Article

A 3D Printed Physical Human–Robot Interface Based on a Sizing System to Facilitate Customization: Wearable Robots for Paraplegia

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Abstract: Wearable robots that assist paraplegia patients should be manufactured according to the shape of the individual wearer. With the development of advanced three-dimensional (3D) printing technologies, such customizations are becoming available. However, conventional 3D printing customization requires extensive template remodeling, which is non-productive and inefficient. This study proposes a 3D-printed (3DP) physical human–robot interface (pHRI) based on a sizing system that facilitates customization to body shapes. The proposed system is a pre-developed pHRI in various sizes and shapes using a human body shape database. Conformity of shapes and dimensions were evaluated visually via shape deviation analysis for 10 persons having paraplegia. With the proposed 3DP-pHRI, the trunk comprised 18 sections and the shank comprised nine. A biased trend of coverage rates in the shank 3DP-pHRI size system was identified. The trunk and shank subsystems were found to be adequate in terms of shapes and dimensions, with values within the mean deviation range of ± 10 mm. A novel 3DP-pHRI size system facilitating customization tool for fabricating wearable robots for paraplegia patients according to body shape was developed, and its effectiveness was assured. The new system can be used for various wearable robot pHRI, and the database is expected to supply a comprehensive pHRI template library.

Keywords: 3D printing; customization; paraplegia; physical human–robot interface; sizing system; wearable robot

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1. Introduction

Research activities in the field of wearable robots have expanded rapidly over the past 10 years, providing remarkable advancements for rehabilitative medicine, assistive living, and similar industries [1]. For people suffering paraplegia caused by spinal-cord injury (SCI), gait training using a wearable robot goes beyond simple walking rehabilitation. It has additional therapeutic effects, such as improving blood circulation, increasing bone density, and easing digestive function [2]. It is also known to significantly lower mortality and improve life expectancy [3]. In the field of rehabilitative medicine, studies have been actively conducted to evaluate the safety, efficacy, and benefits of wearable robot technology for such patients [4–7]. Most research has focused on improvements to machine performance [8]. Although the wearability of such devices is an important factor, developments have not considered this aspect from the user perspective [9]. Moreover, the physical human–robot interface (pHRI) for the wearable robot appliance has been overlooked in related studies [10].

A wearable robot comprises a driving unit, an exoskeleton frame, and a pHRI that connects the human body and the robot. The force generated by the driving unit is transmitted to the pHRI, dispersed through the part contacting the human body, and transmitted to the body [11]. The gait-assistance performance of a wearable robot depends

on how effectively the force generated by the robot is transmitted in this fashion [12]. A recent study reported that a force transmission loss of up to 50% can occur, owing to the relative movement between the wearable robot and the human body, which is exacerbated by improper customization [13]. From a biomechanical perspective, the lower extremities must have enough strength to support the body weight [14]. Accordingly, in addition to the local dysfunction of the parts in question, problems occurring in the lower extremities may lead to other problems that negatively affect the upper body (e.g., pelvis and spine). Considering the biomechanical mechanism of the lower extremities and the potential loss of force generated by the robot driving unit during transmission, the pHRI should be configured to ensure integrated connectivity between the human body and the wearable robot to ensure appropriate contact area for improved comfort and safety [15]. Because people with paraplegia are more susceptible to skin lesions and bedsores, this interaction is a crucial factor [16]. Excessive pressure from pHRI can lead to skin ulcers [17], and improper physical contact often causes pain and discomfort [18,19]. Therefore, it is important to maintain a safe contact pressure applied to the human body via the pHRI so that damage and discomfort can be minimized [20].

Based on this information, it is clear that a wearable robot for people with paraplegia should be manufactured according to the shape of the body of the individual wearer. When examining extant pHRI applications, there have been cases where off-the-shelf orthopedic pHRI were applied to reduce costs [21–23]. However, most were indeed custom-made [10]. The most traditional customization methods have been manually intensive, and include plaster casting and polyurethane foaming. Recently, with the development of three-dimensional (3D) printing manufacturing technology, a new method of customization based on body shape has been introduced. However, such approaches involve direct modeling, which is quite laborious. Direct-modeling customization requires remodeling the baseline template according to the shape of the 3D-scanned body surface, which exhibits low productivity and poor efficiency across multiple patients. In this respect, to increase the usefulness of customization to the body shape via 3D printing, a new method is needed to realize customization without template remodeling.

Therefore, this study proposes a new 3DP pHRI based on a sizing system to facilitate customization via 3D printing. To verify its effectiveness, the conformity of shape and dimension is evaluated. The proposed size-system-based 3DP-pHRI leverages a pre-developed (libraryized) pHRI comprising various sizes and shapes based on a human body shape database.

2. Materials and Methods

This study was conducted based on the hypothesis that conformity of shape and dimensions can be realized by selecting a 3DP-pHRI sizing system that best matches the body shape of the wearer, manufacturing it using 3D printing, and assembling it using a wearable robot. To test this hypothesis, a three-stage research plan was established. In Stage 1, a sizing system for the 3DP-pHRI was designed. In Stage 2, the shape–pattern design of the 3DP-pHRI template was developed. In Stage 3, clinical evaluation took place. This study specifically focuses on Step 1. The remainder will be covered in future research.

Considering the configuration of the selected wearable robot, a sizing system was built for the trunk and shank parts of the human body. A body shape database of people without disabilities was used for the development of this sizing system, owing to the practical difficulty of obtaining body-shape data from people with paraplegia. Regarding system development, a sizing system for the 3DP-pHRI was developed through segmenting sizing sections and generating an average human body model for each section. For the evaluation of the conformity of dimensions, the developed system employed 3DP manufacturing, and visual observations and shape deviation analyses were conducted for 10 persons with paraplegia to examine the effectiveness of body-shape customization.

2.1. Configuration of the Wearable Robot

The wearable robot selected for the study switches from reciprocating gait orthosis (RGOs) to power gait orthosis (PGOs) according to the gait-training stage of physical therapy. It comprises body fixation and driving modules. The body fixation module consists of a trunk module that fixes the waist of the wearer in place and supports the spine, a thigh fixation module that is worn on the thigh, and a shank fixation module that is worn on the calf. The driving module is composed of hip- and knee-joint driving units to generate forces in the joints to induce walking movements. RGOs can be switched to PGOs by selectively combining and using the joint driving units of the driving module. To apply the hip-joint driving unit, it is superimposed on the hip-joint frame, and to apply the knee-joint driving unit, the manual knee joint is replaced with the driving unit. The overall composition of the wearable robot is shown in Figure 1.

