# A UNIVERSAL DESIGN METHOD BASED ON MOTION ANALYSIS BY USING MOTION CAPTURE AND MUSCULOSKELETAL MODEL: CASE STUDY OF PRODUCT SHELF HEIGHT

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**ABSTRACT:** In recent years, many companies have focused on the concept of universal design (UD) to design products that can be easily used by users of diverse body characteristics in order to develop products that take user diversity into consideration. This study proposes the UD method that takes into account physical load in order to realize the design that is easy to use for as many people as possible, which is one of the concepts of UD. The actual motions during product use are measured by using motion capture, and the motions are applied to the musculoskeletal model for motion analysis to evaluate the load on the user's body. This analysis results in deriving the user-friendly solution for each group and aggregating them to derive the UD solution that can be used by as many people as possible with a less physical load. The effectiveness of the proposed method is demonstrated by applying it to the design problem of a shelf height.

**KEYWORDS**: *Universal Design; Motion Capture; Musculoskeletal Model*

## 1.0 INTRODUCTION

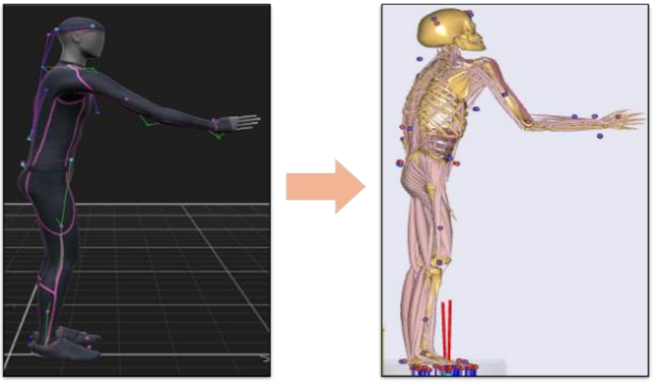
In recent years, the manufacturing industry in Japan has seen an increasing presence of older workers and foreign workers, driven by the aging population and rapid globalization. This increasing workforce diversity has highlighted a critical issue: workspaces designed based on the average body shape of Japanese workers may not adequately accommodate individuals with different body shapes. As a result, certain workers experience heavy physical load and face unequal access to convenience and usability. Therefore, one solution is the concept of universal design (UD), which designs products that can be user-friendly for as many people as possible. UD is a concept advocated by Mace [1] and consists of 7 principles listed in Table 1. UD emphasizes an ergonomic perspective. For example, it involves redesigning equipment and workspaces to enable workers to perform tasks in proper postures, as well as designing tools that minimize the need for excessive physical load. By incorporating UD principles into the work environment, tasks become easier to perform according to the worker's body shape, reducing physical load during work and promoting healthier working conditions.

Table 1: The principles of Universal Design [1]

| | |
|---|---|
| Principle 1 | Equitable use |
| Principle 2 | Flexibility in use |
| Principle 3 | Simple and intuitive |
| Principle 4 | Perceptible information |
| Principle 5 | Tolerance for error |
| Principle 6 | Low physical effort |
| Principle 7 | Size and space for approach and use |

To realize UD, it is essential to understand the physical characteristics of various users and consider the physical load on the user as they work with the product. Studies on product design using biometrics, such as electromyography [2-4] and electroencephalography [5-7], have been conducted for the quantitative evaluation of physical load. However, in those studies, the evaluation is conducted after product prototyping, which is inefficient because of the time and cost required to repeatedly improve the product and evaluate it after improvement. In addition, studies have been conducted using digital human model simulations to efficiently estimate physical load [8-9], but changes in muscle mass due to changes in body shape have not been adequately discussed.

Therefore, this study proposes the UD method that takes into account physical load using motion capture and musculoskeletal model, in order to design "low physical effort" products, which is one of the concepts of UD. A musculoskeletal model is software that can reproduce human motions, body shape, muscle mass, etc. on a computer and perform motion analysis. The actual motions during product use are measured by using motion capture, and the motions are applied to the musculoskeletal model for motion analysis to evaluate the load on the user's body. Figure 1 shows an example of applying motion measured by motion capture to a musculoskeletal model. From the results of musculoskeletal model analysis, derive the user-friendly solution for each group, and aggregate them to derive the UD solution that can be used by as many people as possible with a small physical load. The effectiveness of the proposed method is demonstrated by applying it to the design problem of a shelf height.



