ELSEVIER

Applied Ergonomics 34 (2003) 167–176

APPLIED ERGONOMICS

www.elsevier.com/locate/apergo

Ranking systems for evaluation of joint and joint motion stressfulness based on perceived discomforts

Dohyung Kee[a,*], Waldemar Karwowski[b]

[a] Department of Industrial and Systems Engineering, Keimyung University, 1000 Shindang-dong, Dalseo-gu, Taegu 704-701, South Korea
[b] Center for Industrial Ergonomics, Lutz Hall, Room 445, University of Louisville, Louisville, Kentucky 40292, USA

Accepted 7 October 2002

Abstract

This study aims to develop ranking systems for evaluation of the stressfulness of joints and joint motions based on perceived discomforts measured through an experiment. Twenty healthy male subjects participated in the experiment, where discomforts for varying joint motions in the sitting and standing postures were measured using the magnitude estimation. The results showed that the perceived discomforts were affected by the type of joint motions, size of joint motions, and joints. The joints and joint motions were classified into several distinct classes according to perceived stresses. Three ranking systems based on the perceived discomforts were developed, including classification by the joint motions and joints, by types of joint motions, and by the joints only. The ranking systems revealed that while hip and back motions exhibited higher discomfort ratings than any other joint motion, elbow motions were the least stressful of all joint motions. The ranking systems can be used as a valuable design guideline when ergonomically designing or evaluating workplaces, or as a helpful tool for understanding adverse effects of poor working postures.

Keywords: Joint motion; Discomfort; Musculoskeletal disorders; Ranking systems

1. Introduction

Body discomfort is associated with biomechanical factors such as joint angles, muscle contractions, pressure distribution that produce feelings of pain, muscle soreness, numbness, or stiffness. Minimization of perceived discomfort by eliminating physical constraints can contribute to reduction of the risk for musculoskeletal disorders (Dul et al., 1994; Milner, 1985; Nag, 1991; Putz-Anderson and Galinsky, 1993; Zhang et al., 1996). The warning provided by body discomforts can be seen as an indicator of the mismatches between the person and the task, calling for job redesign (Corlett and Bishop, 1976).

Since Corlett and Bishop (1976) used a diagram of the body to identify the location of an individual's discomfort, discomfort has been largely assessed using the psychophysical methods such as body maps, discomfort scales or questionnaires. Assessment of postural load/discomfort in a given posture is an important step for preventing musculoskeletal disorders and improving work environment. Since the OWAS (Ovako Working Postures Analysing System) method proposed by Karhu et al. (1977), many postural classification schemes have been developed to enable quantitative evaluation of the postural stresses (Genaidy et al., 1994; Juul-Kristensen et al., 1997).

Only a few studies focused on ranking the stressfulness of joint motions, which can be used for understanding adverse effects of working postures on the workers, and as a cost function for predicting human postures. Genaidy and Karwowski (1993) provided a ranking system for the stressfulness of body deviations from neutral postures based on perceived discomfort in non-neutral postures. The ranking showed that hip abduction was the most stressful of all joint motions in the standing posture (rank of 5), hip flexion ranked fourth, and elbow supination, neck lateral bending and hip extension third, etc. Here, a higher rank indicates that the respective joint motion is more stressful.

*Corresponding author. Tel.: +82-53-580-5319; fax: +82-53-580-5165.
E-mail address: dhkee@kmu.ac.kr (D. Kee).

0003-6870/03/$ - see front matter
PII: S0003-6870(02)00141-2

However, the ranking system was confined to the joint motions reaching the limit of range of motions. Genaidy et al. (1995) developed two improved ranking systems for the static, non-neutral postures only, around the joints of the upper extremity and the spine, which were classified by the joint motions and joints, and by the joints. The ranking system by the joint motions and joints revealed that the stressfulness of non-neutral postures was ranked (from highest to lowest): (1) shoulder extension, severe elevation and adduction; (2) wrist severe extension, and elbow supination; (3) wrist severe flexion, shoulder light elevation, and lower back lateral bending, etc. In addition, another ranking by the joints showed that the shoulder scored higher discomfort ratings than other joints, followed by the wrist, elbow, lower back, and finally neck. Here, the same rank of 3 was assigned to the wrist, elbow and lower back. However, these systems were based on the subjective discomforts perceived in limited joint motions of the standing posture according to the existing micro-postural classification schemes, and dealt only with the upper extremities and the spine, not with the whole body.

