cutting plane from the front neck to the back neck point below the face line. The lower parts of arms and legs were removed at the elbow and knee points, respectively.

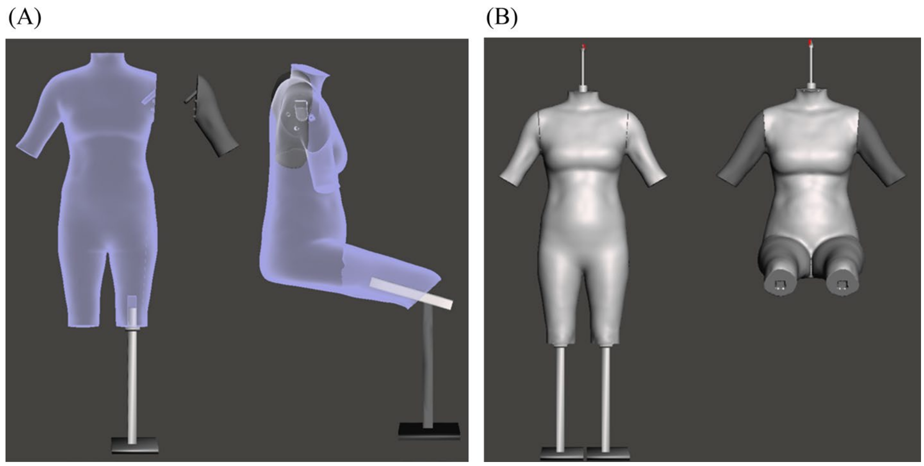


Fig. 3 Detachable arm and leg support (**A**) and final dress form model (**B**)

Accessories

Similar to a commercial dress form, the detachable arm and neck stand were additionally modeled to be applied to the dress form using Rhino 6 software (Fig. 2). Hooks with a 45° angle were designed to be applied to the arm's separation surface. The neck stand and cap were modeled so that the developed dress form could be mounted in the same way as the commercial dress form. The neck stand was created in the shape of a circle with a 1.1 cm diameter with a short cylinder at the bottom to prevent it from breaking when linked to the body's neck. To firmly assemble the neck stand and cap, a 2 cm screw joint was created at the top of the stand. Leg supports were designed in the form of square columns with 3 cm sides to allow the dress form to remain fixed at the same height as the participant. The leg supports were modeled differently in the standing and sitting postures; vertical columns with a stopper were created for the standing posture and bent columns at right angles were created for the sitting posture.

Final models

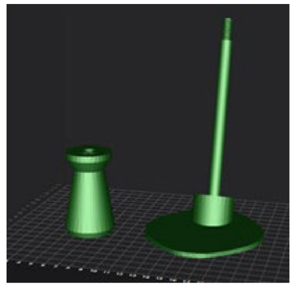
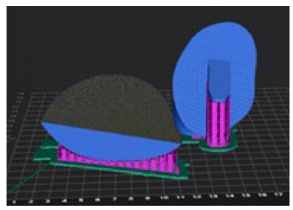
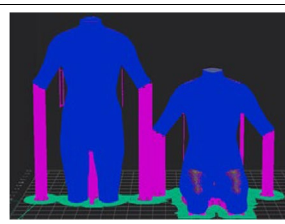
The final shape modeling of the dress form was completed by attaching the accessories. The torso and arms were separated based on the virtual cutting plane from the shoulder to the armpit point. Arm hooks were applied to the separation surface of each arm and the corresponding holes were also created inside the body so that the hooks could be fitted when attached. In both standing and sitting postures, the neck stand was positioned on the torso's neck. To allow the leg supports to be inserted into the dress form's leg, holes were created in the knees' cut edges, which were then fully joined. Figure 3A shows the result of applying the detachable arms and leg supports to the dress form. The completed models of the standing and sitting postures are shown in Fig. 3B.

