Formulation of total perceived discomfort function for entire body in sagittal plane based on joint moment

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Abstract: This study aims to formulate a relationship between total perceived discomfort (TPD) and six joint moments - shoulder, elbow, L5/S1, hip, knee, and ankle. We conducted a manual material handling experiment with varying holding points and load amplitudes and measured joint angles and subjective TPD. Furthermore, joint moments were calculated from the measured joint angles. Three approximation models – sum, maximum, and square sum – were compared in terms of TPD prediction accuracy, and the model that was selected as the TPD function because its average error was lowest. Individually approximated TPD functions for males and females did not show improved accuracy compared with the TPD function for both genders. Therefore, a single TPD function was applied irrespective of gender. The correlation coefficient between measured and predicted TPD functions was compared to those of four observational methods – OWAS, RULA, REBA, and NIOSH lifting equation; that of the proposed TPD function was the highest.

Key Words: Ergonomics, Biomechanics, Function approximation, Digital human.

1. Introduction

A work environment should be designed to minimize physical load, an increase in which can cause musculoskeletal disorders in workers [1], [2]. In product design, too, minimization of physical load is important as a means to enhance the product value [3], [4]. Bioinstrumentation measurements such as EMG are employed in ergonomic design to evaluate the physical load [5]. However, experimental physical load evaluations using bioinstrumentation measurements can only be performed with mockups of work environments or products and subjects that have well-distributed anthropometric dimensions; such experiments therefore require substantial time and cost. In addition, the number of experimental conditions is often restricted because of ethical considerations for subjects, making it impossible to perform experiments involving long durations and high physical loads.

To overcome these problems, studies are focusing on applying digital human modeling (DHM) to the design of work environments and products [6]-[9]. A digital human is a computer model of the anthropometric and physical characteristics of a human. DHM is intended to reduce or eliminate experimental physical load evaluations, and it can be used to achieve effective ergonomic design. Under the most basic static load conditions, several commercial DHM software can evaluate the physical load via joint moments [10], [11]. The joint moment is a reactive moment on each joint against external forces and the self-weight of body segments, and it is considered an indicator of physical load [5]. Multiple joint moments can be obtained by DHM simulation. Researchers investigated the relationship between the objective joint moment and the subjective perceived discomfort for various human joints [12]-[14]. However, an evaluation method for the total perceived discomfort (TPD) of multiple joint moments has not yet been investigated. Designers cannot determine an optimum design solution when they independently evaluate multiple joint moments, because a design change may increase one joint moment while decreasing another. Decision-making therefore becomes difficult when multiple joint moments are in a trade-off relation. Therefore, a TPD function must be formulated so as to determine the ideal design solution from multiple solutions.

Several observational methods are used to assess the TPD of workers [15], [16]. Typical observational methods used by ergonomic practitioners include [17] the Ovako working posture analyzing system (OWAS) [18], [19], rapid upper limb assessment (RULA) [20], [21], rapid entire body assessment (REBA) [21], [22], and NIOSH lifting equation (NLE) [23], [24]. In these methods, the positions of individual body segments and the weight of the load handled are observed and scored with a worksheet, and the TPD is calculated from the summary scores. These methods are implemented in commercial DHM software [25]. These observational methods are straightforward because they only require the observation of workers. However, they cannot be used to perform detailed evaluations of the TPD because the worksheets only coarsely classify the postures of workers and the lifting of weights. Each classified category in the worksheet covers a relatively wide range of body segment postures and handling loads. Thus,
it is possible for different postures to have a measurable difference in TPD even if they are classified into the same category and have the same summary scores. In addition, the observation methods consider the weight of the load handled but not the direction of the force, except for the gravitational direction. In real situations, arbitrary external forces act on the human body. However, the loading conditions of ordinary observation methods cover only limited situations.