To overcome these restrictions of the existing ranking systems, in this study, comprehensive ranking systems for evaluation of the stressfulness of varying joint motions in their full range of motion were developed. The rankings were based on perceived discomfort ratings for almost every joint motion in the sitting and standing postures. The ranking systems were classified by the joints and respective joint motions, the joint motions alone, and the joints alone.

2. Method

2.1. Subjects

Twenty male undergraduate and graduate students volunteered to participate in the experiment aimed to measure perceived body discomforts for varying postures. All subjects were reported to be in good health and were without history of any musculoskeletal disorders. Means and standard deviations of their physical characteristics were: (1) age—25.2 ± 2.6 years; (2) stature—172.1 ± 5.7 cm; and (3) body weight—66.8 ± 6.8 kg.

2.2. Rating method

Of several psychophysical scaling methods, the magnitude estimation method was adopted for measuring perceived discomforts for varying joint motions, because (1) it provides data with the characteristics of the ratio or interval scale which can be analyzed by quantitative statistical techniques (Gescheider, 1985); and (2) this study aims to quantify perceived discomforts for different joint motions which would be applied to some quantitative statistical analysis. The method requires an observer to make direct numerical estimations of the sensory magnitudes produced by various stimuli.

There are three basic methods for assessing the magnitude of a sensation to a given stimulus depending on whether or not a standard is given to the subject for comparison purposes: modulus method, free modulus method, and absolute judgment method (Gescheider, 1985; Han et al., 1998). In this study, the free modulus method of the magnitude estimation, in which the respondent is required to set his/her standard for comparison, was adopted, since a standard stimulus causes the potential biasing effects for the response, and it is better to permit the subjects to choose their own modulus rather than to designate one for them (Gescheider, 1985).

Of varying dependent measures in the magnitude estimation, this study employed the numeric estimate method, which makes the subjects assign numerical values to the intensity of given stimuli. In summary, the free modulus method of the magnitude estimation using the numeric estimates as dependent measure was used to obtain subjective discomfort ratings for varying joint motions.

2.3. Experimental procedures

The experiment consisted of four stages: (1) calibration test; (2) measurement of range of joint motions (ROM); (3) main experiment quantifying perceived discomforts at varying postures; and (4) numerical estimations for verbal categories. Prior to the experiment, the subjects were informed of the purpose and procedures of the experiment.

2.3.1. Calibration test

The calibration test was conducted in order to screen out those subjects who were unable to correctly perform the magnitude estimation. The subjects were asked to assign numerical values appropriate to ten randomly presented line length stimuli (i.e., straight lines) with the maximum to minimum ratio of 100:1. It was checked in the test if the relationship between logarithmically transformed response values and line length stimuli was linear, i.e., the regression coefficient between the two transformed variables was 1.0 ($\alpha = 0.05$), because the exponent of the power function relating subjective magnitude to line length stimuli is known to be 1.0 (Gescheider, 1985). All 20 subjects passed the test.

2.3.2. Measurement of range of motion

At the second stage, the ROM values of the joint motions (Table 1) were measured in the sitting and

Table 1
Joint motions measured in this study

Joint	Joint motion: Posture: Sitting	Standing
Wrist	Flexion Extension Radial deviation Ulnar deviation	Flexion Extension Radial deviation Ulnar deviation
Elbow	Flexion Supination Pronation	Flexion Supination Pronation
Shoulder	Flexion Extension Adduction Abduction Medial rotation Lateral rotation	Flexion Extension Adduction Abduction Medial rotation Lateral rotation
Neck	Flexion Extension Rotation Lateral bending	Flexion Extension Rotation Lateral bending
Lower back	Flexion Rotation Lateral bending	Flexion Extension Rotation Lateral bending
Hip	Flexion Abduction Internal rotation External rotation	Flexion Extension Adduction Abduction Internal rotation External rotation
Knee	Not measured	Flexion
Ankle	Flexion Extension Adduction Abduction	Flexion Extension Adduction Abduction

standing postures, which were used in determining levels of joint motions in the main experiment. The definitions of joint motions were adopted from the existing studies. Definitions for the wrist, elbow, neck, hip, knee and ankle motions were taken from Murrell (1969); those for the shoulder motions from Chaffin and Andersson (1991), and Kroemer et al. (1994); and those for the back movements from Hsiao and Keyserling (1991), and Kee (1996).