Figure 1. Hardware configuration of the wearable robot.

2.2. Analysis of Sizing System Generation Method

With reference to previous studies related to size-system generation [24–36], applicable techniques and sample data for segmenting body sections and creating an average human body model were analyzed. Table 1 shows the results.

Table 1. Analysis of size-system generation method.

Division		Applicable Technique	Sample Data Type
Size-section Segmentation		Grid method	2D Human body measurement data
		Clustering method	
Average Human model generation	Modeling method utilization	Optimization method	3D Human body shape-model data
		Wireframe modeling	
	Database utilization	Morphing modeling	Scan-template model-pair database
		Template model fitting	

Statistical analysis techniques (e.g., the Grid method) are mainly used for segmenting sizing sections, and two-dimensional (2D) human body measurement data are used as sample data. The segmentation of the size section is based on the total coverage rate (e.g., 95%) and the minimum coverage rate (e.g., 2%) throughout the human body dimension database, forming a grid in the order of relatively high coverage rates until the specified coverage rate is satisfied. The segmentation of the size section can be approached in three ways: the grid method, the clustering method, and the optimization method, according to the method of determining the grid [27,33]. The grid method generates several standardized grids to satisfy the specified total coverage rate (e.g., 95%) based on important variables [34]. The clustering method determines the appropriate number of clusters by analyzing the decreasing trend in the average distance between objects belonging to the cluster according to the change in the number of clusters (e.g., 2 to 50) [35]. The optimization method is a section segmentation method that minimizes total loss while maximizing target acceptance rate by using a loss function and an optimization algorithm [36]. Among the three methods, the grid method, which is most commonly used in the anthropometry field, was used as a method for subdividing the size section.

Regarding the modeling techniques applicable to provide average human body model generation, wireframe modeling and morphing are generally used, and 3D human body shape model data are used as sample data. When using a database for average human body model generation, the template model-fitting technique is the most common, and the scan model database, including feature information, is used for sample data. According to a previous study [24], wireframe modeling is advantageous for various averaging practices that require high precision, and body section modeling using a human body model is performed to complement the missing body shape information between the sections of the wireframe. According to other studies [25,26], morph modeling is advantageous for rapid averaging techniques that do not require high precision, but it requires controlling noise factors, such as polygon-count adjustments and shape removal, to ensure reliability. According to additional studies [29–32], the template model-fitting technique generates an average model by matching the topology of 3D human body shape models, and it requires a database of pre-fitted scan-template model pairs. In this study, among the three approaches for average human body model generation, wireframe modeling, which is advantageous for precise averaging, was selected.

2.3. Sizing System Development

To develop a sizing system, the process of segmenting size sections using the grid method and generating an average human body model using the wireframe modeling technique for each section was planned. For segmenting the size sections, a development process was planned to select important variables based on methods presented in the literature [24,27,28] and to form a representative grid through cross analysis between the important variables. Table 2 shows the planned process of size-section segmentation.

For generating the average body model for each section, a development process was planned to select the 3D sample model for each size section based on the method presented in the study of [24] and to analyze the cross-section of the selected sample models to generate the average wireframe. Table 3 shows the planned process of average model generation.

Table 2. Size-section segmentation process.

Step	Content
1. Obtaining sample data	2D human body measurement data are used.
2. Selecting important variables	Three body measurements for body shape classification are selected as the important variables.
3. Segmenting important variables into section	Important variables are segmented into section through a descriptive statistical analysis.
4. Primary cross-tabulation analysis	Primary size sections are generated based on the important variables 1 and 2.
5. Secondary cross-tabulation analysis	Final size sections are generated by applying the important variable 3 to the primary size sections.
6. Forming the representative grid	Representative grid for each section is formed after generating the sample data into a 3D scatterplot.
7. Generating size of important variables for each representative grid	Mean value of each important variable of the sample data included in each representative grid is calculated.

Table 3. Average model generation process.

Step	Content
1. Obtain sample models	3D human body shape model data are used.
2. Classify sample models	Sample models are classified based on the range of the section by the representative grid.
3. Select template model	One template model is selected in the range of important variables ± 10 mm for each representative grid.
4. Select sample model	Based on the similarity to the template model, five sample models are selected for each representative grid.
5. Body-section analysis	Body sections, including the body cross-sections, longitudinal-sections, and side seams of the five sample models, are extracted for each representative model.
6. Generate average wireframe	Average body sections are generated by averaging each extracted section.
	An average wireframe is generated based on the average body sections.
7. Body cross-section modeling	To supplement the shape information between the cross-sections of the wireframe, body cross-section modeling is performed based on the template model, and the cross-section models are merged into one.

2.3.1. Segmenting the Size Section

To obtain sample data, 2D human body measurement data of 199 Korean adult males provided by the human body measurement database of the sixth Size-Korea project (2010) were used.

To select the important variables of height, hip circumference, and lower-drop, the body-size variables defining the standard body shapes of adult males were selected. Height is an important variable associated with body size; hip circumference is an important variable associated with volume, and lower-drop (the difference between the hip circumference and the waist circumference (omphalion)) is an important variable associated with physical features.

To segment the important variables into sections, they were evenly divided into 10 section along a range of minimum–maximum values, 10 size sections were generated as shown in Table 4, and the normal distribution of 10 equally divided sections was confirmed through frequency analysis of the size sections for each important variable.

In the primary cross-tabulation analysis, the dimensions of the important height and hip circumference variable are coded on a nominal scale of 10 sections using the SPSS statistics analysis program, and then cross-tabulation analysis is performed to determine the distribution of the size section between the height and hip circumference important variables. The calculation results of primary cross-tabulation are shown in Table 5. The chi-square value was 71.465 and the p -value was 0.049. Since $p < 0.05$, it was confirmed that the difference between groups was statistically significant. As for height, section 6 showed the highest frequency with 23.6%. As for hip circumference, section 5 showed the highest frequency with 23.6%.

Table 4. Division of important variable section.

Section	Height (mm)	Freq.	Hip Circumference (mm)	Freq.	Lower-Drop (mm)	Freq.
1	1542–1573	1	796–827	1	0–20	10
2	1573–1604	5	827–858	3	20–40	13
3	1604–1635	10	858–889	17	40–60	21
4	1635–1666	18	889–920	38	60–80	27
5	1666–1697	22	920–951	47	80–100	32
6	1697–1728	47	951–982	42	100–120	33
7	1728–1759	38	982–1013	30	120–140	26
8	1759–1790	32	1013–1044	10	140–160	19
9	1790–1821	13	1044–1075	8	160–180	14
10	1821–1852	13	1075–1106	3	180–199	4

Table 5. Results of primary cross-tabulation calculation.