Dress form development with 3D printing

Prototyping

Table 3 lists the printed prototypes for inspecting the accessories and the entire body. The neck stand and cap were printed to confirm strength and assembly. The printed

Table 3 3D rendering and printed results of prototypes

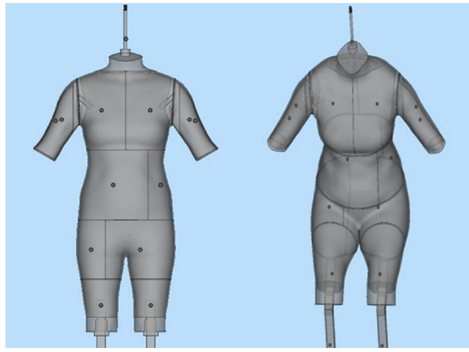
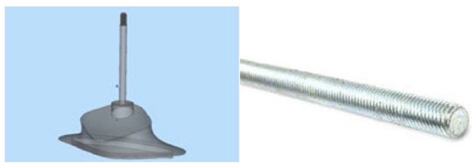
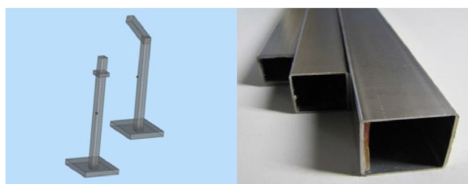
Part	Rendering	3D Printed Prototype
Neck stand and cap		
Arm hook		
Body		

screw assemblies were precise enough to join together. As the neck stand was very thin, it was easily broken even with a tight grip. Therefore, a metal cylinder was inserted inside the neck stand to improve its durability. The detachable hooks of the arm were output in half-size to check whether they were properly engaged. For arm hooks and torso-side holes, two printed prototypes with 0.5 mm and 1 mm margins in each direction were compared to determine an appropriate margin. A 0.5 mm margin was found to be appropriate for a good fit of the hook without shaking after assembly. The entire bodies of the standing and sitting postures were output at a size of 15% to check for modeling errors and shape distortion. The modeling of the standing posture did not require any modification; in the sitting posture, there was a minor issue: both legs almost stuck together in the crotch area without any space as the thigh fat spread to the side. To address this issue, the final model was modified by cutting the contact surface of the crotch area so that the developed dress form could perform the function of garment fitting suitably in situations such as pulling a pair of pants onto the legs.

Full-size dress forms

Before printing, the models were converted to a format suitable for 3D printing and then sliced into several pieces based on the 3D printer's maximum output size using slicing software (Table 4). The torso was divided into eight pieces, in similar locations as much as possible, for both postures. Given that there was a possibility of minor errors around the cut line of the dress form in the printing and assembly process, we

Table 4 3D slicing results and inserted materials

Part	Image	Remark
Body		Torso: 8 pieces Arm: 2 pieces
Neck		Inserting a metal bolt into the neck stand
Leg support		Inserting aluminum square pipes into the leg supports

ensured that the cut line did not pass through important parts of the body such as the chest, waist, and hips. The leg supports were printed integrally with the bottom plates and square columns without division. Assembly rails were created at the interfaces. On the neck stand, which required strength enhancement during prototyping, an inside hole was created to insert a metal bolt. The square aluminum pipes were inserted into the leg supports to securely shore up the dress forms.

STL files of the divided pieces were converted into G-code files containing output information such as movement, extrusion, heating, and sensing commands with preset printing speed and thickness. The thickness of the outer walls of the dress forms was set to 5 mm in consideration of the balance between the desired strength and the output time. The interior was emptied to reduce the weight for easy portability. The layer thickness of the entire output was 0.254 mm and the support structures were automatically generated based on a 45° angle.

The production process of the full-size dress form using 3D printing is shown in Fig. 4. The printed pieces were glued after the support structures were removed. As the FDM-type printer produces layer lines and a rough surface on the output, several post-processing steps were required to smoothen the printed dress forms surface. In this study, the post-processing involved putty application, sanding and washing, primer application, and painting. The post-processing procedures were as follows.