(a) (b)

Figure 1: an example of applying motion to a musculoskeletal model: (a) motion and (b) musculoskeletal model

Figure 2 shows examples of "low physical effort" products: train straps and restroom handwashing stations. As these two examples show, "low physical effort" products often offer multiple options to make it user-friendly for as many people as possible. For example, in this restroom, handwashing stations, the left side is the main sink, which is user-friendly for many people, and the right side is the optional sink, which is user-friendly for children and people with disabilities. Therefore, in this study, the design solution is a combination of main product size and optional product size that is user-friendly for as many people as possible.



(a) (b)

Figure 2: Examples of "low physical effort" products: (a) train straps and (b) restroom hand washing stations

## 2.0 METHODOLOGY

As mentioned in Section 1.0, conventional studies have not accounted for changes in muscle mass due to changes in body shape. In addition, the motion during the product use in digital human model simulations is created by the designer and may deviate from the actual motion. To solve these problems, the proposed method uses musculoskeletal models of various body shapes to estimate physical load to design UD products that take into account changes in muscle mass due to changes in body shape. In addition, the validity of the motions is ensured by measuring the motions during product use by motion capture.

### 2.1 Definition and measurement of motion

The designer defines the target motion based on interviews and behavioral observations. Then, the product dimensions are changed within the target motion range, and the user's motions during use of the product are measured by using motion capture.

### 2.2 User classification

The designer defines the targeted users. After that, the mean and standard deviation of the targeted users are calculated, and the users are classified based on these values. The elements used for classification are the body parts required when creating the musculoskeletal model.

### 2.3 Motion analysis by using musculoskeletal models

Create a musculoskeletal model for each of the groups classified in section 2.2. After that, motion analysis is performed by applying the motions measured in section 2.1 to the musculoskeletal models. In this study, the AnyBody Modeling System, a commercial software, was used as the musculoskeletal model [10]. In the system, the human body is modeled as a rigid link with muscles represented as wires. When the model is subjected to body motion, the body load during the motion is calculated by inverse kinematics.

### 2.4 Approximation equation creation, data normalization, and solution derivation for each group

For each of the groups classified in section 2.2, approximate equations for product dimensions and physical load are created from the analysis results in section 2.3. Then, normalization is performed using equation (1) so that the minimum value of the physical load is 0.0 and the maximum values is 1.0, and the value is the "Score".

$$Score = \frac{Physical\ Load - Minimum\ Physical\ Load}{Maximum\ Physical\ Load - Minimum\ Physical\ Load} \quad (1)$$

The lower the Score, the lower the physical load during product use. Therefore, the product is user-friendly for the group. The designer defines a decision value and uses the Score to find a usable dimension for the group.

### 2.5 Find the percentage of groups satisfied with the main product dimensions

From the solution for each group obtained in section 2.4, find the percentage of groups that are satisfied at each product dimension. The dimensions used in this section are the main product dimensions.

### 2.6 Find the percentage of groups satisfied with the optional product dimensions and determination of the design solutions

Do section 2.5 again for groups that were not satisfied in section 2.5. The dimensions used in this section are the optional product dimensions. From the results, we obtain the combination that satisfies the conditions defined by the designer, which is the design solution.

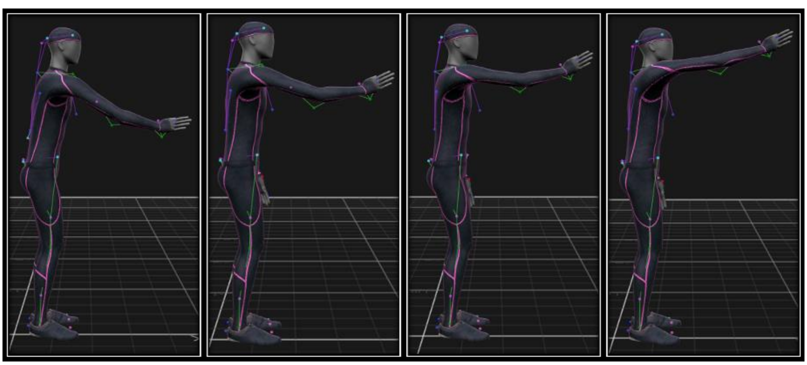
## 3.0 CASE STUDY: DESIGN OF PRODUCT SHELF HEIGHT

Retail stores, such as convenience stores and supermarkets are facilities used by users of various body shapes. Therefore, the height of product shelves must be set at an appropriate height, taking into account not only the weight of the products but also the various body shapes of the users. In practice, however, the height is often not appropriately set, resulting in the handling of heavy products in a stooped posture, which causes back pain. As a result, there is a need to design product shelves that take into account the physical load during product use. In this chapter, we design a product shelf height that can be used with less physical load for all Japanese males.