		Section of Hip Circumference										Total
		1	2	3	4	5	6	7	8	9	10	
Section of height	1	Freq.	0	0	1	0	0	0	0	0	0	1
	1	total %	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
	2	Freq.	0	0	1	2	0	2	0	0	0	5
	2	total %	0.0%	0.0%	0.5%	1.0%	0.0%	1.0%	0.0%	0.0%	0.0%	2.5%
	3	Freq.	1	1	1	1	3	2	1	0	0	10
	3	total %	0.5%	0.5%	0.5%	0.5%	1.5%	1.0%	0.5%	0.0%	0.0%	5.0%
	4	Freq.	0	0	2	8	3	3	2	0	0	18
	4	total %	0.0%	0.0%	1.0%	4.0%	1.5%	1.5%	1.0%	0.0%	0.0%	9.0%
	5	Freq.	0	1	2	5	5	6	2	0	1	22
	5	total %	0.0%	0.5%	1.0%	2.5%	2.5%	3.0%	1.0%	0.0%	0.5%	11.1%
	6	Freq.	0	1	5	12	13	8	6	1	1	47
	6	total %	0.0%	0.5%	2.5%	6.0%	6.5%	4.0%	3.0%	0.5%	0.5%	23.6%
	7	Freq.	0	0	1	8	9	10	7	3	0	38
	7	total %	0.0%	0.0%	0.5%	4.0%	4.5%	5.0%	3.5%	1.5%	0.0%	19.1%
	8	Freq.	0	0	3	1	8	7	7	3	2	32
	8	total %	0.0%	0.0%	1.5%	0.5%	4.0%	3.5%	3.5%	1.5%	1.0%	16.1%
	9	Freq.	0	0	1	1	3	1	3	2	1	13
	9	total %	0.0%	0.0%	0.5%	0.5%	1.5%	0.5%	1.5%	1.0%	0.5%	6.5%
	10	Freq.	0	0	0	0	3	3	2	1	3	13
	10	total %	0.0%	0.0%	0.0%	0.0%	1.5%	1.5%	1.0%	0.5%	1.5%	6.5%
total		Freq.	1	3	17	38	47	42	30	10	8	199
total		total %	0.5%	1.5%	8.5%	19.1%	23.6%	21.1%	15.1%	5.0%	4.0%	100.0%

The process of section removal and grouping in primary cross-tabulation analysis was as follows. In the cross-tabulation, the initial 100 sections were filtered down to 63 by removing hip-circumference sections 1, 2, and 10 and height section 1, which were the maximum–minimum extrema with a total appearance frequency of less than 2%. Next, 12 sections with an appearance frequency of 0% were deleted to filter the 63 sections to 51 (Figure 2a). Then, the sections were grouped based on the coverage rate of 2 to 6.5% to filter the 51 sections to 25 (Figure 2b). In the primary cross-tabulation analysis, 25 primary

size sections with a total coverage rate of 95.5% were generated based on height and hip circumference data through the interpretation of the cross-tabulation, as shown in Table 6.

Figure 2. Section removal and grouping process of primary cross-tabulation: (a) section removal and (b) section grouping.

Table 6. Results of primary cross-tabulation analysis.

Section	Height (mm)	Hip Circumference (mm)	Freq.	Coverage Rate (%)
1	1573–1635	858–920	5	2.5
2	1573–1635	920–1013	8	4.0
3	1635–1666	858–920	10	5.0
4	1635–1666	920–1013	8	4.0
5	1666–1697	858–920	7	3.5
6	1666–1697	920–951	5	2.5
7	1666–1697	951–1013	8	4.0
8	1697–1728	858–889	5	2.5
9	1697–1728	889–920	12	6.0
10	1697–1728	920–951	13	6.5
11	1697–1728	951–982	8	4.0
12	1697–1728	982–1075	8	4.0
13	1728–1759	858–920	9	4.5
14	1728–1759	920–951	9	4.5
15	1728–1759	951–982	10	5.0
16	1728–1759	982–1044	10	5.0
17	1759–1790	858–920	4	2.0
18	1759–1790	920–951	8	4.0
19	1759–1790	951–982	7	3.5
20	1759–1790	982–1013	7	3.5
21	1759–1790	1013–1075	5	2.5
22	1790–1821	858–982	6	3.0
23	1790–1821	982–1075	6	3.0
24	1821–1852	920–982	6	3.0
25	1821–1852	982–1075	6	3.0
Total			190	95.5

In the secondary cross-tabulation analysis, after data coding of the height and hip circumference important variable dimension into 25 sections and the lower-drop important variable dimension into 10 sections, cross-tabulation analysis was performed to determine the distribution of the size section between the height and hip circumference and the lower-drop variable. The calculation results of secondary cross-tabulation are shown in Table 7. The chi-square value was 269.041, and the p -value was 0.008. Since $p < 0.05$, it was confirmed that the difference between groups was statistically significant. In the height and hip circumference, section 10 showed the highest frequency with 6.8%. In the lower-drop, sections 5 and 6 showed the highest frequency with 16.8%.

Table 7. Results of secondary cross-tabulation calculation.