A detailed and versatile evaluation method for TPD should be established so as to apply the DHM to arbitrary design problems of work environments and products. TPD evaluation based on joint moments is suitable for this purpose because joint moments are continuous and can therefore be used for a detailed evaluation of TPD. In addition, joint moments are versatile TPD indicators because they can be calculated for arbitrary external force directions. Thus, the present study aimed to determine the best approximation model for TPD functions among three proposed models. We focused on the formulation of the TPD function for the entire body. To simplify the problem, the rigid human link model used in this study was constructed in two-dimensional space (i.e., sagittal plane), and a static external load was applied. A manual material handling experiment was performed with varying holding points and load amplitudes, and the joint angles and subjective TPD were measured. Then, six joint moments—shoulder, elbow, L5/S1, hip, knee, and ankle joint moments—were calculated based on the measured joint angles. The response surfaces of the TPD were approximated by three different models—sum, maximum, and square sum. The accuracy of the response surfaces was compared to determine the best approximation model. In addition, the need for individual formulations for each gender was statistically investigated. The accuracy of the proposed function was compared to that of four typical observational methods—OWAS, RULA, REBA, and NLE—and the advantage of the proposed function was investigated.

2. Method

2.1 Experimental conditions

Twelve healthy Japanese subjects (six males and six females), aged between 21 and 26, participated in this experiment. All were university students and none had musculoskeletal disorders. Their mean (SD) stature and body mass were 165 (8.18) cm and 59.9 (12.2) kg, respectively. The experimental factors in this study were distance d and height h of the weight holding point and mass of weight w. Then, six joint moments—shoulder, elbow, L5/S1, hip, knee, and ankle joint moments—were calculated based on the measured joint angles. The response surfaces of the TPD were approximated by three different models—sum, maximum, and square sum. The accuracy of the proposed function was compared to that of four typical observational methods—OWAS, RULA, REBA, and NLE—and the advantage of the proposed function was investigated.

2.2 Calculation of joint moment ratio.

The six joint moments were calculated based on the measured joint angles of each subject. The biomechanical models for the calculation were constructed based on the stature and body mass of each subject. The length and weight of each body segment were quoted from Chaffin et al. [5]. Then, the calculated joint moments were divided by the maximum joint moment of each joint and gender to obtain the joint moment ratio $r$ ($r = [0, 1]$). Here, the maximum joint moments a human can exert were quoted...
from Chaffin et al. [5] and the National Institute of Technology and Evaluation, Japan [28].

2.3 Approximation models and comparison of accuracy.

In our previous study, we investigated the relationship between the perceived discomfort and the joint moment ratio for 12 joint motion directions of the upper limb and concluded that the logistic function was appropriate for expressing the perceived discomfort [14]. In this study, the logistic function was used as the platform for the approximation model of the TPD function. Eksioglu [29] applied the sum of multiple EMGs as the indicator of TPD so as to determine the optimum grip span. Objective functions have been applied to estimate muscle loads with biomechanical models because an excessive number of muscles exists in relation to the mechanical degrees of freedom at the joints. The common criteria are minimization of the sum of squared muscle-force or that of the maximum muscle-force [30]. In this study, we assumed that the TPD is affected by the sum, maximum, or square sum of joint moments based on the abovementioned researches [29], [30]. The sum, maximum, and square sum models are respectively defined as follows:

\[ T = \frac{1}{1 + \exp \left\{ a \left( \sum_{i=1}^{6} r_i - b \right) \right\}} \]  

\[ T = \frac{1}{1 + \exp \left\{ a(\max_i r_i - b) \right\}} \]  

\[ T = \frac{1}{1 + \exp \left\{ a \left( \sum_{i=1}^{6} r_i^2 - b \right) \right\}} \]

where \( T \) and \( r_i \) denote the TPD (i.e., objective variable) and \( i \)-th joint moment ratio (i.e., explanatory variable), respectively. \( a \) and \( b \) are regression coefficients that were obtained by the least-squares method. It should be noted that the TPD is normalized to [0, 1], whereas the subjective TPDs (i.e., CP-50 scores) were measured in [0, 50].