### 3.1 Definition and measurement of motion

Figure 3 shows the image of motions during a product shelf use in retail stores. In this case study, one Japanese male subject, 167 cm tall, was measured 15 different motions of lifting a 3 kg object displayed on the product shelf by changing the height of the shelf between [100, 140]cm as a motion when using a product shelf. Figure 4 shows examples of the measured motions.

Figure 3: The image of motions during a product shelf use



(a) (b) (c) (d)

Figure 4: Examples of the measured motions: (a)100cm, (b)114cm, (c)126cm and (d)140cm shelf height

## 3.2 Definition and classification of users

In this case study, the target users are defined as all Japanese males. The elements used for classification were height and BMI, which were necessary when creating the musculoskeletal model, and the mean and standard deviation (σ) were determined based on National Health and Nutrition Survey [11] conducted by the Ministry of Health, Labor and Welfare in 2016. Each variable was then divided into a range of [-2σ, 2σ], and users were classified into 72 groups. Table 2 summarizes the values used for classification, and Figure 5 shows an overview of the physical property ranges for the classified groups. For example, we can see that the range of physical characteristics for group 1 is [159.0, 161.0] cm for height and [28.5, 31.5] for BMI.

Table 2: Values used for classification

| Variable name | Mean value | Standard deviation ($\sigma$) | $-2\sigma$ | $2\sigma$ |
|---|---|---|---|---|
| Height [cm] | 171.4 | 5.7 | 160.0 | 182.8 |
| BMI | 22.6 | 3.7 | 15.2 | 30.0 |

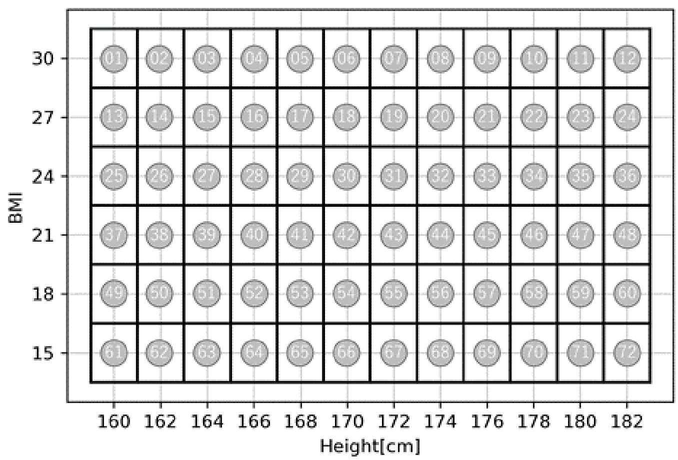
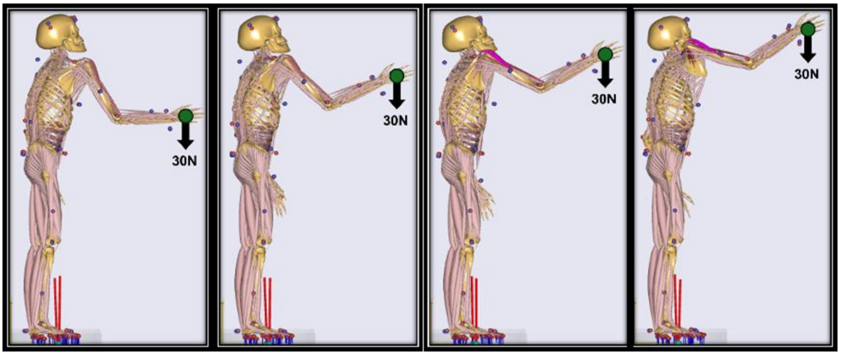



Figure 5: Overall view of user groups

## 3.3 Motion analysis by using musculoskeletal models

Create a musculoskeletal model for each of the groups classified in section 3.2. After that, motion analysis is performed by applying the motions measured in section 3.1 to the musculoskeletal models. Figure 6 shows examples of the created musculoskeletal models.