		Section of Lower-Drop										Total
		1	2	3	4	5	6	7	8	9	10	
Section of height-hip circumference	1	Freq.	0	0	0	1	0	2	1	1	0	5
		total %	0.0%	0.0%	0.0%	0.5%	0.0%	1.1%	0.5%	0.5%	0.0%	2.6%
	2	Freq.	1	1	1	1	1	1	1	0	0	8
		total %	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.0%	0.0%	4.2%
	3	Freq.	1	0	0	1	5	1	0	2	0	10
		total %	0.5%	0.0%	0.0%	0.5%	2.6%	0.5%	0.0%	1.1%	0.0%	5.3%
	4	Freq.	0	1	0	3	3	1	0	0	0	8
		total %	0.0%	0.5%	0.0%	1.6%	1.6%	0.5%	0.0%	0.0%	0.0%	4.2%
	5	Freq.	0	0	1	2	1	0	1	1	0	7
		total %	0.0%	0.0%	0.5%	1.1%	0.5%	0.0%	0.5%	0.5%	0.0%	3.7%
	6	Freq.	1	0	1	0	1	0	2	0	0	5
		total %	0.5%	0.0%	0.5%	0.0%	0.5%	0.0%	1.1%	0.0%	0.0%	2.6%
	7	Freq.	0	3	2	0	1	2	0	0	0	8
		total %	0.0%	1.6%	1.1%	0.0%	0.5%	1.1%	0.0%	0.0%	0.0%	4.2%
	8	Freq.	0	0	0	0	0	0	3	1	1	5
		total %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.5%	0.5%	2.6%
	9	Freq.	1	0	2	1	2	4	1	0	1	12
		total %	0.5%	0.0%	1.1%	0.5%	1.1%	2.1%	0.5%	0.0%	0.5%	6.3%
	10	Freq.	0	0	1	1	5	1	1	3	0	13
		total %	0.0%	0.0%	0.5%	0.5%	2.6%	0.5%	0.5%	1.6%	0.0%	6.8%
	11	Freq.	0	2	1	3	0	2	0	0	0	8
		total %	0.0%	1.1%	0.5%	1.6%	0.0%	1.1%	0.0%	0.0%	0.0%	4.2%
	12	Freq.	2	0	2	2	0	1	0	0	1	8
		total %	1.1%	0.0%	1.1%	1.1%	0.0%	0.5%	0.0%	0.0%	0.5%	4.2%
	13	Freq.	0	0	0	0	2	2	0	2	3	9
		total %	0.0%	0.0%	0.0%	0.0%	1.1%	1.1%	0.0%	1.1%	1.6%	4.7%
	14	Freq.	0	0	0	1	2	1	2	0	3	9
		total %	0.0%	0.0%	0.0%	0.5%	1.1%	0.5%	1.1%	0.0%	1.6%	4.7%
	15	Freq.	0	1	0	4	1	1	3	0	0	10
		total %	0.0%	0.5%	0.0%	2.1%	0.5%	0.5%	1.6%	0.0%	0.0%	5.3%
	16	Freq.	3	1	1	2	2	1	0	0	0	10
		total %	1.6%	0.5%	0.5%	1.1%	1.1%	0.5%	0.0%	0.0%	0.0%	5.3%
	17	Freq.	0	0	0	0	0	1	1	0	1	4
		total %	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.5%	0.0%	0.5%	2.1%
	18	Freq.	0	0	0	0	0	3	3	1	1	8
		total %	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	1.6%	0.5%	0.5%	4.2%
	19	Freq.	0	0	2	0	2	1	1	1	0	7
		total %	0.0%	0.0%	1.1%	0.0%	1.1%	0.5%	0.5%	0.5%	0.0%	3.7%
	20	Freq.	0	0	0	2	1	1	1	1	0	7
		total %	0.0%	0.0%	0.0%	1.1%	0.5%	0.5%	0.5%	0.5%	0.0%	3.7%
	21	Freq.	0	1	2	0	1	0	0	1	0	5
		total %	0.0%	0.5%	1.1%	0.0%	0.5%	0.0%	0.0%	0.5%	0.0%	2.6%

Table 7. Cont.

		Section of Lower-Drop										Total
		1	2	3	4	5	6	7	8	9	10	
22	Freq.	0	0	0	0	1	2	2	0	1	0	6
	total %	0.0%	0.0%	0.0%	0.0%	0.5%	1.1%	1.1%	0.0%	0.5%	0.0%	3.2%
23	Freq.	0	0	3	1	0	0	1	1	0	0	6
	total %	0.0%	0.0%	1.6%	0.5%	0.0%	0.0%	0.5%	0.5%	0.0%	0.0%	3.2%
24	Freq.	0	0	0	1	0	2	0	3	0	0	6
	total %	0.0%	0.0%	0.0%	0.5%	0.0%	1.1%	0.0%	1.6%	0.0%	0.0%	3.2%
25	Freq.	0	1	0	1	1	2	1	0	0	0	6
	total %	0.0%	0.5%	0.0%	0.5%	0.5%	1.1%	0.5%	0.0%	0.0%	0.0%	3.2%
total	Freq.	9	11	19	27	32	32	25	19	13	3	190
	total %	4.7%	5.8%	10.0%	14.2%	16.8%	16.8%	13.2%	10.0%	6.8%	1.6%	100.0%

The process of section removal and grouping in secondary cross-tabulation analysis is as follows. In the cross-tabulation, the initial 250 were filtered down to 225 by removing the lower-drop section 10, which was the maximum–minimum extreme section with a total appearance frequency of less than 2%. Next, 108 sections with an appearance frequency of 0% were deleted to filter the 225 sections down to 117, and seven sections showing the lowest appearance frequency in the maximum–minimum extreme section of height and hip circumference were removed to provide 110 sections (Figure 3a). Then, those sections were grouped based on the coverage rate of 2 to 4.3% to filter the 110 sections into 34 (Figure 3(b1,2)). These were grouped again based on the coverage rate of 4.2 to 7.3% to filter the 34 sections into the final 18 (Figure 3c). In the secondary cross-tabulation analysis, 18 final sections with a total coverage rate of 90.5% were generated based on height, hip circumference, and lower-drop data from the interpretation of the cross-tabulation, as shown in Table 8.

The number of general size sections applied to clothes, shoes, gloves, hats, etc., ranges from 5 to 10. Considering that these products are products with relatively high design tolerances compared to the products under study, it was considered appropriate to determine the number of size sections of body shape fit between 15 and 20. In addition, assuming that the number of size sections is, at most, 20, the coverage rate of each size section is selected based on an approximate value of 5%. Based on the criteria for excluding extreme sections of less than the 5th % and more than the 95th % in product size design reflecting human dimensions, the total coverage rate was set as a target of 90%. The proposed size system-based 3DP-pHRI is a method that selects the 3DP-pHRI size system that is closest to the human body shape of the wearer from the previously developed (libraryized) pHRI and produces it using 3D printing. In this respect, the number of size sections is not subject to a large limitation; however, setting a size section that is too compact can complicate the process of selecting a size system suitable for the wearer. Accordingly, 18 size sections were finally selected in consideration of the human fitness (total coverage rate: 90.5%), as shown in Table 8.

The characteristics of each section of the selected size section are as follows. Based on the height and hip circumference important variable, sections 1 to 3 correspond to the lower 14.5% range, sections 16 to 18 correspond to the upper 16.5% range, and sections 4 to 15 correspond to the median 59.5% range. Based on the important lower-drop variable, the lower sections 1–3 and the upper sections 16–18 have a single category, and the 12 size sections of the median sections 4–15 are size sections with three different body shape ratios (thin, normal, and fat). According to the characteristics of this size section, it can be seen that the generated size section has a size division that appropriately reflects the shape of the human body.