2.3.3. Main experiment

The joint motions used in the study are shown in Table 1, which included almost every possible joint motion occurring in the sitting and standing postures. In the seated position, a chair with backrest perpendicular to the seat pan and no armrest was used. In the standing posture, the subjects were asked to stand on the board with height of 20 cm.

The joint motions and their levels were selected as independent variables, and numeric value of perceived discomfort as dependent variable. The ROMs for each joint motion were equally divided into five levels for measurement of perceived discomforts: 0% (neutral), 25%, 50%, 75%, and 100%. Perceived discomfort ratings were measured at the five %ROM positions in each joint motion. For example, in the joint motion of shoulder flexion, discomforts were obtained at flexion of about 0°(0%ROM), 49°(25%ROM), 97°(50%ROM), 146°(75%ROM), and 194°(100%ROM).

In the experiment, the subjects were instructed to rate their perceived discomfort for a given posture using the numerical estimation and free modulus method of the magnitude estimation. In other words, the subjects were required to hold a given posture without an external load for 60 s according to the experimental design one at a time, and to assign a number to every posture so that their impression of the size of the number matches their impression of the intensity of perceived discomfort for a posture. A rest of 60 s was given following each experimental treatment. The subjects rated their perceived discomfort level for a given posture during the 60 s rest. The instruction adapted for the judgement of perceived discomforts from those used by Zwislocki and Goodman (1980) was presented with the subjects before experiment. No reference numbers and verbal anchors as in the traditional category scaling method were given to the subjects so that they could assign a subjective number to the intensity of perceived discomfort using their own scale. The experimental plan and data analysis procedures for the magnitude estimation are described in detail in the previous literatures (Gescheider, 1985; Han et al., 1998; Lodge, 1981).

Two hundreds and seventy-six treatments were tested in this study. All experimental treatments were randomly presented to each subject. The subjects attended eight consecutive sessions on eight separate days. Each experimental session was composed of 5 min warm-up using the bicycle ergometer (Aerometer, Lafayette Co., 1987), 10 practice trials and 35 experimental trials, which lasted about 80 min. In the warm-up, the subjects were asked to run the bicycle at their own paces for 5 min.

2.3.4. Numerical estimations for verbal categories

Finally, the numerical estimates for nine verbal categories were obtained from all subjects immediately after finishing the experiment for measuring perceived discomforts. The selected nine verbal categories are frequently used in the psychophysical method, which are as follows: "extremely poor," "very poor," "poor," "a little poor," "so–so," "a little good," "good," "very good," and "extremely good." The subjects were asked to make numerical estimations for the nine verbal categories using the same scale as in the main experiment measuring perceived discomforts.

2.4. Data transformation

Since the free modulus method of the magnitude estimation was used to obtain the subjects' perceived discomfort ratings, each subject utilized different reference values to represent the intensity of his own perceived discomfort ratings. Therefore, the raw data were normalized using the following transformation suggested by Hwang and Yoon (1981):

$$\text{Normalized discomfort}_{ijk} = \frac{\text{raw data}_{ijk} - \text{min discomfort}_k}{\text{max discomfort}_k - \text{min discomfort}_k} \times 100,$$

where i = ith level of motion; j = jth joint motion; k = kth subject; raw data_{ijk} = discomfort at the ith level of the jth joint motion in the kth subject; max discomfort_k = maximum discomfort in the kth subject; min discomfort_k = minimum discomfort in the kth subject; normalized discomfort_{ijk} = normalized discomfort at the ith level of the jth joint motion in the kth subject.

After normalizing, the averages of the transformed discomfort data for 20 subjects in each experimental treatment were calculated and used as relative discomforts in the following analysis.

Next, the relative discomfort index (RDI) was defined to compare perceived discomforts across the joint motions, which was obtained by dividing the sum of discomfort ratings for all levels of the movements in each joint motion by the total amount of traveled movements. This allowed to define the discomfort rating value for each degree of joint angle, i.e., a unit discomfort rating for a joint motion. The relative discomfort index was calculated as follows:

$$\begin{aligned}\text{RDI}_j &= \sum_{i=1}^{N} \text{relative discomfort}_{ij} / (0.25 + 0.50 + 0.75 + 1.0) \\ &\quad * \text{ROM}_j \\ &= \sum_{i=1}^{N} \text{relative discomfort}_{ij} / 2.5 * \text{ROM}_j,\end{aligned}$$

where i = ith level of motion; j = jth joint motion; N = number of levels of motion; relative discomfort_{ij} = average of normalized discomforts over 20 subjects at the ith level of the jth joint motion; ROM_j = range of motion of the jth joint motion.

