UNIVERSAL DESIGN METHOD CONSIDERING PHYSICAL CHARACTERISTICS AND PHYSICAL LOAD BASED ON DIGITAL HUMAN MODEL: A CASE STUDY OF HEIGHT-ADJUSTABLE STANDING TABLE

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ABSTRACT: In recent years, the concept of universal design (UD) has been drawing much attention, and various companies are currently working on the design of products, homes, and spaces that incorporate this concept. However, a general design method has not been established, and the work is usually conducted based purely on the experience of the individual designer. This takes its toll in terms of time and cost. In this study, design variables are classified according to both the physical characteristics of the target users, which are expressed as range values, and the product information, such as dimensions. Moreover, the load on the user's body is quantitatively calculated through digital human modeling. From this, an interval calculation is made from which to derive a set of design solutions that fulfill the performance brief. Thus, this paper proposes a UD method that considers physical load, and the effectiveness is shown by applying the proposed method to a specific design project looking at a height-adjustable standing desk.

KEYWORDS: *Universal Design; Digital Human Model; Physical Load; Cluster Analysis*

1.0 INTRODUCTION

Due to the upward shift of the average age in Japanese society and the increase in foreign workers in recent years, it has emerged that not all users can access, or enjoy the convenience of, certain products equally. For some, because of their particular physical characteristics, a heavy burden is placed on their body when using general products. Therefore, the concept of universal design (UD), being the design of products that are comfortable to operate for the widest range of physical types, has been attracting attention, and various companies and organizations are working on designing products, houses, and spaces that incorporate it. To realize UD, it is essential to understand the physical characteristics and needs of various users and to translate them to design values. However, a general design method has not been satisfactorily established [1]. In the current practice, the designer derives a solution through the traditional process of prototype production, evaluation, and trial and error of product improvement based on past experience and close observation. However, to design a product that is easy and comfortable to use, it is necessary to consider the physical load on the user as they work with the product. Studies on product design using biometrics, such as electromyography and electroencephalography, have been conducted for the quantitative evaluation of physical burden [2–4]. However, in those studies, the evaluation is performed after the product is prototyped, so it takes time and money to improve the product and repeat the evaluation after the improvement. Moreover, the experiment results can only be regarded as relevant for a narrow group of target users because the experiment might be conducted using as few as 20 subjects. For this reason, there is a need for an efficient evaluation method for physical load, targeting "all people," which is the definition of UD [5].

Murakami and Deguchi [6] have proposed a method for considering the design of shapes and spaces that take quantitative diversity of users into account by using interval arithmetic. It is possible to design a system that takes into account the diversity of users in a unified and systematic manner by expressing quantitative diversity such as body size and physical ability as intervals and performing various calculations in the design using interval arithmetic. Murakami and Deguchi [6] applied the proposed method, which incorporates interval arithmetic, to the problem of determining the height of a push-button installed on a wall. Then, the method calculates the interval from the equations to derive an optimal button height that guarantees usability for a user whose height is from 1.2 to 1.8 m. This method uses the design variables to derive the optimal button height to guarantee the user's physical information and usability. The method expresses the design variables as a range of values and performs an interval operation, which takes into account various user heights and shows that UD is feasible. However, since only the height is taken into account in the body information, and the relationship between design variables and required performance is derived from a simple model diagram using trigonometric functions, it is difficult to add body information such as weight and arm length in addition to height, and to create relationships for complex postures.