The accuracy of the three response surfaces was compared using the average absolute error (AAE). The AAE for the \( i \)-th function model was calculated as follows:

\[ AAE_i = \frac{1}{N} \sum_{j=1}^{N} \left| T_{ij} - \hat{T}_{ij} \right| \]

where \( T_{ij} \) and \( \hat{T}_{ij} \) denote the normalized subjective TPD and approximated TPD for the \( j \)-th calculation condition of the joint moment ratio, respectively. \( N \) is the number of training data that are used for constructing the response surfaces; it is given by the product of the numbers of experimental conditions and subjects. The AAEs of the response surfaces were compared among the three approximation models. One-way ANOVA was conducted at a significance level of 5%, and Tukey’s post-hoc tests were conducted to compare the three models.

2.4 Comparison between genders

The TPD function must be formulated for each gender if both have markedly different functions. In this study, the need for individual formulation for each gender was determined by comparing the AAEs of each gender’s and all subjects’ response surface as follows:

Step 1: The response surfaces of each gender are approximated.

Step 2: The AAEs of the male and female subjects’ response surface (\( E_m \) and \( E_f \), respectively) are calculated.

Step 3: The AAEs of all subjects’ response surface for male and female subjects (\( e_m \) and \( e_f \), respectively) are calculated.

Step 4: T-tests (5% significance level) between \( E_m \) and \( e_m \) and between \( E_f \) and \( e_f \) are conducted. If there are no significant differences for both genders, all subjects’ response surface is applied for both genders. Otherwise, the two response surfaces are individually formulated for both genders.

2.5 Comparison with observational methods

The proposed TPD function was compared with four observational methods – OWAS, RULA, REBA, and NLE. Predicted TPDs were obtained using each of these methods, and the correlation coefficients between them and the measured subjective TPD were compared among the four observational methods and the proposed TPD function. The four observational methods are briefly described below; for details, refer to each reference.

OWAS: OWAS [18], [19] is a method aimed at evaluating the physical load of the entire body. OWAS has four evaluation factors: back (4 postures), arms (3 postures), legs (3 postures), and weight of the load handled (3 categories). Observers decide the postures and category of the four factors based on the observation of the working posture of workers. Then, the decided postures and category are used to determine the total OWAS score. The total score has four levels (1 to 4), with a higher level indicating a higher physical load.

RULA: RULA [20], [21] is a method aimed at evaluating mainly the physical load of the upper limb. The posture scores are calculated for two groups: upper arms, lower arms, and wrist (Group A) and neck, trunk, and legs (Group B). Additional scores are given to the posture scores based on the load handled and repetitive muscular activity, and then, the sub-summary scores of the two groups are obtained. The total score of RULA is determined by a judgment table from the two sub-summary scores. The total score has seven levels (1 to 7), with a higher level indicating a higher physical load.

REBA: REBA [22], [23] is a method aimed at evaluating the physical load of the entire body. Its basic concept and
3. Accuracy of response surface

Result of low-back musculoskeletal disorders.

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dles on the load. All multipliers have values between 0
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ers smaller, and they reach 0 when the defined threshold
limits are violated. Higher LI indicates higher physical
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low-back musculoskeletal disorders.

3. Result

3.1 Accuracy of response surface

Table 1 shows the average, SD, minimum, and maximum values of the normalized subjective TPD and six joint moment ratios of each gender. In table 1, average, SD, minimum, and maximum value of 18 experimental conditions are shown. The subjective TPDs are normalized from 0 to 1. The subjective TPD is distributed over the entire range. The averages of the joint moment ratios are 0.12-0.22, minimum values are approximately 0.0, and maximum values are 0.35-0.68. The response surfaces of TPD based on the sum, maximum, and square sum models were respectively obtained as follows:

\[ T = \frac{1}{1 + \exp \{-3.17 \sum_{r=1}^{6} r_i - 1.45\}\} \] (7)

\[ T = \frac{1}{1 + \exp \{-12.6 (\max_r r_i - 0.364)\}\} \] (8)

\[ T = \frac{1}{1 + \exp \{-11.0 \sum_{r=1}^{6} r_i^2 - 0.417\}\} \] (9)

Figure 2 shows the response surfaces and plots of the normalized subjective TPD. The dots represent the index of joint moment ratio (i.e., sum, maximum, or square sum) and measured TPD of each trial. The lines indicate the approximated TPD functions. The subjective TPDs increase as the sum, maximum, and square sum of the joint moment ratios increase. Figure 3 shows the AAEs of the three response surfaces. The error bars represent the SD. The AAE of the sum model is significantly lower than that of the maximum and square sum models.