- Removal of extreme sections of less than 2% of the total acceptance rate
- Removal of sections with zero frequency
- Removal of sections with an acceptance rate of less than 0.5% in extreme sections

		Section of lower-drop									
		1	2	3	4	5	6	7	8	9	10
Section of height-hip circumference	1	0.0%	0.0%	0.0%	0.5%	0.0%	1.1%	0.5%	0.5%	0.0%	0.0%
	2	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.0%	0.0%
	3	0.5%	0.0%	0.0%	0.5%	2.6%	0.5%	0.0%	1.1%	0.0%	0.0%
	4	0.0%	0.5%	0.0%	1.6%	1.6%	0.5%	0.0%	0.0%	0.0%	0.0%
	5	0.0%	0.0%	0.5%	1.1%	0.5%	0.0%	0.5%	0.5%	0.0%	0.5%
	6	0.5%	0.0%	0.5%	0.0%	0.5%	0.0%	1.1%	0.0%	0.0%	0.0%
	7	0.0%	1.6%	1.1%	0.0%	0.5%	1.1%	0.0%	0.0%	0.0%	0.0%
	8	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.5%	0.5%	0.0%
	9	0.5%	0.0%	1.1%	0.5%	1.1%	2.1%	0.5%	0.0%	0.5%	0.0%
	10	0.0%	0.0%	0.5%	0.0%	2.6%	0.5%	0.5%	1.6%	0.0%	0.5%
	11	0.0%	1.1%	0.5%	1.6%	0.0%	1.1%	0.0%	0.0%	0.0%	0.0%
	12	1.1%	0.0%	1.1%	1.1%	0.0%	0.5%	0.0%	0.0%	0.5%	0.0%
	13	0.0%	0.0%	0.0%	0.0%	1.1%	1.1%	0.0%	1.1%	1.6%	0.0%
	14	0.0%	0.0%	0.0%	0.5%	1.1%	0.5%	1.1%	0.0%	1.6%	0.0%
	15	0.0%	0.5%	0.0%	2.1%	0.5%	0.5%	1.6%	0.0%	0.0%	0.0%
	16	1.6%	0.5%	0.5%	1.1%	1.1%	0.5%	0.0%	0.0%	0.0%	0.0%
	17	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.5%	0.0%	0.5%	0.5%
	18	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	1.6%	0.5%	0.5%	0.0%
	19	0.0%	0.0%	1.1%	0.0%	1.1%	0.5%	0.5%	0.5%	0.0%	0.0%
	20	0.0%	0.0%	0.0%	1.1%	0.5%	0.5%	0.5%	0.5%	0.0%	0.0%
	21	0.0%	0.5%	1.1%	0.0%	0.5%	0.0%	0.0%	0.5%	0.0%	0.0%
	22	0.0%	0.0%	0.0%	0.0%	0.5%	1.1%	1.1%	0.0%	0.5%	0.0%
	23	0.0%	0.0%	1.6%	0.5%	0.0%	0.0%	0.5%	0.5%	0.0%	0.0%
	24	0.0%	0.0%	0.0%	0.0%	0.5%	1.1%	0.0%	1.6%	0.0%	0.0%
	25	0.0%	0.5%	0.0%	0.5%	0.5%	1.1%	0.5%	0.0%	0.0%	0.0%

(a)

		Section of lower-drop									
		1	2	3	4	5	6	7	8	9	10
Section of height-hip circumference	1						1.1%				
	2	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%		
	3	0.5%			0.5%	2.6%	0.5%		1.1%		
	4		0.5%		1.6%	1.6%	0.5%				
	5			0.5%	1.1%	0.5%		0.5%	0.5%		
	6	0.5%		0.5%		0.5%			1.1%		
	7		1.6%	1.1%		0.5%	1.1%				
	8							1.6%	0.5%	0.5%	
	9	0.5%		1.1%	0.5%	1.1%	2.1%	0.5%		0.5%	
	10			0.5%	0.5%	2.6%	0.5%	0.5%	1.6%		
	11		1.1%	0.5%	1.6%		1.1%				
	12	1.1%		1.1%	1.1%		0.5%			0.5%	
	13					1.1%	1.1%		1.1%	1.6%	
	14				0.5%	1.1%	0.5%	1.1%		1.6%	
	15		0.5%		2.1%	0.5%	0.5%	1.6%			
	16	1.6%	0.5%	0.5%	1.1%	1.1%	0.5%				
	17						0.5%	0.5%		0.5%	
	18						1.6%	1.6%	0.5%	0.5%	
	19			1.1%		1.1%	0.5%	0.5%	0.5%		
	20				1.1%	0.5%	0.5%	0.5%	0.5%	0.5%	
	21		0.5%	1.1%		0.5%			0.5%		
	22					0.5%	1.1%	1.1%		0.5%	
	23			1.6%	0.5%			0.5%	0.5%		
	24				0.5%		1.1%		1.6%		
	25						1.1%				

(b1)

		Section of lower-drop									
		1	2	3	4	5	6	7	8	9	10
Section of height-hip circumference	1										
	2										
	3										
	4										
	5										
	6										
	7										
	8										
	9										
	10										
	11										
	12										
	13										
	14										
	15										
	16										
	17										
	18										
	19										
	20										
	21										
	22										
	23										
	24										
	25										

(b2)

		Section of lower-drop									
		1	2	3	4	5	6	7	8	9	10
Section of height-hip circumference	1										
	2										
	3										
	4										
	5										
	6										
	7										
	8										
	9										
	10										
	11										
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	14										
	15										
	16										
	17										
	18										
	19										
	20										
	21										
	22										
	23										
	24										
	25										

(c)

Figure 3. Section removal and grouping process of secondary cross-tabulation: (a) section removal; (b1) 1st section grouping—coverage rate-based classification; (b2) 1st section grouping—summation of coverage rates and section numbering; (c) 2nd section grouping.

Table 8. Results of secondary cross-tabulation analysis.

Section	Height (Mm)	Hip Circumference (Mm)	Lower-Drop (Mm)	Freq.	Coverage Rate (%)
1	1573–1635	858–1013	0–180	10	5.0
2	1635–1666	858–920	0–180	10	5.0
3	1635–1666	920–1013	0–180	8	4.0
4	1666–1697	858–1013	0–80	10	5.0
5	1666–1697	858–1013	80–180	9	4.5
6	1697–1728	858–1075	0–60	11	5.5
7	1697–1728	858–951	60–120	14	7.0
8	1697–1728	858–951	120–180	11	5.5
9	1697–1728	951–1075	60–180	9	4.5
10	1728–1759	858–982	0–100	11	5.5
11	1728–1759	982–1044	0–100	9	4.5
12	1728–1759	858–1044	100–140	10	5.0
13	1728–1759	858–1044	140–180	8	4.0
14	1759–1790	858–982	0–120	9	4.5
15	1759–1790	858–982	120–180	9	4.5
16	1759–1790	982–1075	0–180	12	6.0
17	1790–1821	858–1075	0–180	12	6.0
18	1821–1852	920–1075	0–180	8	4.0
Total				180	90.5

When forming the representative grid, the 180 sample data points included in the size section were plotted on a 3D scatterplot based on three important variables: height, hip circumference, and lower-drop (Figure 4a). A representative grid for each of the 18 size sections generated by cross-analysis were then formed (Figure 4b). Each generated size section was used as a reference size section to classify the sample models during average human body model generation.