On the other hand, since the dimensions of each body part, such as seat height and shoulder width, as well as height, vary, it is necessary to consider individual differences in body dimensions to design a product that satisfies all users. Therefore, Kawano and Fukui [7] proposed a design method using the digital human model (DHM), which reproduces the posture and motion of a user in the use of a product on a computer and analyses the body load by simulation [8-10]. In the first step of the method, the target user and each body part to be considered are defined. Next, the set body parts are arranged in ascending order, and the 5th percentile human is defined as the largest person in the group that accounts for 5% of the total number of people from the smallest one, and the 95th percentile human is defined as the largest person in the group that accounts for 95% of the total number of people from the smallest one. The design method considering the above individual differences was applied to the chair design. The subjects were Japanese males and females between 20 and 29 years old, and the body dimensions were set as the seat height. As a result, the range of seat height and its adjustment range were derived. In addition, although the DHM was used to calculate the height of the seat surface from the ground by creating a seated posture of the user, it may also be applicable to the evaluation of physical load and other usability. However, because the study calculated the seating heights of two representative users and derived a range of values from these two results as the design solution, even for users of the same height, the body load may differ due to differences in the dimensions of each body part. Therefore, even for a user of the same height, the body load may be different due to the differences in dimensions of each body part.

To solve these problems, this study proposes a UD method that considers physical load using DHM, which is a computer simulation of a person's posture and movement when working with the product. This study classifies users according to body shape characteristics such as long arms by using hierarchical cluster analysis, expresses the physical characteristics of each user group as a range value equivalent to the product information, and analysing the physical load during product use using the different physical characteristics of each group in DHM. Thereafter, this paper proposes a design solution that fully satisfies the constraints and required performance of a specific design brief and meets the needs of any user, whatever their physical characteristics. The effectiveness of the proposed method is demonstrated by applying it to the design problem of a height-adjustable standing desk.

2.0 PROPOSED METHOD

2.1 User Classification by Cluster Analysis

In this section, the authors introduce a UD method that encompasses a wide variety of physical characteristics and user burdens by grouping users according to body characteristics. In order to consider the body characteristics of various users, the users supposed to be used are grouped by body characteristics.

2.2 Selection and Classification of Design Variables and Performance Variables

Generally, a factor that a designer can control is defined as a design variable. However, when implementing UD, it is necessary to incorporate the fixed parameters of human body characteristics that are beyond the designer's control [11]. Therefore, the proposed method classifies design variables into two types: physical information and product information as shown in Table 1. Furthermore, although there is a limit to the range of movement in the physical information, such as angle limitations in a human joint, any variable that can be moved to use the product within the range is defined as a constrained controllable factor that the designer can alter to a certain extent. Conversely, variables that represent human physical characteristics such as height and weight may not, realistically, be changed by the designer and are classified as uncontrollable factors. Similarly, for product information, variables such as product dimensions and mass are defined as controllable factors, and those determined by set standards are considered fixed and uncontrollable. By treating product characteristics and body characteristics equally as design variables, physical diversity can be quantitatively incorporated into product information. Table 1 shows the characteristics of controllable and uncontrollable factors in the design variables.

Physical load like user's back pressure and joint movement when using a product is classified as required performance. A constraint condition is one that recognizes a state where the user can use the product with minimum strain, for example, the "reachable range" in the design of the depth of a desk.

Table 1: Characteristics of controllable factors and uncontrollable factors in the design variables

Type		Name	Characteristics
Design variables	Physical information	Controllable factor	Joint angles that can be adjusted within physical limits
		Uncontrollable factor	Dimensions of body parts such as height
	Product information	Controllable factor	Product dimensions whose values can be adjusted by the designer
		Uncontrollable factor	Product dimensions etc. determined by standards

2.3 Setting the Range of Design Variables and Performance Variables and Deriving Relational Expressions

The values of design and performance variables are represented as ranges, and the relational expression between them may be derived. Design variables are added based on product information, such as product dimensions, and measured values of physical characteristics, such as height. In this process, to derive the relational expression, a designer creates a model diagram of the user's posture while using the product based on the set design variables and constraints. The physical load is analyzed by DHM using the orthogonal table of experimental design, and the relational expression is derived using a radial basis function (RBF) interpolation [12].