3.2 Influence of gender

The response surfaces of TPD for male \( T_m \) and female \( T_f \) subjects were approximated using the sum model, which has the lowest AAE among the three models. The response surfaces for each gender were obtained as follows:

\[ T_m = \frac{1}{1 + \exp \{-3.55 \sum_{r=1}^{6} r_i - 1.29\}\} \] (10)
the distribution of sampling points is closer to a straight line when a method appropriately expresses the TPD. The maximum total score of OWAS and REBA is respectively 3 and 8 from the measured posture and load conditions in this study, whereas their original upper limit is respectively 4 and 15. In the NLE method, the multipliers in Eq. (5) reach zero when the defined threshold limits are violated; then, LI, which is the total score of NLE, reaches infinity. In this study, several experimental conditions violated the threshold limits; thus, their total scores reached infinity. However, the infinite scores cannot be plotted in the graph, and the correlation coefficient cannot be calculated. Therefore, the total scores of NLE that violated the threshold limits were assumed to be 1 for descriptive purposes.

For OWAS, the subjective TPDs are widely distributed from 0 to 1 irrespective of the total score of OWAS. For RULA, the subjective TPDs are distributed in lower and higher ranges when the total score of RULA is 2 and 7, respectively. However, as for OWAS, the subjective TPDs are distributed in the entire range when the total scores of RULA are 3 to 6. For REBA, NLE, and the proposed function, the subjective TPDs increase as the total scores of each method increase. However, for NLE, the subjective TPD are distributed in the entire range when the total score of NLE is 1. The proposed TPD function has the highest correlation coefficients among the five methods.

4. Discussion

4.1 Selection of approximation model for TPD function

According to Figure 3, the sum model provides the best accuracy among the three models. The TPD may be affected by the sum of joint moments than by their maximum or square sum. Therefore, the response surface using the sum model is appropriate for the TPD function among the three models. However, the AAE of the sum model is ~16%, and it may be far from sufficiently high accuracy. A more complex approximation model may improve the accuracy of the response surface; for example, different weight coefficients are applied to each joint moment to fit the response surface to the data in this study. However, the overestimation may cause a lack of generalization capability. In other words, if the accuracy of a response surface is highly improved for the data in this study, the accuracy may markedly worsen for other problems. Therefore, we conclude that the sum model is the preferable approximation method for the TPD function.

4.2 Influence of gender

Figure 4 implies that the accuracy is not improved even though two response surfaces are individually constructed for male and female subjects. Therefore, there is not much difference between the TPD functions for male and female subjects. This is because different maximum joint mo-

Table 2  Correlation coefficients between measured and predicted TPD.

| Method | OWAS | RULA | REBA | NLE | TPD function |
|--------|------|------|------|-----|--------------|
|        | 0.161| 0.429| 0.593| 0.436| 0.722        |

3.3 Comparison with observational methods

Figure 5 shows the relationship between the measured and the predicted TPD by the four observational methods – OWAS, RULA, REBA, and NLE – and the predicted TPD function (i.e., Eq. (7)). The vertical axes indicate the measured TPD and the horizontal axes, the total scores of each observational method (i.e., OWAS, RULA, REBA, and NLE) and the predicted value of TPD function. The distribution of sampling points will be closer to a straight line when a method appropriately expresses the TPD. Table 2 describes the correlation coefficients between the measured and the predicted TPD. In Figure 5, the distribution of sampling points is closer to a straight line when a method appropriately expresses the TPD. Therefore, the distribution of sampling points is closer to a straight line when a method appropriately expresses the TPD. The maximum total score of OWAS and REBA is respectively 3 and 8 from the measured posture and load conditions in this study, whereas their original upper limit is respectively 4 and 15. In the NLE method, the multipliers in Eq. (5) reach zero when the defined threshold limits are violated; then, LI, which is the total score of NLE, reaches infinity. In this study, several experimental conditions violated the threshold limits; thus, their total scores reached infinity. However, the infinite scores cannot be plotted in the graph, and the correlation coefficient cannot be calculated. Therefore, the total scores of NLE that violated the threshold limits were assumed to be 1 for descriptive purposes.