Figure 4. Results of representative grid method: (a) results of 3D scatter plot generation and (b) result of formation of representative grid by size section.

When generating the sizes of important variables for each representative grid, the mean height, hip circumference, and lower-drop values of the sample data included in each representative grid were calculated to generate the size of important variables for each representative grid, as shown in Table 9, and the generated size of important variables was used as the reference size for selecting the template model in the process of average human body model generation.

Table 9. Dimensions of important variables by representative grid.

Section	Height (Mm)	Hip Circumference (Mm)	Lower-Drop (Mm)
1	1618	945	87
2	1651	902	95
3	1652	959	76
4	1679	942	46
5	1681	930	115
6	1714	964	35
7	1712	925	94
8	1712	903	145
9	1712	983	93
10	1741	950	75
11	1739	1009	48
12	1738	941	118
13	1739	915	165
14	1768	945	90
15	1772	927	142
16	1772	1013	99
17	1803	971	104
18	1836	980	120

2.3.2. Generation of Average Human Body Model by Section

To obtain the sample models, the 3D human body shape model data of 195 Korean adult males provided by the human body measurement database of the sixth Size-Korea project (2010) were used.

To classify the 195 models obtained, 180 models in the range of the 18 size sections were used as samples, and they were classified according to the 18 size sections so that each section included about 10 sample models.

To select the template model, one model was selected in the ± 10 mm range of important variables dimensions for each representative grid. For sections 17 and 18, where no template model was detected, selection of a deviation range of ± 20 mm was made. For sections 4 and 9, where no template model was detected even within the deviation range of ± 20 mm, selection was based on the data from the human body measurement database of the fifth Size-Korea project (2003 to 2004).

When selecting the sample models, five sample models were chosen based on the similarity to the selected template model for each representative grid after removing outliers based on ratio, posture, symmetry, and tendency from the classified sample models.

For body-section analysis, the five sample models selected for each section were pre-processed. The area excluding the upper part of the 20-cm level above the waist (omphalion) and the lower part of the lateral malleolus was selected as the range of body-section analysis. Based on the 28 body sections consisting of 24 cross-sections, two longitudinal-sections, and two side seams, the body sections of each sample model were extracted (Figure 5).

Figure 5. Reference plane for section analysis.

When generating an average wireframe, the average cross-sections, longitudinal sections, and side seams were generated by averaging each set extracted, and the average longitudinal sections and side seams were combined first, followed by the incorporation of the cross-sections (Figure 6). The same fixed values were used for the cross-section height, the longitudinal section width, and the side seam length, and the same reference plane was used for extracting the body sections.

Figure 6. Process of average wireframe generation.

To supplement the shape information between the cross-sections of the wireframe, body cross-section modeling was performed based on the template model, and the cross-section models were merged into one. The average human body model for each of the 18 size sections was created via body cross-section modeling, as shown in Figure 7. The data of the average human body model generated for each section were used as the reference surface shape data for the development of the 3DP-pHRI based on the size system.

Figure 7. Results of average human body model generation by section.

2.3.3. Development of 3DP-pHRI Based on Size System

To develop the 3DP-pHRI based on the sizing system, the coordinate positions of the wearable robot model were adjusted in consideration of the connectivity between the average human body model for each section and the wearable robot. Based on the adjusted wearable robot model, postures (e.g., upper-lower body axis angle and leg spacing of each average human body model) were adjusted. Next, the basic shape models of the trunk and shank were developed in the order of section extraction, surface creation, front section removal and extension, shape boundary line trim, and thickness application by referring to the surface shape of each average human body model. Figure 8 shows an example for the process of developing the 3DP-pHRI based on the sizing system, and Figure 9 shows the results of developing the 3DP-pHRI in 18 size sections.

Figure 8. Procedure of development of 3DP-pHRI based on size system.

Figure 9. Result of development of 3DP-pHRI based on size system.

3. Results and Discussion

3.1. Prototyping of 3DP-pHRI Based on the Sizing System

In this study, a size system-based 3DP-pHRI is proposed as a new alternative that can implement the body shape-fit without need for 3D scanning of the body and the remodeling of the pHRI digital template model in the body shape-fit of a wearable robot using 3D printing. To this end, we propose an approach to library 3DP-pHRI into various sizes and shapes using the human body shape database. In Section 2.3, a total of 18 size sections were derived, and the size system of trunk and shank 3DP-pHRI was developed by referring to the surface shape of the average human model of each size section. To evaluate the conformity of the developed 3DP-pHRI's size system in shape and dimensions, prototyping was performed by 3D printing. In prototyping, FDM-type 3D printing equipment (NIPPO nanodaX, NANODAX CO., Ltd., Tokyo, Japan) with a nozzle diameter of 1 mm and a laminated layer thickness of 0.5 mm, which can print large-sized digital models at a high speed, was used. A 3DP-pHRI based on the size system was fabricated using a PP material filament.

For the trunk, 18 sections were used. After excluding nine sections based on shape deviation analysis, nine sections were manufactured for the shank (Figure 10).

Figure 10. Results of 3DP-pHRI 3D printing: (a) 18 trunk 3DP-pHRI 3D printing and (b) nine shank 3DP-pHRI 3D printing results.

3.2. Evaluation of Conformity of Shape and Dimensions

Regarding the conformity of shape and dimensions, the effectiveness of the 3DP-pHRI customization based on the sizing system was evaluated by visual observation and shape deviation analysis. Ten persons with paraplegia were selected as subjects for evaluation, and their physical information is shown in Table 10. In the visual observation, the 3DP-pHRI prototyped using 3D printing was directly matched to the human body shape of the subject to be evaluated, and the trend of shape and dimensional suitability was confirmed. From the shape deviation analysis, the deviations between the human body shape data of 10 persons with paraplegia and the 3D model data of the trunk and shank 3DP-pHRIs selected for visual observation were examined to numerically analyze the conformity of shape and dimensions.

Table 10. Ten subjects' physical information.