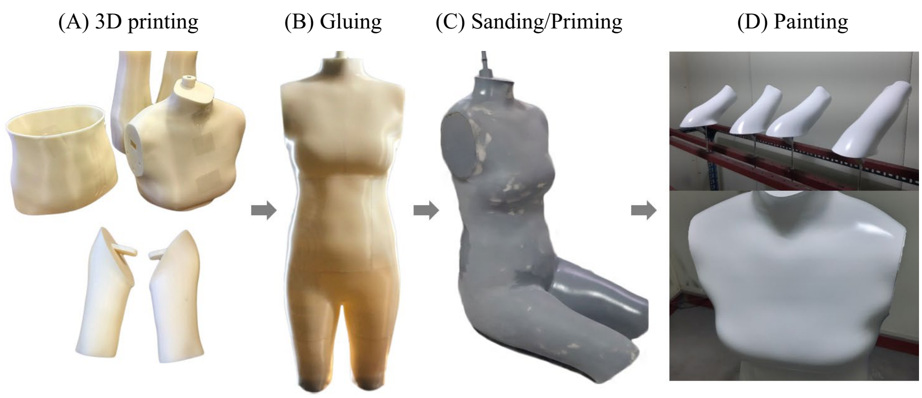


Fig. 4 3D printing and post-processing procedures for dress form production

1. Diluted epoxy putty was thinly applied to the surface of the output to fill the layer lines in prints and then the surface was polished using sandpaper. After washing, the same process was repeated twice to smoothen the surface.
2. A light gray primer was applied to the outputs. Given that the primer was composed of very small particles, it was used to obtain a smooth finish on printed pieces before painting and to fill in the fine layer lines. It also served to help the paint settle well on the surface of the outputs.
3. A semi-glossy white paint was applied. A less reflective paint was chosen with a bright color, which helps the scanner to capture the image better; this was because we planned to scan the completed dress forms to evaluate their shape and dimension accuracy. The paint was allowed to dry over a sufficient amount of time.

The completed dress forms for middle-aged Korean women in standing and sitting postures are shown in Fig. 5. They could be installed either with the dress form stand or with leg supports like the general dress form used in the apparel industry. The developed dress forms well reflected the body shapes of women in their 40 s and 50 s, who tend to have a proportionally long upper body length, prominence at the waist and abdomen, relatively flat hips, and increased circumference, width, and thickness.

Accuracy evaluation of dress forms

Completed dress forms were body-scanned and their accuracy for the representative body data before the modeling stage and modeling data was evaluated through morphological similarity comparison, cross-sectional image comparison, surface area and volume comparison, and mesh deviation analysis.

Morphological similarity comparison

The images of completed dress forms were compared with the representative participant's original scanned images (Table 5) to evaluate whether the dress form accurately reflected her body shape and dimensions. The overall shape and the curve of the protrusion were very similar, however, minor differences were owing to the modeling process having to meet the requirements for the industrial dress form. The participant's body had a rough surface, clearly showing the contour of the scan suit and the shape of the

Fig. 5 3D printed full-size dress form in a standing posture (**A**) and a sitting posture (**B**)

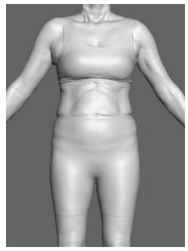
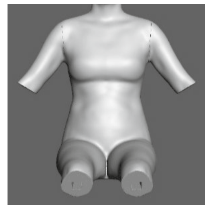
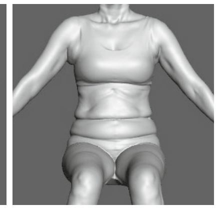
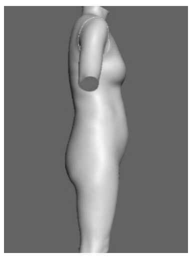
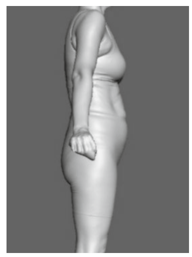
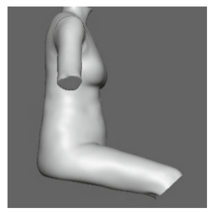
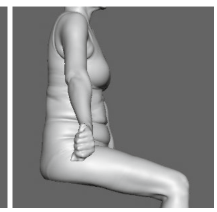
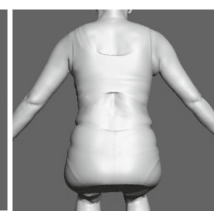
muscles and fat. By contrast, the dress forms had a smoother surface as irregularities including bumps and wrinkles on the surface had been intentionally softened to make it suitable for dress form use. The left and right sides of the participant's body, like other human bodies, were not perfectly symmetrical, so the left side had been mirrored for the dress forms to make it symmetrical. Overall, the 3D printed dress forms well reflected the dimensional characteristics of the participant's body, such as a flat hip and abdominal protrusion, while meeting the dress form requirements.