3. Results

3.1. Normalized discomforts and RDIs

Averages of the normalized discomforts in each level of joint motions, and RDIs in each joint motion across 20 subjects for the sitting and standing postures are summarized in Tables 2 and 3, respectively. Perceived discomforts for all joint motions in both postures increased linearly or quadratically as the joints deviated away from neutral positions. Neutral position is the posture that any joint motion is not occurred, i.e., angle of any joint motion is 0°. Furthermore, there were drastic increments of discomforts when deviation from the neutral position in each joint motion exceeded 75% of the maximum range of motion. It was also found that RDIs were significantly different depending upon the joints and joint motions involved.

3.2. Numerical estimations for verbal categories

The numerical estimates of the nine verbal descriptors were also normalized using the same method as in the perceived discomforts for joint motions. Representative discomfort levels for the nine verbal categories were calculated by taking the average values of the normalized responses across 20 subjects (Table 4). Two extreme verbal descriptors, "extremely poor" and "extremely good," corresponded to the normalized discomfort values of 100.0 and 0.0, respectively. "So-so" was found to have the discomfort level of 34.6. The values quadratically increased as discomfort category moved from "extremely good" to "extremely poor."

3.3. Ranking of stressfulness by the joint motions and joints

Based on the results of Duncan's multiple range test (SAS GLM procedure) for the perceived discomfort data in each joint ($\alpha = 0.05$), a ranking for the stressfulness of joint motions relative to elbow motions was proposed (Table 5). The elbow motions including flexion, supination and pronation were grouped into a category, which showed the least discomfort of all joint motions. The motions were assigned the rank of 1. A joint motion with higher number indicates that it is more stressful. As shown in Table 5, there were no differences in the ranking between the sitting and standing postures except for hip flexion and abduction.

The rankings of the movements around the hip were higher than those of any other movement. Elbow, neck and knee motions were found to be less stressful than other joint movements. In the sitting posture, hip flexion and external rotation with the ranking of 8 had higher values of discomfort ratings than any other joint motion, followed by shoulder lateral rotation, lower

Table 2
Averages of normalized discomforts and RDI[a] in the sitting posture

Joint	Motion level	Flexion		Extension		Radial deviation		Ulnar deviation	
		Discomforts	RDI	Discomforts	RDI	Discomforts	RDI	Discomforts	RDI
Wrist	0%	8.83	0.59	8.83	0.71	8.83	1.48	8.83	0.86
	25%	13.68		15.15		12.55		16.36	
	50%	16.47		19.50		18.00		19.10	
	75%	23.67		27.72		27.44		25.76	
	100%	38.65		44.10		40.81		37.65	
Elbow		Flexion		Supination		Pronation			
	0%	2.38	0.22	9.00	0.33	9.00	0.47		
	25%	12.66		11.17		11.10			
	50%	15.27		16.01		16.69			
	75%	17.88		20.63		25.64			
	100%	31.64		40.20		39.84			
Shoulder		Flexion		Extension		Adduction		Abduction	
	0%	1.81	0.33	1.81	0.97	16.21	1.63	16.21	0.57
	25%	23.56		23.00		24.46		27.37	
	50%	34.41		34.08		30.59		35.57	
	75%	40.07		49.55		41.67		43.97	
	100%	59.17		65.85		66.73		66.24	
		Medial rotation		Lateral rotation					
	0%	20.96	0.58	20.87	2.44				
	25%	26.23		29.59					
	50%	28.64		38.62					
	75%	39.13		47.29					
	100%	53.26		58.76					
Neck		Flexion		Extension		Rotation		Lateral bending	
	0%	2.20	0.59	2.20	0.67	2.20	0.51	2.20	0.83
	25%	13.90		15.85		8.27		10.90	
	50%	18.93		32.28		14.80		17.29	
	75%	25.58		42.89		20.75		29.66	
	100%	40.41		64.32		46.34		53.47	
Lower back		Flexion		Rotation		Lateral bending			
	0%	2.56	0.68	2.56	0.81	2.56	2.24		
	25%	20.19		14.50		20.67			
	50%	31.98		26.46		45.13			
	75%	45.41		37.66		53.25			
	100%	59.62		59.06		69.10			
Hip		Flexion		Abduction		Internal rotation		External rotation	
	0%	2.34	2.29	2.34	1.27	2.34	1.99	2.34	2.83
	25%	47.41		38.76		38.22		36.28	
	50%	56.09		54.61		43.75		49.37	
	75%	66.78		66.52		55.51		65.34	
	100%	85.43		79.80		69.39		80.28	
Ankle		Flexion		Extension		Adduction		Abduction	
	0%	1.36	0.95	1.36	1.09	1.36	0.96	1.36	0.78
	25%	9.92		12.02		10.66		9.39	
	50%	14.83		17.63		14.07		13.18	
	75%	22.84		29.86		24.53		19.53	
	100%	36.80		40.38		40.49		36.59	

