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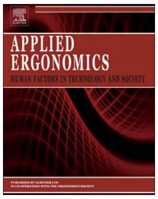

Perceived discomfort functions based on joint moment for various joint motion directions of the upper limb

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ABSTRACT

The aim of the present study was to formulate the relationship between the perceived discomfort and the joint moment ratio for twelve joint motion directions of the upper limb by considering the between-subject variability, and to investigate the effect of joint motion direction. Three approximation models (i.e., linear, exponential, and logistic function models) were compared in terms of the accuracy of predicting the perceived discomfort, and the logistic function was selected because its average error was lowest. The concept of L-R fuzzy number was used to consider the individual variability of perceived discomfort, and a simplified distribution of perceived discomfort was represented. Cluster analysis showed that the twelve discomfort functions formed two clusters: one for elbow flexion and a second for the remaining joint motions. The data show that elbow flexion is more sensitive than other joint motions to increases in the joint moment ratio.

1. Introduction

Biomechanical analysis and electromyogram (EMG) recordings are widely used to evaluate physical stress and fatigue; they are also applied to design problems of work environments and consumer products in order to reduce physical work load (Chaffin et al., 2006; Tsang and Vidulich, 2006). EMGs record the actual electrical activity of a muscle. However, EMG recordings require preliminary measurements, such as measurement of the maximum voluntary contraction for normalization (U.S. Department of Health and Human Services, 1992); hence, it is time consuming and imposes strain on subjects. In addition, measured EMG recordings evaluate muscle load on only the intended motion; thus, re-measurement of EMGs is necessary when the design variables of work environments and consumer products are changed.

Physical load evaluation based on a biomechanical model with the joint angle and joint moment requires the measurements of only the joint angle and external force. Therefore, the experimental cost and strain on subjects may be lower for a biomechanical analysis than for EMG measurements. Biomechanical analysis does not necessarily require experimentation, because the analysis can be performed if the joint angles and external forces are given; hence, a biomechanical analysis can be used for the re-evaluation of the physical stress with a design change more effectively. The time that can be allocated to improving work environments or designing consumer products is decreasing with each passing year, in conjunction with the shortening of the development period. That is, an ergonomic physical load evaluation should be performed effectively in a short time. Thus, it is essential to develop an ergonomic design using a biomechanical analysis model that performs physical load evaluation more efficiently than EMG measurements (Lestrelin and Trasbot, 2005; LaFiandra, 2009).

Research on postural discomfort imposed by varying joint angles has been reported (Kee and Lee, 2012). The relationships between the perceived discomfort and joint angle have been studied (Kee and Karwowski, 2001, 2004; Chung et al., 2003). Miedema et al. (1997) studied the effects of joint angle and duration on perceived discomfort, whereas Carey and Gallwey (2005) along with Khan et al. (2010) investigated the effects of joint angle and repetition. The ranking of perceived discomfort of joint motions have been investigated (Genaidy and Karwowski, 1993; Kee and Karwowski, 2003). The relationship between perceived discomfort and joint angle can be used to evaluate the discomfort of arbitrary human postures. However, in real situations of working or using a product, arbitrary external forces will act on the human body, and arbitrary moments will act on each joint. In addition, because perceived discomfort is affected more by the joint moment than the joint angle

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(Carey and Gallwey, 2002; Dickerson et al., 2006), the relationship between perceived discomfort and joint moment should be quantified to improve the accuracy of perceived discomfort evaluation.

The maximum joint moments that subjects can exert have been measured (Amundsen, 1990; Chaffin et al., 2006; National Institute of Technology and Evaluation, 2009). In these reports, the average maximum joint moment among subjects was measured, and the relationship between the maximum joint moment and joint angle was represented. Boussenna et al. (1982) investigated the relationships between the perceived discomfort and joint moments of the hip, knee, and ankle. Wang et al. (2004) investigated the relationship between the perceived discomfort and biomechanical parameters, including the joint moments when depressing a clutch pedal. Mukhopadhyay et al. (2007) investigated the effects of the joint moment of forearm pronation, forearm rotation angle, elbow angle, and exertion frequency on the perceived discomfort. However, they did not investigate the quantitative effect of the joint moment magnitude on perceived discomfort.