Cross-sectional image comparison

For the dress form, modeling, and representative body, the cross-sectional images of the main body areas were overlapped and analyzed (Fig. 6).

In the standing posture, the cross-sections of the dress form and the original modeling corresponded to each other in all of the main circumferences; it provided evidence that the 3D printing process accurately captured and reproduced critical body dimensions that are important for apparel fitting. Comparing the dress form with the representative body, there was no significant difference found in the left shape as the dress form was modeled by mirroring the left shape of the representative body shape. The right shape of the dress form was slightly different from the representative body in some areas, including the chest, bust, underbust, and waist circumferences. These differences were likely caused by the modeling process of simplifying the bumpiness

Table 5 3D scanned image comparison

Division	Standing Posture		Sitting Posture	
	Dress Form	Representative Body	Dress Form	Representative Body
Front				
Side				
Back				

of the skin and making the body symmetrical. The overall shape of the dress form followed the original contour of the representative body.

In the sitting posture, similar to the standing posture, there were no notable distinctions between the dress form and the modeling, confirming the accuracy of the 3D printing process in replicating the human form. The comparison of the dress form to the representative body shape revealed a close resemblance in the left side contour, with the representative body exhibiting slightly reduced waist and abdominal circumferences. The observed differences in waist and abdominal circumferences between the dress form and the representative body were attributed to the modeling process, which involved smoothing out surface irregularities and filling slight compressions induced by the scan suits. Notably, in the hip and thigh circumferences, the representative body exhibited a reduction in frontal dimensions relative to the dress form, reflecting the simplification of lower abdominal creases and folds during the modeling process. The dress form's cross-sectional shape of knee circumference followed that of the representative body, although the location of the right leg was slightly different due to the symmetry process during dress form modeling.

In summary, the dress form and modeling exhibited significant similarity, supporting the viability of 3D printing for creating accurate models of the human body.

Although the dress form generally reflected the representative body shape, there were slight differences attributed to the modeling process, which included smoothing the contour of the scan suit and accounting for folds in the lower abdomen in sitting posture. Despite this, the dress form demonstrated a high level of fidelity to the representative body shape, affirming the potential of 3D printing for creating accurate models of the target body.

Surface area and volume comparison

Table 6 presents the body surface area and volume of the dress forms and representative body in the standing and sitting postures. The modeling was excluded from this evaluation as the arm accessories and hole for the leg support may have affected the body surface area and volume. For comparison under the same conditions, the areas below the elbow and mid-knee were deleted from both the dress forms and the representative body before calculating body surface area and volume.