(a) (b) (c) (d)

Figure 6: Examples of the created musculoskeletal model: (a)100cm, (b)114cm, (c)126cm and (d)140cm shelf height

### 3.4 Approximation equation creation, data normalization, and solution derivation for each group

From the analysis results in section 3.3, approximate equations for product dimensions and physical load are created for each of the groups classified in section 3.2. In this case study, the L5/S1 intervertebral disc compression force was used as the body load from the guidelines for low back pain risk established by the National Institute for Occupational Safety and Health (NIOSH) [12]. After that, the approximate equation was created by using smoothing splines. In addition, normalization is performed by using equation (1) so that the minimum value of physical load is 0.0 and the maximum value is 1.0, and the value is defined as Score. In this case study, the decision value of Score is defined as 0.6, and the height at which Score is less than the decision value of Score is defined as the height that is user-friendly for the group to use. As a specific example, Figure 7 shows the graph of the approximate equation for the group of 160 cm height and BMI 15, and Figure 8 shows the graph of the normalization for the same group. In this group, normalization was performed by defining the minimum physical load of 540.7 N as 0.0 and the maximum value of 569.8 N as 1.0. As a result, [106.9, 118.8] cm was obtained as a user-friendly shelf height.

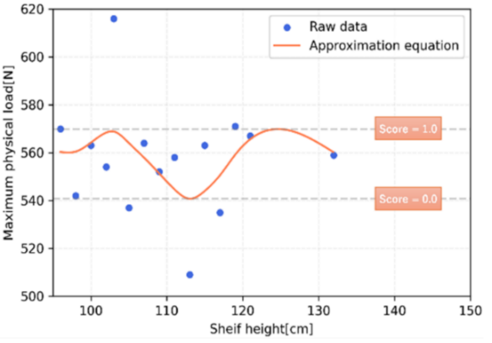



Figure 7: The approximate equation for the group of 160 cm and BMI 15

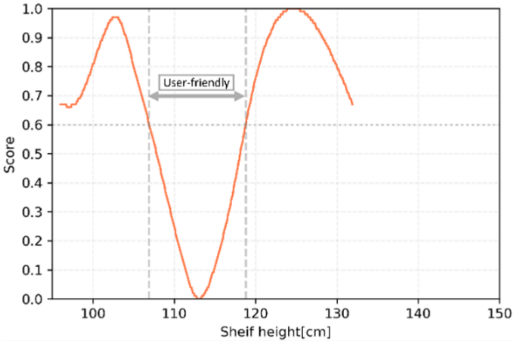



Figure 8: The normalization for the group of 160 cm and BMI 15

## 3.5 Find the percentage of groups satisfied with the combination of main and optional shelves

The analysis results obtained in section 3.4 show different shelf height ranges for different groups. Figure 9 shows the shelf height range obtained at each height. In this case study, the range for which data are available for all groups (the red range in Figure 9, [109.0, 132.0] cm) is defined as the design range.

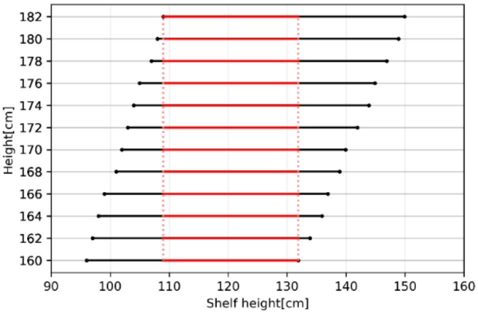



Figure 9: The shelf height range obtained at each height

From the results in section 3.4, determine the percentage of groups that can be satisfied when the main and optional shelves are combined within the design range. Figure 10 shows a visualization of the percentage of satisfied groups at a particular shelf combination. Each axis represents the main shelf height, the optional shelf height, and the percentage of the group that is satisfied. For example, we can see that the area enclosed by this green circle is a more user-friendly combination of shelves because it is higher than the rest of the area.