	Gender	Age (Year)	Height (cm)	Weight (kg)	Injury Level	ASIA Scale	Onset (Year)
Sub1	male	65	163	53	T10	A	2006
Sub2	male	48	163	66	L1	C	2004
Sub3	male	54	165	74	T10	A	2005
Sub4	male	47	170	80	L1	A	2015
Sub5	male	64	168	70	C7	C	2011
Sub6	male	60	168	86	T8	A	2006
Sub7	male	58	176	72	T10	A	2007
Sub8	male	52	171	64	T12	A	2001
Sub9	male	52	175	66.2	T11	A	2013
Sub10	male	53	180	78	T11	A	1992

ASIA: American spinal cord injury association impairment scale.

3.2.1. Evaluation by Visual Observation

For reliable visual observations, each subject wore tights, and a standing traction device was used to induce a standing posture identical to the state of static balance while wearing a wearable robot. After completing the preparation process, the 3DP-pHRI, which was produced by estimating the location where the trunk and shank are equipped on the wearable robot, was directly matched to the human body shape of the subject, and the conformity of the shape and dimension was evaluated by visual observation (Figure 11).

Figure 11. Scenes and criteria for evaluation by visual observation.

In the visual observation of the trunk 3DP-pHRI, the trunk 3DP-pHRI, which showed the highest conformity in shape and dimensions, was selected as the sizing system based on the degree of conformity for the curve shape of the rear vertical section and the degree of contact in the circumferential direction. In the visual observation of the shank 3DP-pHRI, the shank 3DP-pHRI, which showed the highest conformity in shape and dimensions, was selected as the sizing system based on the degree of conformity for the curve shape of the side vertical section and the degree of contact in the circumferential direction (Figure 11).

Table 11 shows the results of selecting 18 trunk 3DP-pHRI size systems and nine shank 3DP-pHRI size systems according to the visual observation criteria for 10 persons with paraplegia. Trunk sections 4, 5, 9, and 16 were selected twice, and sections 6 and 10 were selected once. Shank sections 5, 10, and 14 were selected once, section 2 was twice, and section 7 was selected five times. The trunk and shank sizing systems selected showed conformity in shape and dimensions at an appropriate level for each subject. However, the shank system showed a biased tendency in the frequency of selection. Additionally, as with the selection results of trunk10–shank5 of Sub1, the trunk and shank sizing systems for each subject tended to be selected in different sections. This seems to have been caused by the body-shape specificity of people with paraplegia, who experience a decrease in the lower limb muscles because of disuse, which suggests that the shank 3DP-pHRI size system requires adjustments.

Table 11. Results of selecting 3DP-pHRI size systems.

	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Sub7	Sub8	Sub9	Sub10
Trunk section	10	5	6	9	4	16	16	5	4	9
Shank section	5	14	7	10	7	7	7	2	7	2

3.2.2. Evaluation by Shape Deviation Analysis

A handheld Artec Eva 3D scanner by Artec was used to extract the human body shape data of 10 persons with paraplegia. To obtain a surface shape close to the actual human body shape of the subject, 3D scanning was performed, while the subject wore tights in a standing posture using a traction device (Figure 12a). Figure 12b shows the human body shape data of 10 persons with paraplegia generated by 3D scanning. In preparation for shape deviation analysis, each position from the data was primarily adjusted in the 3D coordinate space by reflecting the position where the 3DP-pHRI was equipped to the wearable robot to determine the relative locations of the human body and the 3DP-pHRI model data. The shape deviation comparison function of Artec Studio 9 software was used for shape deviation analysis, calculated using the data of 10 human body and 3DP-pHRI model pairs completed using a matching process (Figure 13). Artec Studio 9 software can analyze the mean and standard deviation of shape deviations in the normal direction from two 3D data items with morphological similarity.

As a result of analyzing shape deviation, the average deviation of the trunk 3DP-pHRI showed a minimum value of 4.2 mm in sub2, and a maximum value of 9.32 mm in sub4. The average shape deviation of the shank 3DP-pHRI showed a minimum value of 1.9 mm in sub5, and a maximum value of 7.58 mm in sub10 (Table 12). The following three data sources were referenced for the tolerance range for evaluating the suitability of the analyzed shape deviation. In ISO 20685-1 (2018), the tolerance range of body depth is 5 mm [37], and the result report of the 2016 Korean human body size survey suggested the tolerance range of large width as 5.44–10.0 mm [38]. In the study of [24], the tolerance range of the human body cross section in the normal direction was suggested as 10 mm. The tolerance range for conformance evaluation was set to 10 mm by additionally considering the error range of 5–10 mm suggested in the above reference materials and the allowable error range due to the characteristics of the open structure of 3DP-pHRI.

Figure 12. Secure human body shape data: (a) 3D scanning of human body shape and (b) 10 subjects' human body shape data.

Figure 13. Results of evaluation by shape deviation analysis.

Table 12. Results of evaluation by shape deviation analysis (unit: mm).

		Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Sub7	Sub8	Sub9	Sub10
Trunk pHRI	Mean	5.44	4.20	6.83	9.32	4.10	5.37	7.32	4.54	4.52	8.12
	SD	5.26	4.73	7.22	9.17	4.72	4.23	4.57	5.00	6.03	7.65
Shank pHRI	Mean	4.94	2.91	3.71	3.27	1.90	2.39	2.54	2.72	2.56	7.58
	SD	5.04	4.30	4.04	3.97	2.30	3.08	3.24	3.10	3.24	4.66

As a result of analyzing the average of the shape deviation in the normal direction for 10 human body 3DP-pHRI model pair data, all values were within 10 mm of the error

range, confirming that the developed 3DP-pHRI based on the sizing system had conformity in shape and dimensions at an appropriate level.

3.3. Discussion

In this study, to libraryize 3DP-pHRI into various sizes and shapes, the method of subdividing the size section and the method of generating the average human model for each section was used. There are three methods for subdividing the size section: the grid method, the clustering method, and the optimization method. The grid method, which is most commonly used in the field of anthropometry, was used as the method for subdividing the size section. There are three methods of generating an average human body model: wireframe modeling, morphing modeling, and template model fitting transformation. The wireframe modeling, which is advantageous for averaging work that requires precision, was used as the average human body model generation method.

Products that have a size system such as clothing, shoes, gloves, and hats have a relatively low body fit sensitivity compared to wearable robots, and are manufactured using a mass production method. In the existing mass production method, the approach of developing all the size sections subdivided into 10 or more and the average human model for each section and applying them to the product is not suitable because production efficiency and economy are low. For this reason, in the case of applying the size system of a product line that requires conformity to the shape and dimensions of a human body, most of the approaches are to build a size system based on simple dimensions such as circumference, length, and width using a two-dimensional body size database. In most cases, only one to four limited average human models representing 25th–75th % are created and used as a supplement to product development.