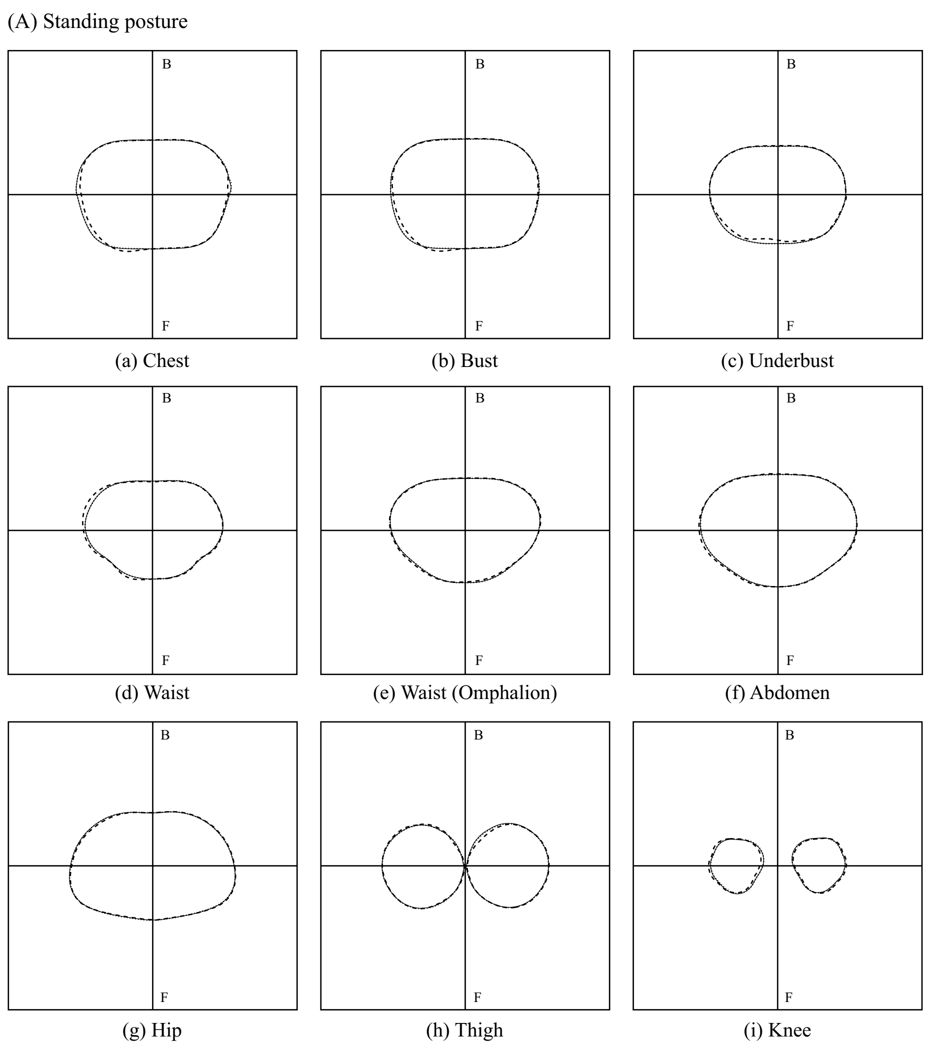


Fig. 6 Cross-sectional images of a standing posture (**A**) and a sitting posture (**B**)