Dickerson et al. (2006) investigated the effects of the shoulder joint moment, position of operation object, and stature of subjects on perceived discomfort in a simulated workstation. Perceived discomfort, which was measured by varying the direction and magnitude of external force, was mostly affected by, and represented as a linear function of, the shoulder joint moment. However, they did not investigate the effect of joint motion direction of the shoulder joint (i.e., extension, flexion, abduction, adduction, internal rotation, and external rotation). In addition, the perceived discomforts of the elbow and wrist joints were not considered, although the discomfort of other joints may be as important as that of the shoulder joint. Moreover, the abovementioned reports on the relationship between the perceived discomfort and joint moment or joint angle did not quantify individual differences. The perceived discomfort function for upper limb joints should be formulated by considering the variability so as to take into account human diversity during developing ergonomic design.

The objective of the present study was to formulate the relationship between the perceived discomfort and joint moment by considering the variability of subjective evaluation, and to consider differences among the joint motion directions of the upper limb (i.e., shoulder extension, shoulder flexion, shoulder adduction, shoulder abduction, shoulder internal rotation, shoulder external rotation, elbow extension, elbow flexion, wrist extension, wrist flexion, wrist ulnar deviation, and wrist radial deviation). In this study, the perceived discomforts of subjects were measured when they exerted joint moments of arbitrary magnitude in each joint motion direction. The response surfaces of perceived discomfort were approximated by three different approximation models: linear, exponential, and logistic function models. The logistic function model was selected as the best approximation model because its accuracy was highest among the three models. The concept of fuzzy number was used to represent the variability of perceived discomfort among subjects. Finally, clustering the evaluation functions of perceived discomfort for each joint motion direction revealed that the function for the upper limb could be divided into two clusters.

2. Method

2.1. Measurement of perceived discomfort

Ten healthy Japanese male subjects, aged between 21 and 25, participated in this experiment. All of them were university students, right handed, and none of the subjects had a musculoskeletal disorder. Their stature, weight, and gripping force are listed in Table 1.

The target joint motion directions were the six directions of the shoulder joint (i.e., shoulder extension, shoulder flexion, shoulder adduction, shoulder abduction, shoulder internal rotation, and shoulder external rotation), two directions of the elbow joint (i.e., elbow extension and elbow flexion), and four directions of the wrist joint (i.e., wrist extension, wrist flexion, wrist ulnar deviation, and wrist radial deviation). The subjects sat and exerted joint moments by holding a weight with the dominant hand in the instructed upper limb postures shown in Fig. 1. Note that the forearm is in the pronated position in Fig. 1(i) and in the supinated position in Fig. 1(j); the others are in neutral positions. The joint moment was calculated by magnitude of holding weight and the related segment length of each subject.

The maximum joint moment for each subject was measured, after which joint moments with magnitudes of approximately 20, 40, and 60% of the premeasured maximum joint moment were added by adjusting the weight. The subjects kept the instructed postures for 10 s. The magnitude of joint moments was controlled by adjusting the weight. In addition, joint moments lower than the abovementioned magnitudes were added if a subject judged the magnitude as excessive. There was a 5-min rest period after each trial.

The perceived discomfort was measured by the category partitioning scale 50 (CP-50) (Shen and Parsons, 1997). The 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). Thus, the ranges for each category are given as follows:

"Very slight discomfort": 1–10
"Slight discomfort": 11–20
"Discomfort": 21–30
"Severe discomfort": 31–40
"Very severe discomfort": 41–50

Each of the categories is further subdivided into 10 scale points. Subjects first choose the category to which a stimulus belongs, and then choose the degree among the 10 scale points. In this study, the subjects were instructed to rate their perceived discomfort for each magnitude of joint moment assuming the discomfort they perceive when exerting their maximum moment to be 50. The maximum discomfort level was set for all maximum joint moment in each subject and joint motion direction. It should be note that subject may not feel the same level of discomfort between the maximum joint moments at different joint motion directions.

This experiment was approved by the Research Safety and Ethics Committee of Tokyo Metropolitan University.

2.2. Selection of approximation model

The perceived discomfort probably increases as the magnitude of the joint moment increases. Therefore, the approximation model for the perceived discomfort function must be a monotonically

Table 1
Stature, weight, and gripping force of subjects.

Subject	Stature [cm]	Weight [kg]	Gripping force [kgf]
A	186	70.6	56
B	172	63.0	41
C	172	62.1	34
D	182	82.0	55
E	163	58.0	33
F	168	50.0	47
G	160	64.0	44
H	177	76.0	50
I	171	61.9	38
J	172	64.2	48
Average	172	65.2	44.6
S. D.	7.96	9.09	8.09