Function approximation model for prediction of total perceived discomfort considering differences of discomfort characteristics depending on body part

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Introduction: A work environment should be designed to minimize physical load of workers (Hägg, 2003). To achieve efficient physical load evaluation and ergonomic design, studies are focusing on applying digital human modeling (DHM) to the design of work environments (Bubb and Fritzsche, 2009). Several commercial DHM software can evaluate the physical load via joint moments. Researchers investigated the relationship between the objective joint moment and the subjective perceived discomfort (PD) for various human joints (Hall and Dickerson, 2010; Chihara et al., 2014). However, an evaluation method for the total perceived discomfort (TPD) of multiple joint moments has not yet been investigated. Thus, the present study aimed to propose an approximation model for TPD functions. To simplify the problem, the rigid human link model was constructed in two-dimensional space, and a static external load was applied. The accuracy of the proposed function was compared to that of four typical observational methods—OWAS (Karhu et al., 1977), RULA (McAtamney and Corlett, 1993), REBA (Hignett and McAtamney, 2000), and NIOSH lifting equation (NLE) (Waters et al., 1993)—and the advantage of the proposed function was investigated.

Method: Twelve Japanese university students (six males and six females) participated in this experiment. The experimental factors were distance and height of weight holding point (20% or 40% and 60%, or 80% of their stature, respectively) and mass of weight (0.0, 5.0, or 10 kg for male and 0.0, 2.5, or 5.0 kg for female). The subjects kept the instructed postures for 10 s, and five joint angles were measured from video images (see Fig. 1). Six joint moments—shoulder, elbow, L5/S1, hip, knee, and ankle joint moments—were calculated, and they were divided by the maximum joint moment to obtain the joint moment ratio \( r \) \((r = [0, 1])\) (Chaffin et al., 2006). The subjective TPD was measured using category partitioning scale 50 (CP-50) (Shen and Parsons, 1997). CP-50 has a starting point (i.e., 0 = no) and five categories (i.e., very slight discomfort, slight discomfort, discomfort, severe discomfort, and very severe discomfort). Each of the categories is further subdivided into 10 scale points. The higher score represents the higher TPD.

The TPD is formulated as the average and maximum of PDs. The PD function is defined as follows (Chihara et al., 2014):

\[
t_i = \frac{1}{1 + \exp[a_i(r_i - b_i)]}
\]  

where \( t_i \) denotes the PD for \( i \)-th joint. \( a_i \) and \( b_i \) are regression coefficients. The TPD \( T \) is defined as follows:

\[
T = (1 - p) \sum_{i=1}^{6} t_i + p \cdot \max t_i
\]

\[
p = \frac{1}{1 + \exp[a_p(\max t_i - b_p)]}
\]

where \( p \) represents the transition parameter of the average and maximum terms, and \( a_p \) and \( b_p \) are the regression coefficients. The regression coefficients were obtained by the least-squares method. Predicted TPDs were obtained using the four observational methods and the proposed TPD function, and the correlation coefficients between them and the measured subjective TPD were compared.
Results: Table 1 shows the regression coefficients of each joint and the transition parameter. Fig. 2 and Fig. 3 show the PD functions and transition parameter. The PD function of elbow rises in the lowest joint moment ratio followed by that of L5/S1 and shoulder. The transition parameter rises and reaches 1.0 immediately when the maximum PD exceeds zero.

Fig. 4 shows the relationship between the measured and the predicted TPD. Table 2 describes the correlation coefficients between the measured and the predicted TPD. In the NLE method, the total score of NLE reaches infinity when the defined threshold limits are violated. In this study, the total scores that violated the threshold limits were assumed to be 1 for descriptive purposes. The proposed TPD function has the highest correlation coefficients among the five methods.

Discussion: Among the six joints, the PDs of elbow, shoulder, and L5/S1 rise in relatively lower joint moment ratio; therefore, the reduction of physical load for upper limb and lower back is more significant than that for lower limb. The transition parameter reaches 1.0 in almost entire range of maximum PD. It implies that the TPD may be affected by the maximum of joint moments than by their average.

The predicted values of TPD function well accorded with the TPD compared with the other methods. 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., 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. Therefore, the proposed TPD function serves as a detailed and versatile evaluation method for TPD.

![Fig. 1. Definition of measured joint angles](image)

### Table 1 Regression coefficients of perceived discomfort functions and transition function.

<table>
<thead>
<tr>
<th>Regression coefficients</th>
<th>Shoulder</th>
<th>Elbow</th>
<th>L5/S1</th>
<th>Hip</th>
<th>Knee</th>
<th>Ankle</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_i, a_p$</td>
<td>-15.8</td>
<td>-21.7</td>
<td>-16.5</td>
<td>-15.0</td>
<td>-13.5</td>
<td>-13.9</td>
<td>-209</td>
</tr>
<tr>
<td>$b_i, b_p$</td>
<td>0.291</td>
<td>0.212</td>
<td>0.278</td>
<td>0.564</td>
<td>0.547</td>
<td>0.658</td>
<td>0.0219</td>
</tr>
</tbody>
</table>
**Fig. 2** Perceived discomfort functions.

**Fig. 3** Transition parameter

**Fig. 4** Relationship between measured and predicted TPD: 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. It should be noted that the TPD is normalized to [0, 1].

**Table 2** Correlation coefficients between measured and predicted TPD.

<table>
<thead>
<tr>
<th></th>
<th>OWAS</th>
<th>RULA</th>
<th>REBA</th>
<th>NLE</th>
<th>TPD function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.161</td>
<td>0.429</td>
<td>0.593</td>
<td>0.436</td>
<td>0.840</td>
</tr>
</tbody>
</table>
References