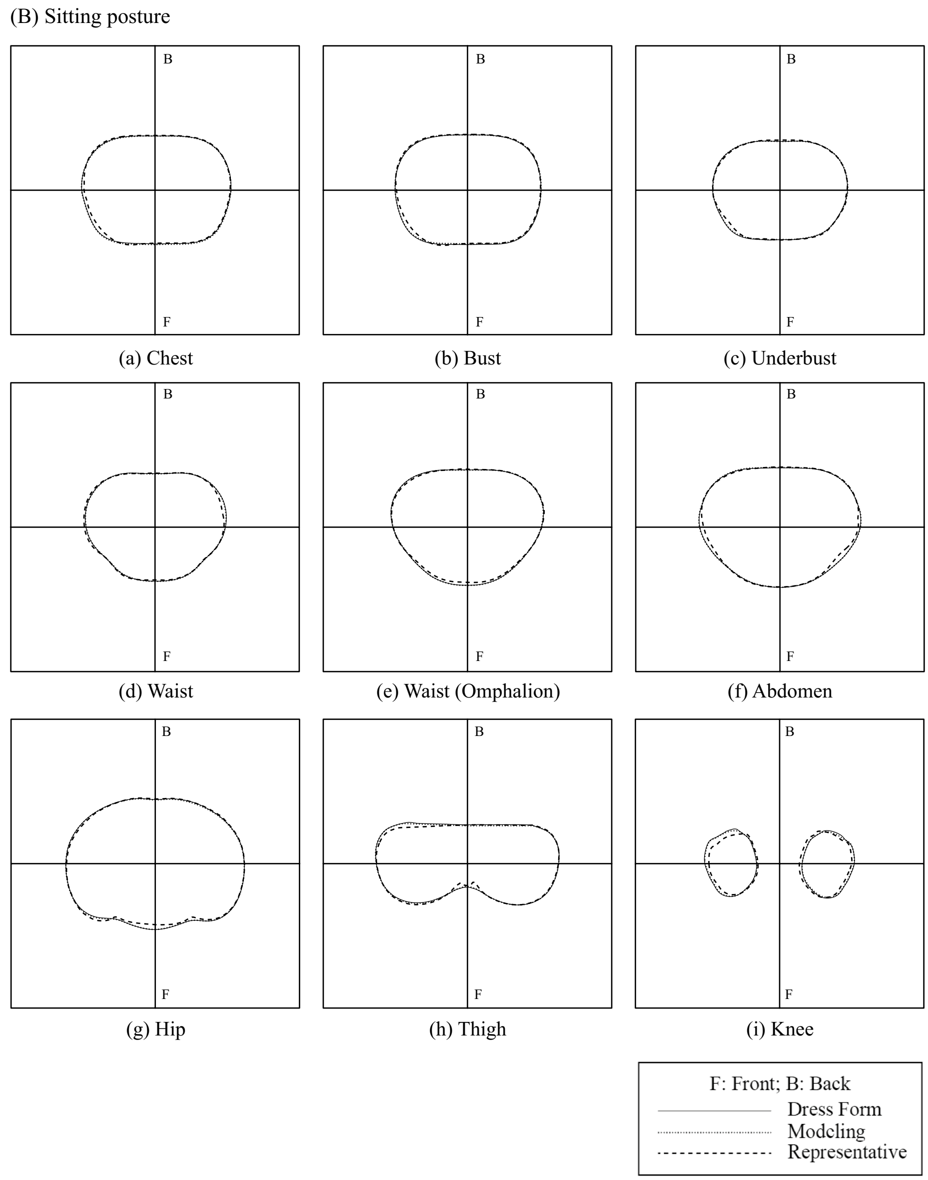


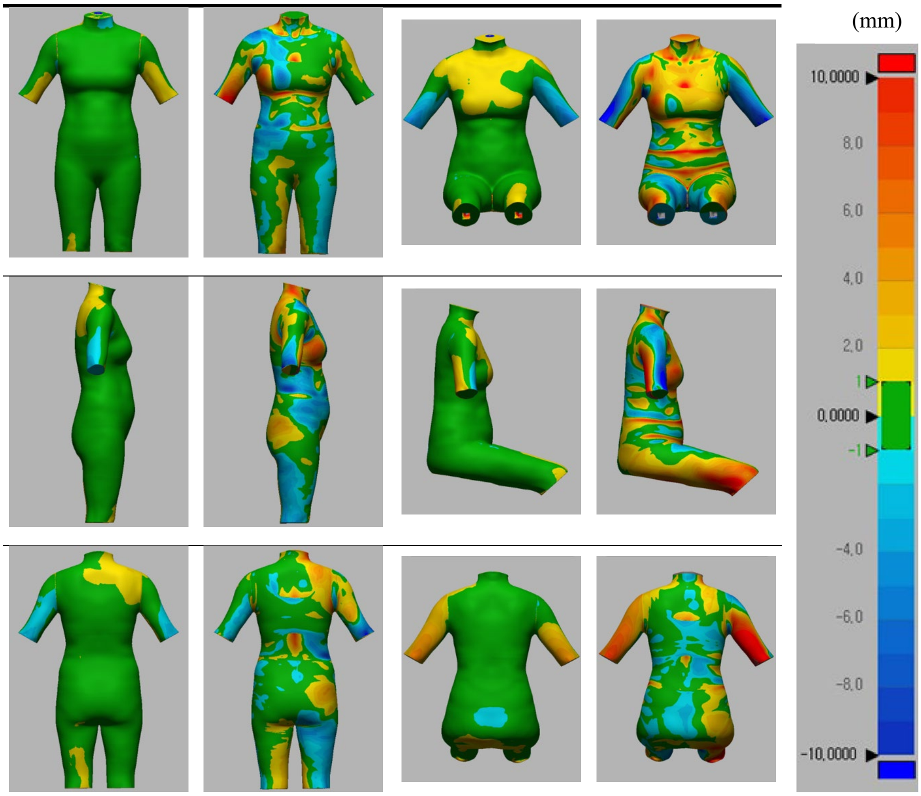
Fig. 6 continued

Table 6 Surface area and volume comparison

Posture	Item	Dress form (A)	Representative body (B)	Change rate (%)
Standing	Surface area (cm^2)	9775.23	9930.16	− 1.58
	Volume (cm^3)	45,837.68	45,866.26	− 0.06
Sitting	Surface area (cm^2)	10,256.35	10,345.85	− 0.87
	Volume (cm^3)	48,135.50	47,328.32	1.68

Table 7 Mesh deviation analysis results based on completed dress forms

Standing Posture		Sitting Posture	
Deviation 1 (Dress form and modeling)	Deviation 2 (Dress form and representative body)	Deviation 1 (Dress form and modeling)	Deviation 2 (Dress form and representative body)



The green zone identifies regions where the deviation is within an acceptable distance value (± 1 mm). The zone from yellow to red identifies the regions where the dress form was larger than the comparison target. The zone from sky blue to dark blue identifies the regions where the dress form was smaller than the comparison target

The body surface areas of the standing dress form have decreased by 1.58% compared to that of the representative body. For the sitting posture, the body surface areas of the dress form were 0.87% smaller than those of the representative body. The volumes of the standing dress form had reduced by 0.06% compared to those of the representative body, while the volumes of the sitting posture dress form had increased by 1.68% compared to those of the representative body.

These differences likely occurred in the process of modeling, e.g., making a symmetrical body shape and smoothing body surfaces. In summary, the differences in area and volume between the dress form and representative body in both the standing and sitting postures were less than 2%. These results show that the final produced dress form was very similar to the representative body, even after completing various processes to create the dress form such as modeling, 3D printing, and post-processing.

Mesh deviation analysis

To evaluate the accuracy of 3D printing through more sophisticated analysis, the 3D shapes of completed dress forms were compared using 3D modeling and original scan data of the representative participant's body. Using the mesh deviation function of the Design X (3D Systems, USA) software, the discrepancies between the two groups were analyzed (Table 7). Deviation 1 was a comparison of the dress form and 3D modeling, while deviation 2 was a comparison of