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Figure 4 implies that the accuracy is not improved even though two response surfaces are individually constructed for male and female subjects. Therefore, there is not much difference between the TPD functions for male and female subjects. This is because different maximum joint mo-
ments were set for males and females; hence, the joint moment ratios were normalized considering the differences in muscle force characteristics depending on the gender. Thus, a single discomfort function represented by Eq. (7) is applied irrespective of gender.

4.3 Comparison of proposed function and observational methods

According to Figure 5, OWAS clearly cannot evaluate the TPD in detail because its total score is coarsely classified. The total score of RULA shows relatively finer classification than that of OWAS, suggesting that its correlation coefficient is relatively higher as well. However, good correspondence cannot be found between the total score of RULA and TPD when the range of the total score of RULA is 3 to 6. The RULA evaluation may not sufficiently reflect the physical load of lower limbs, and it cannot evaluate the load of the entire body because RULA is a method specified for the upper body. NLE shows good correspondence when its total score is less than 1. However, the TPD is widely distributed when the total score is 1. In other words, high and low TPD exist simultaneously when the predefined threshold limits of NLE are violated. Therefore, NLE can properly evaluate the TPD within its threshold limits but not beyond. REBA and the TPD function show higher correlation coefficients than the other methods, and their predicted values correspond to the TPD. REBA is an evaluation method for the entire body, and therefore, it properly evaluates the TPD by considering the load of both the upper and the lower limbs. In addition, the TPD function also properly evaluates the discomfort by considering the load of each joint.

In this study, a manual material handling task was conducted to compare the observational methods, because these methods mainly consider the external forces of gravitational direction. However, the proposed TPD function can be applied to the evaluation of a working situation in which an external force with arbitrary direction acts on the body, e.g., pushing downward and horizontal pushing or pulling tasks. In addition, the predicted value of the TPD function is a continuous quantity whereas that of OWAS, RULA, and REBA is a discrete value; thus, the TPD function is intended to obtain a detailed evaluation of the TPD. The correlation coefficient of the measured and predicted TPD of the function is actually higher than that obtained from the observational methods. Therefore, the proposed TPD function serves as a detailed and versatile evaluation method for TPD.

5. Conclusions

In this study, a function approximation model for the TPD of the entire body was investigated. The training data set for function approximation was constructed based on a manual material handling task, and three approximation models – sum, maximum, and square sum – were used to predict the TPD. The major findings are as follows:

1. The AAE of the sum model is significantly lower than those of the maximum and square sum models. Among the three models, the sum model is the preferred approximation model for the TPD function.

2. The individual approximation of the TPD function for
each gender does not significantly improve the accuracy compared with the response surface for both genders. Therefore, there is no need to individually approximate the TPD functions for males and females.

3. The correlation coefficient between the measured and the predicted TPD is highest for the proposed TPD function among the five evaluation methods. The TPD function is more detailed and accurate evaluation method than the ordinary observational methods.

The TPD function predicted by the sum model is the objective function for the work environment and product design when the physical load of the entire body is the main determinant factor. The TPD function in the sagittal plane was constructed in this study. This function should be extended to three-dimensional physical load evaluation for better applicability to practical working conditions. In addition, this function should be applied to a working condition with arbitrary external force directions to investigate its accuracy.

It should be noted that the TPD function in this study for these subjects. Although we had intended to include subjects of all age groups, only young students readily consented to participate because it was easy to ask them to be the subjects. It is possible that different age groups have different TPD functions. Moreover, the TPD function may be affected by not only the age but other factors such as stature, body mass, and BMI. Therefore, the TPD function should be formulated by including the influential input factors so as to improve the accuracy of the function.

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