2.4 Derivation of Design Solution Candidates

In this process, the possibility distribution is derived by interval arithmetic and narrowed down. First, the designer establishes the distribution using the relational expression derived in Section 2.3. Next, when there is a range in which the distribution does not satisfy the constraint condition, it is narrowed down. The narrowing method divides the range of design variables, and the possibility distribution is derived through a recombination of the divided design variables. An evaluation is then made as to whether the range of the constraint condition has, or has not, been satisfied, and the range that does not satisfy the constraint condition is deleted. Consequently, a set of design solutions that satisfy the constraint condition is obtained. However, among the design variables classified in Section 2.2, the uncontrollable factor represents the physical characteristics of the user. Therefore, based on the definition of UD used in this research particularly "to satisfy all users", the designer does not divide the uncontrollable factor. Therefore, only the range of controllable factors is divided during the search for the design solution. Figure 1 shows a conceptual diagram of the narrowing of the design solution sets.

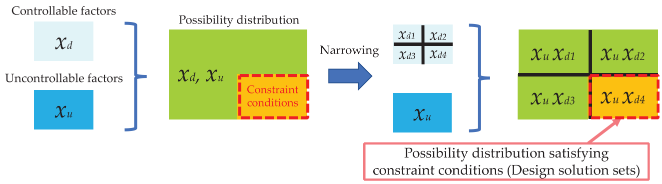


Figure 1: Conceptual diagram of the narrowing of design solution sets

2.5 Evaluation of Design Solution Candidates and Determination of Design Solutions

By using DHM to analyse and evaluate the physical load of the design solution candidates derived in Section 2.4, the designer can determine the appropriate combination of design variables as a design solution.

3.0 CASE STUDY: HEIGHT-ADJUSTABLE STANDING TABLE

Worktables and countertops are integral to domestic settings, and manufacturing plants also make heavy use of table-height surfaces for line work, often with workers required to stand for long periods. However, a long time spent standing to work can cause muscle fatigue and lower back pain as muscles compress blood vessels and blood flow deteriorates. Therefore, the user must be able to adjust the height of their worktable. The "ideal" worktable height has been the focus of research for over 30 years, but the physical burden on the body when using the product has not been discussed [13–14]. Therefore, this study applies the proposed novel design process to select the height of a standing table used by the multiple workers.

3.1 User Classification by Cluster Analysis

The employees whose work required them to stand at a table were classified according to their physical characteristics using a hierarchical cluster analysis. The measured values used such as height were from a physical characteristics database containing the details of 523 Japanese adult men. Eight design variables namely, height, weight, hand length, forearm length, upper arm length, foot length, lower leg length, and upper leg length were selected for our study, with the Mahalanobis distance and the Ward method used to recognize the variations in physical characteristics among the users in our sample. Figure 2 shows the results of the hierarchical cluster analysis that classified the workers. In this study, the number of clusters was 10.

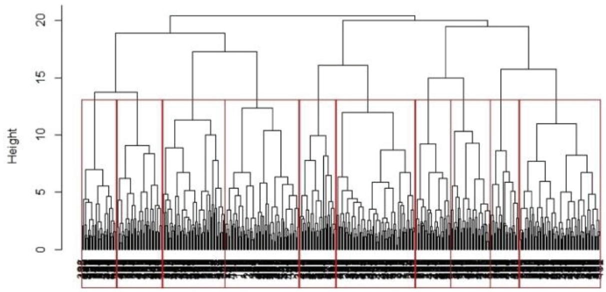


Figure 2: Result of the cluster analysis

3.2 Classification and Range Specification of Design and Performance Variables

The design and performance variables were organized according to the classifications shown in Table 1, and the range value of each variable was defined. In this study, the authors elected to model posture when using a standing table, as shown in Figure 3. In this instance, the standing table was used under the condition that the user did not lift any luggage and no external force acted on their hands. The design variables were as follows: the constrained controllable factors were defined as the shoulder angle S, waist angle θ, and elbow angle E; the uncontrollable factors were defined as height h and weight W, and their ranged value was the minimum and maximum height and weight of each group. Furthermore, the lower back compressive force Bw was defined as a performance variable, and its range was defined based on the standard established as in [15]. Moreover, the standing table depth was defined as a constraint condition. Table 2 shows the ranges of design and performance variables for group 1.