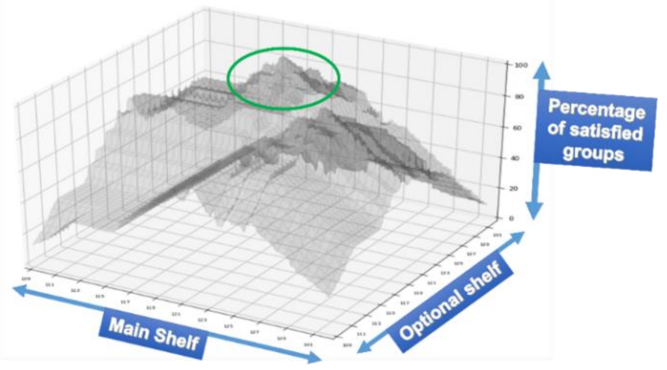



Figure 10: Visualization of the percentage of satisfied groups at a particular shelf combination

### 3.6 Determination of the design solutions

Finally, we determine the design solution based on the results of section 3.5. The designer evaluates and chooses the appropriate combination of options according to the design purpose and design intent. In this case study, a design solution is defined as a combination of options that is user-friendly for more than 90% of the groups in order to satisfy as many groups as possible. And then, the combination of options is visualized to make it easier for the designer to understand. The red range in Figure 11 shows the combination of options that satisfy more than 90% of the groups.

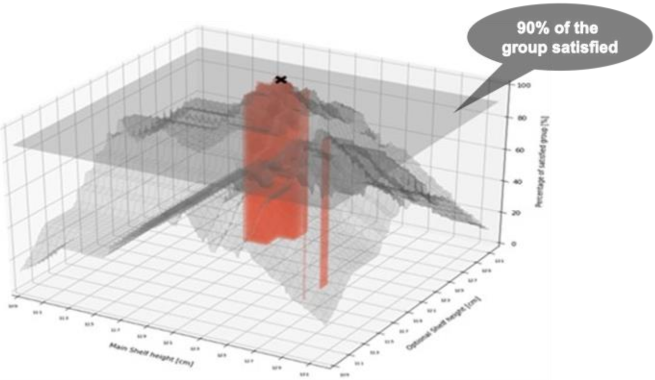



Figure 11: Combination of main shelf and optional shelf that is user-friendly for more than 90% of the groups

### 3.7 Discussion and future work

The results of Section 3.6 indicate that designing the main shelf height within the range of [117, 119] cm and the optional shelf height within the range of [125, 127] cm can satisfy more than 90% of the target groups. Fujimura et al. [13] reported that the load on the intervertebral disc compression force decreases during heavy lifting when the height of the loading platform exceeds 60% of a user's height. When the results of Section 3.6 are converted into height ratios based on the mean value of height shown in Table 2, the main shelf height range is 68–69% of the height, while the optional shelf height range is 73–74% of the height. These results are consistent with the findings of Fujimura et al. [13] Conversely, Fujimura et al. also reported an increase in shoulder load when the height of the loading platform exceeded 60% of a user's height. However, the present study focuses solely on the load on the lower back without accounting for the load on the shoulders. Future work addresses this limitation by considering not only the load on the lower back but also the load on other muscles including the shoulders.

Furthermore, there was a group of individuals who were not satisfied even within the design range presented in Section 3.6. Upon examination, this group consisted primarily of users with higher BMI values. To meet the needs of such users, the concept of barrier-free design [14] is essential. Barrier-free design refers to the creation of environments or products that are accessible to all individuals, regardless of their physical abilities, by removing barriers that may hinder access or use. Although often confused with UD, barrier-free design is not synonymous with it. Barrier-free design specifically emphasizes providing accessibility for users with disabilities.

Therefore, by incorporating barrier-free design, it is possible to efficiently design user-friendly products for groups who were not satisfied in Section 3.6. Accordingly, future work is to incorporate the principles of barrier-free design into the proposed method.

## 4.0 CONCLUSION

This paper proposed a UD method that takes into account physical load by using motion capture and musculoskeletal model. In this method, actual motions during product use were measured by using motion capture, and motion analysis was performed by using a musculoskeletal model to evaluate the load on the user's body. Moreover, the effectiveness of the proposed method was shown by applying it to the design problem of retail store merchandise shelf height.

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