[a] RDI represents relative discomfort index.

Table 3
Averages of normalized discomforts and RDI[a] in the standing posture

Joint	Motion level	Flexion		Extension		Radial deviation		Ulnar deviation	
		Discomforts	RDI	Discomforts	RDI	Discomforts	RDI	Discomforts	RDI
Wrist	0%	8.96	0.53	8.96	0.66	8.96	1.26	8.96	0.81
	25%	12.40		14.93		11.58		14.44	
	50%	16.43		18.04		16.91		17.81	
	75%	21.45		21.42		22.39		22.67	
	100%	35.48		43.84		31.77		37.16	
Elbow		Flexion		Supination		Pronation			
	0%	5.81	0.23	10.21	0.32	10.21	0.41		
	25%	12.73		14.86		13.03			
	50%	16.71		16.51		14.33			
	75%	19.06		18.10		18.23			
	100%	30.82		35.87		33.77			
Shoulder		Flexion		Extension		Adduction		Abduction	
	0%	5.95	0.28	5.95	0.81	14.01	1.34	14.01	0.49
	25%	16.52		19.43		21.15		22.92	
	50%	23.67		26.22		26.83		30.03	
	75%	34.23		39.29		31.19		38.48	
	100%	54.97		55.60		54.38		55.98	
		Medial rotation		Lateral rotation					
	0%	14.37	0.44	14.37	1.74				
	25%	18.05		21.02					
	50%	21.75		25.02					
	75%	30.67		32.43					
	100%	42.33		46.07					
Neck		Flexion		Extension		Rotation		Lateral bending	
	0%	5.95	0.55	5.95	0.55	5.95	0.50	5.95	0.70
	25%	12.17		13.38		10.09		10.35	
	50%	17.51		23.78		13.58		14.07	
	75%	24.31		35.44		17.53		23.44	
	100%	35.69		51.45		43.30		42.92	
Lower back		Flexion		Extension		Rotation		Lateral bending	
	0%	5.95	0.59	5.95	2.59	5.95	0.52	5.95	1.97
	25%	22.08		29.09		14.41		22.80	
	50%	34.02		48.00		20.27		34.94	
	75%	43.44		64.98		29.27		51.02	
	100%	65.13		84.91		52.74		67.73	
Hip and knee		Flexion		Extension		Adduction		Abduction	
	0%	5.95	1.21	5.95	1.73	5.95	2.35	5.95	1.53
	25%	31.60		38.01		25.00		39.42	
	50%	47.62		44.29		31.69		56.56	
	75%	69.89		59.47		42.68		66.86	
	100%	87.34		72.76		59.34		83.43	
Hip and knee		Internal rotation		External rotation		Flexion (Knee)			
	0%	15.34	1.93	15.34	2.51	5.95	0.56		
	25%	44.86		50.10		27.17			
	50%	49.15		56.65		32.63			
	75%	56.16		70.76		41.04			
	100%	71.17		83.15		56.49			
Ankle		Flexion		Extension		Adduction		Abduction	
	0%	10.80	1.23	10.80	1.27	10.80	1.31	10.80	1.09
	25%	15.33		16.45		16.01		15.84	
	50%	18.73		21.95		22.10		19.92	
	75%	26.48		30.48		31.72		25.72	
	100%	39.45		38.12		44.26		39.29	

Note: the header row "Motion" spans the columns from Motion level onward.

[a] RDI represents relative discomfort index.