the dress form and the participant's body. The deviation between shapes was indicated in green within ± 1 mm. If the shape of the dress form was larger than the comparison target, the color was graded from yellow to red, depending on the degree of difference. If the shape of the dress form was smaller than the comparison target, the color was graded from sky blue to dark blue, depending on the degree of difference. The maximum deviation range was set to ± 10 mm.

The results of the mesh deviation analysis for deviation 1 (dress form and modeling) in both postures were as follows: the discrepancies were within ± 1 mm in most areas, while the yellow and blue colors on the back shoulder, thigh, and arm areas showed deviations within ± 2 mm, confirming the accuracy of the 3D printing. On the arm, the yellow color appeared in the front area and the blue color in the back. This was not considered to represent actual shape differences between the two data but was assumed to be due to the slight angle difference associated with the assembly process of the detachable arm. The dress form was slightly larger than the modeling in the shoulder and thigh areas due to post-processing steps such as primer application and painting.

Deviation 2 (dress form and representative body) showed a relatively wider discrepancy distribution. This was because the dress forms were developed by intentionally modifying the representative participant's body to have the general characteristics of the industrial dress form. The dress forms on the neck, front waist, and back were larger than the participant's body, which was due to the use of a filling brush function during the modeling process to simplify the irregularities associated with muscle and fat. The discrepancies in the armpit and back waist were likely caused by the process of smoothing the sagging bumps of fat. The red line along the underbust and waist (omphalion) circumference was caused by these areas being filled and smoothened to eliminate the outline of the scan suit during the modeling. The sitting posture had a wider distribution than the standing posture as more parts needed to be modified for dress form modeling, such as intensified abdominal protrusions and the sticking of both thighs. Overall, in both postures, the similarities of the left side of the bodies were relatively higher than those of the right because the dress forms were produced by mirroring the left side of the representative body.