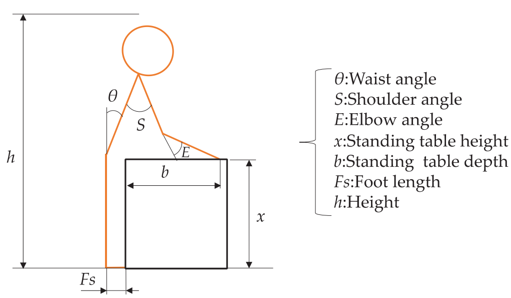


Figure 3: Posture model for standing table

Table 2: Range of design and performance variables for group 1

Type		Characteristics	Name	Symbol	Range
Design variables	Physical information	Constrained controllable factor	Waist angle [°] Shoulder angle [°] Elbow angle [°]	θ S E	[0, 45] [0, 45] [0, 45]
		Uncontrollable factor	Height [cm] Weight [kg]	h W	[140.2, 170.1] [41.6, 67.4]
	Product information	Controllable factor	Standing table height [cm]	x	$x > 0$
Performance variables		Required performance	Lower back compressive force [N]	Bw	$Bw < 3400$
		Constraint condition	Standing table depth [cm]	b	$b > 0$

3.3 Derivation of Relations and Design Solution Candidates

This study used the orthogonal design experiment from the experimental design method for the waist, shoulder, and elbow angles, and set the angle of the neck so that the line of sight would face the working position. The heights and weights were divided into five levels: the minimum value, -1σ, average value, 1σ, and maximum value. In addition, the waist, shoulder, and elbow angles are divided into five levels from 0 degree to 45 degrees. Table 3 shows the level value of group 1.

Next, the designer measured the lower back compressive force Bw, standing table height x, and standing table depth b by DHM using the values in the orthogonal table. Relational expressions of these were created from the measured values obtained by using RBF interpolation of the response surface method. Using the conditions defined above, an interval calculation was made and a set of design solution candidates that satisfied the required performance was derived.

Table 3: Group 1 factor-level relationship

Factor (design variables)	Level				
	1	2	3	4	5
Height h [cm]	140.2	152.3	158.2	164.0	170.1
Weight W [kg]	41.6	49.8	55.5	61.1	67.4
Waist angle θ [°]	0	11.25	22.5	33.75	45
Shoulder angle S [°]	0	11.25	22.5	33.75	45
Elbow angle E [°]	0	11.25	22.5	33.75	45

3.4 Results

This study used DHM to create a set of design solution candidates that promoted a posture that decreased lower back compressive forces. The optimum posture to attain the minimum physical load is the condition that waist angle θ is 0°, shoulder joint angle S is 0°, and elbow joint angle E is 0°. Figure 4 shows the range of standing table height for each group. Table 4 shows the range of design solutions for all clusters and the lumbar disk compressive forces while using the table.

The standing table height x in [67, 85] cm was obtained as a common solution in this case study, as shown in Figure 4. Figure 5 shows an example of the posture while using the table.

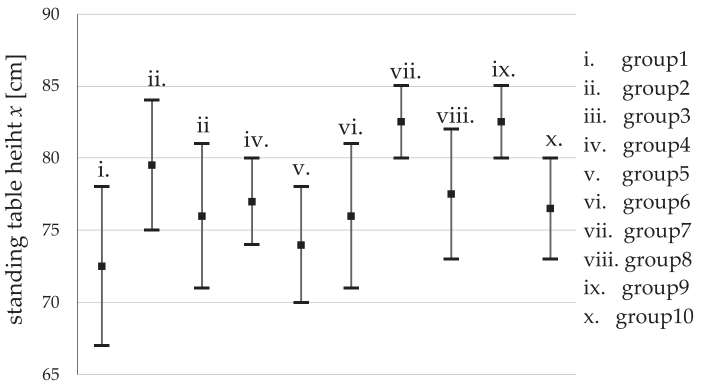
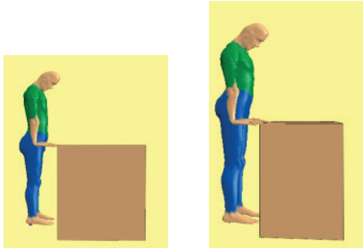