However, since the wearable robot for the disabled with leg paralysis needs to be customized for pHRI so that an integrated connection between the human body and the robot can be made, a simple dimension-based size system applied to existing products and a wide range of median values are not suitable. In addition, 3DP-pHRI based on a size system using a limited number of average human body models cannot implement an appropriate body shape fit. Therefore, the size system of 3DP-pHRI should be subdivided into more detailed size sections and an average human model representing each subdivided section should be created and developed by referring to the shape of the human body surface of each created model. In this study, we developed 3DP-pHRI based on the size system that is subdivided into 18 size sections and libraryized by applying the most effective method among the methods used in the development of the existing size system. The value and importance of this study in that 3DP-pHRI based on a size system that can be mass customized with relatively little effort compared to the existing body shape customization of the wearable robot, which required significant effort, was developed and presented as a new alternative.

In this study, the pHRI of a wearable robot for rehabilitation training for people with paraplegia was studied. Patients with paraplegia due to SCI are divided into subacute and chronic phases based on 6 months after the onset of SCI. The subacute period is a period of intensive rehabilitation training. The subacute leg paralysis disorder has relatively less muscle contraction compared to the chronic leg paralysis disorder, and the muscle contraction is minimized depending on how actively rehabilitation training is performed during the subacute period. The wearable robot selected as the study target is the primary treatment target for subacute lower limb paralysis disorders, and the secondary treatment target for partial paralysis disorders such as subacute stroke and hemiplegia.

To develop the size system of the wearable robot's 3DP-pHRI targeting such users, a human body shape database should be used. However, there are various difficulties in securing a database of the human body shape of people with lower limb paralysis disorder. Since persons with lower limb paralysis cannot maintain standing state on their own, it must be erected using an artificial standing holding device. The 3D scan should be performed in a state where there is no physical interference factor that unnecessarily

obstructs the human body shape. For these two reasons, securing a database of human body shape for people with leg paralysis disorder can be achieved through a very long-term project over several years.

In this study, a size system was developed using a database of normal persons due to the fact that it targets persons with subacute paralysis, which is the stage before sudden muscle contraction due to paralysis of the lower extremities, and the practical difficulty of securing the human body shape database of persons with paralysis of the lower extremities. In addition, the shape of the human body varies according to factors, such as country, adult-child, male-female, and so on. In this study, as the first step of the gradual study, the size system of 3DP-pHRI was developed using the human body shape database for Korean male adults.

A size system-based 3DP-pHRI was developed and proposed as a new alternative to realize the body shape-fit without the 3D scanning process and template remodeling process in the 3D printing body-fit of the wearable robot. In the existing template remodeling-based 3D printing body fit, the 3D scanning of the human body shape of the wearer is indispensable. It is very cumbersome and complicated because a specially designed standing posture maintenance device must be used to 3D scan the human body shape of a person with a paralysis disorder, and falls may occur in some cases due to insufficient safety management. 3D scanning data is additionally required for post-processing.

There is a variation in effort and time required according to the function of the 3D modeling program used in the remodeling process for 3D printing body shape fit based on template remodeling up to now. 3D modeling programs are divided into surface-based modeling and solid-based modeling. For 3D printing production, solid-based modeling that completely fills the interior is most suitable. Existing solid-based modeling programs include polygon-based 3D animation-only modeling programs (e.g., Maya, 3D Max, Blender, etc.) and parametric solid modeling programs (e.g., SOLIDWORKS, CATIA, Proe, etc.) used for product design. Since 3DP-pHRI has an organic double-curve shape, it is difficult to use a parametric solid modeling program. Modeling program dedicated to 3D animation is advantageous for realizing an organic double-curved surface, and template remodeling can be implemented by utilizing some functions such as 'wrap geometry on a surface'. However, these programs have a disadvantage in that it is difficult to control dimensions such as the thickness or contour shape of a template based on parameters in the process of automatic deformation remodeling. As the shape complexity of the template increases, errors in automatic deformation remodeling increase.

Therefore, it is considered that 3D printing body fit based on template remodeling is not yet a feasible alternative due to the difficulty of the 3D scanning of the human body shape of the paralyzed person and the still incomplete automatic transformation remodeling process. In this respect, the size system-based 3DP-pHRI developed and proposed in this study is considered a more effective alternative compared to the existing template remodeling-based 3D printing body shape customization. However, research on the development of a dedicated platform that solves the difficulties of the 3D scanning process and that can fully implement the 3DP-pHRI remodeling process automatically is valuable as the ultimate future research goal.

4. Conclusions

This study is significant in that it provides a new 3DP pHRI based on the sizing system that does not require baseline remodeling for the customization of a wearable robot to fit a patient's body shape. The effectiveness of the innovation was verified by evaluating its conformity of shape and dimensions. The new 3DP pHRI was developed by segmenting size sections and creating an average human body model for each. The conformity of shape and dimensions was evaluated by visual observation and shape deviation analysis for 10 persons with paraplegia. The main research results are summarized as follows:

- (1) For size segmentation, 199 2D human body measurement data points were used as sample data. Using the grid method technique, 18 size sections meeting the coverage rate of 4–7% each, and a total coverage rate of 90.5% were defined.
- (2) For the generation of the average human body model, 195 3D human body shape model data items were used as sample data, and a wireframe modeling technique based on body-section analysis was used to generate the average human body model for each of the 18 size sections.
- (3) For system development, 18 trunk and nine shank sections were produced as sizing subsystems by referring to the surface shapes of the generated 18 average human body models.
- (4) From the visual observation, a biased tendency of the shank-sizing system was identified. From the shape deviation analysis, all trunk and shank subsystems showed conformity of shape and dimensions at an appropriate level with a deviation range of 10 mm.

The 3DP-pHRI system developed in this study can be applied to various wearable robot pHRI situations, and it is expected to contribute to a useful pHRI template library through follow-up research. In this study, a body shape database of people without disability was used to develop the sizing system, owing to the practical difficulty of obtaining such data from paraplegia patients. Owing to this limitation, the coverage rate bias mentioned above was identified. To overcome this problem, the application of structural parameter shape designs to induce variable controllability should be considered next. The follow-up studies will involve research on a structural parameter shape design to reinforce the shape control functions for the 3DP-pHRI based on the sizing system, as well as an empirical clinical evaluation research considering the coupling relationship with the robot.

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