To summarize the results of the mesh deviation analysis, deviation 1 (dress form and modeling) had a very slight difference, which confirmed the accuracy of the 3D printing results from modeling. Deviation 2 (dress form and representative body) had a relatively wide deviation distribution, however, as a result of analyzing the detailed color map, it was found that the differences were attributable to the modeling process for the use and commercialization of the dress form. For both standing and sitting postures, it was confirmed that the dress forms developed in this study accurately reflected the main characteristics of middle-aged Korean women's bodies.

Conclusions

Capturing body surface changes in different postures is essential for developing properly fitting clothing, which can be achieved by a thorough collection of body shape information. However, traditional measurement-based approaches have not adequately captured the complex shape changes of the human body. This study addresses this issue by developing dress forms using 3D technology as a tool to better understand the dimensional changes of the body in standing and sitting postures. Using the completed dress forms, we discovered that the human body undergoes complex dimensional changes when transitioning from standing to sitting, particularly in areas such as the abdomen and hip.

This study highlights the importance of incorporating body shape information through 3D printed dress forms to improve clothing fit. Furthermore, we presented the process of acquiring data for the entire body in sitting and standing postures using a portable scanner, which is an improvement upon previous studies that reported missing data points and incomplete regions when scanning the human body in sitting postures. The feasibility of imitating the human body with 3D printing was confirmed by evaluating the accuracy of the printed dress through a comprehensive analysis. The results of this study validate the potential of 3D printing technology to develop dress forms that precisely reflect human dimensions and body shapes by combining 3D body scanning, modeling, and printing techniques.

Compared to the traditional method, the proposed method for developing dress form does not require skilled technicians, simplifies the production process, and can be customized according to the body shape suitable for any target group.

We developed a full-size dress form by selecting a representative participant whose size was close to the average of the target group based on the national anthropometric survey data. Our method allows for the comparison of the shape and garment fitting of the developed dress form with the actual representative participant's body, enabling an evaluation of the accuracy and usability of the developed dress form. Moreover, our approach has the potential to supplant the use of live models in the apparel industry, as dress forms can be utilized for repeated garment fittings under the same conditions, resulting in reduced time and cost requirements.

Future studies could use the proposed method to develop dress forms that accurately reflect the body shape of various races and age groups. While this study selected one representative body for dress form development, further research is needed to comprehensively investigate how human body sizes change according to posture, by examining a larger sample size. Additional work may involve the application of 3D body scanning and 3D printing in an industry setting to better understand human body dimensions for various dynamic postures.

In conclusion, gaining a comprehensive understanding of human body shapes and measurements is a crucial step toward developing clothing with improved fit, mobility, and comfort. This study provides a foundation for future studies regarding the accurate collection and reproduction of human body dimensions using 3D technologies. With the advancement of 3D printing technology and the acquisition of accurate body shape information, it is now feasible to produce dress forms that accurately reflect human dimensions and body shapes, resulting in improved clothing fit and comfort for wearers.

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This work is based on the part of the master's thesis of the first author.

Authors' contributions
MY performed data collection and data analysis and drafted the manuscript under DK's supervision. DK guided the design of the study and finalized the manuscript. Both authors read and approved the final manuscript.

Authors' information
MY is a Ph.D. candidate at the University of Minnesota. She received her B.S. and M.A. from Ewha Womans University in South Korea. She is a research assistant in the Human Dimensioning Lab, where she researches 3D body scanning, dynamic anthropometry, sizing, and fit for advanced wearable products, as well as the development of medical and protective wearable products.
DK is a professor in the Department of Fashion Industry, College of Science & Industry Convergence at Ewha Womans University. DK's research area focuses on anthropometry study, clothing sizing system, and patternmaking using 3D body scanning, 3D virtual garment simulation, and 3D printing technologies.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This research was conducted under the approval and supervision of Ewha Womans University Institutional Review Board (IRB Approval No: ewha-201901-0017-02) regarding ethical issues including consent to participate.

Competing interests
The authors declare that they have no competing interests.

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