Figure 4: Standing table height for each group

Table 4: Design solution and physical load of each group

Cluster of groups	Range of standing table heights x [cm]	Range of lower back compressive forces Bw [N]
Group 1	[67, 78]	[207, 624]
Group 2	[75, 84]	[248, 801]
Group 3	[71, 81]	[230, 750]
Group 4	[74, 80]	[204, 734]
Group 5	[70, 78]	[213, 754]
Group 6	[71, 81]	[192, 717]
Group 7	[80, 85]	[236, 664]
Group 8	[73, 82]	[183, 663]
Group 9	[80, 85]	[325, 1206]
Group 10	[73, 80]	[245, 825]



Height h = 140.2 cm
Weight W = 41.6 kg

Height h = 182.5 cm
Weight W = 72 kg

Figure 5: Posture when using the standing table

3.5 Comparison between the Proposed Method and the Method without User Classification

This study compared the proposed method with one that produced design solutions derived without the user classification process. Table 5 shows the different ranges of lower back compressive force in design solutions derived from each method.

Table 5: Comparison between the proposed method and design solutions derived without user classification

	Design solutions with user classification		Design solutions without user classification	
	Height x [cm]	Lower back compressive force Bw [N]	Height x [cm]	Lower back compressive force Bw [N]
Minimum	67	183	68	227
Maximum	85	1206	82	1179

3.6 Discussions

From the results of the interval calculation, it was confirmed that the waist angle θ = 0°, the shoulder angle S = 0°, and the elbow angle E = 0° were the optimum postures in this case study. The optimum postures are considered due to the center of gravity of the upper body is closely related to the lumbar disc compressive force, as established through DHM, which illustrated that the compressive force increases as the angle increases. Moreover, a model in this range would create an almost upright posture, but since the standard was set for the wrist to be horizontal to the standing desk, the standing desk height x in [67, 85] (cm) could be obtained. In the method without user classification, the range of the lower back compressive force was narrower than in our proposed method. However, because an interval calculation was made, some users were found to have minimum and maximum values for all parameters. Therefore, without user classification, the reliability of the design solution could not be guaranteed because of the influence of body types that do not exist in the database. In this case study, the passage of time was not taken into account. However, a person who works standing up all the time would be able to use the standing desk height with the least physical load over time. Moreover, the authors discovered that by classifying users by cluster analysis, it was possible to prevent the inclusion of users that were not targeted in the design brief. From the above, the authors performed a user classification by cluster analysis, expressed the physical diversity of users with range values, and evaluated the physical load using DHM for the obtained design solution candidates. It is possible to design a standing table that creates less demanding physical loads on users' lower backs.

4.0 CONCLUSION

This paper proposed a UD method that considered various physical characteristics and loads. In this method, by using cluster analysis, the user's physical characteristics were expressed as range values in the same way as product information, and the physical load was evaluated using DHM for the obtained design solution candidates. Moreover, the effectiveness of the proposed method is demonstrated by applying to the design problem of a height-adjustable standing table and deriving the standing desk height x in [67, 85] cm, which is easy for all users to use, and comparing it with the conventional method. By comparing the proposed method and the method without cluster analysis, the proposed methods were able to visualize the effects of users with physical characteristics that do not exist, which are caused by treating physical characteristics with a range of values by using cluster analysis.

It should be noted that in this study, the number of clusters was set at 10 when classifying users by cluster analysis, but there is no clear method for how this decision should be made. This task depends on the designer, which constitutes a burden on them. Therefore, in the future, it is necessary to establish a standard method of determining the appropriate number of clusters that considers the degree of UD required and the manufacturing costs. In addition, this study does not take into account human movements and changes in posture over time. Therefore, it is necessary to analyze human movements using DHM and to consider more diverse uses of the products in the future.

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