Table 4
Discomfort levels corresponding to verbal categories

Category	Discomfort level
Extremely poor	100.0
Very poor	79.9
Poor	63.5
A little poor	48.8
So–so	34.6
A little good	25.3
Good	15.2
Very good	7.1
Extremely good	0.0

back lateral bending, and hip internal rotation. In the standing position, lower back extension, hip adduction and external rotation scored higher discomfort ratings than other joint motions, followed by shoulder lateral rotation, lower back lateral bending, hip extension, abduction, and internal rotation.

The developed ranking differed from the ranking systems proposed by Genaidy and Karwowski (1993), and Genaidy et al. (1995), which pointed out that hip abduction in the standing posture had the highest rank of all joint motions, and shoulder extension, severe elevation and adduction were the most stressful, respectively.

3.4. Ranking of stressfulness by the joint motions

Using the same statistical analysis method as in the previous ($\alpha = 0.05$), another ranking system for evaluation of stressfulness by type of joint motions irrespective of the joints involved in the joint motions was also developed (Fig. 1). Although many of the joints have their own joint motions, all joint motions dealt with in this study were grouped depending upon the axis on which a joint motion pivots, and plane in which the motion occurs. The grouping resulted in ten types of joint motions: flexion, extension, radial deviation, ulnar deviation, supination, pronation, adduction, abduction, rotation, and lateral bending. Rotation included medial and lateral rotation in the shoulder, rotation in the neck and lower back, and internal and external rotation in the hip.

For developing this ranking system, the average values of RDIs over types of joint motions were used. Ten types of joint motions were divided into four groups depending upon the values of mean RDIs. The ranking was made relative to the average RDI level of elbow supination and pronation motions (i.e., the average RDI of the two joint motions was about 0.39), which were found to be the least of the ten types of joint motions considered in this study. The ranking revealed that the discomfort ratings by type of joint motions were ranked (from highest to lowest) as follows: (1) radial deviation, rotation, adduction, and lateral bending (rank of 4); (2) extension (rank of 3); (3) flexion, ulnar deviation, and abduction (rank of 2); and (4) supination, and pronation (rank of 1).

3.5. Ranking of stressfulness by the joints

In order to develop a ranking for the stressfulness of movements by the joints, the joint discomfort index (JDI) was defined as the average of RDIs over all joint motions around a given joint. Based on the same analysis method using JDIs for all the joints ($\alpha = 0.05$), two ranking systems relative to the JDI value of the elbow were provided for the sitting and standing postures, respectively. The results showed that rankings for the sitting and standing postures were almost identical except for the shoulder and ankle joints (Table 6). In the sitting posture, the hip joint was the most stressful, followed by the shoulder and lower back, wrist and ankle, neck, and then elbow. Like the sitting posture, in the standing posture the hip joint exhibited the largest discomfort, the lower back and ankle placed second, the wrist and shoulder were third, the neck and knee were fourth. The elbow joint had the smallest level of discomfort in both postures. The overall stressfulness for the body joints was ranked as follows: (1) hip; (2) lower back; (3) wrist, shoulder, and ankle; (4) neck, and knee; and (5) elbow.

This is not in agreement with the ranking reported by Genaidy et al. (1995), which showed that the shoulder was more stressful than other joints, while neck had the lowest discomfort rating among the joints of the upper extremity and spine. In this study, the hip had the highest rank, while the shoulder ranked third.

4. Discussion and conclusions

Three ranking systems for the stressfulness of the joint motions and joints were proposed, which were based on perceived discomfort ratings obtained using the magnitude estimation method. The results showed that discomfort levels were significantly affected by the types of joint motions, size of joint motions, and joints. On the basis of the discomfort levels for varying joint motions, several distinct classes of the joint motions and joints were assigned different ranks of postural stress with the characteristics of the ratio scales. Unlike the existing ranking systems reflecting just the size of discomfort rating values, the developed rankings were based on RDIs, i.e., unit discomfort ratings for each joint angle where the total amount of traveled movements in each joint motion was considered. The ranks in each ranking system can be directly compared with each other in terms of the size of perceived discomfort, because they are the ratio scale that can be applied to four arithmetic rules such as addition, subtraction, multiplication, and

Table 5
Comparison of ranking systems for stressfulness of the joint motions

Ranking joint	Present study			Genaidy and Karwowski			Genaidy et al.	
		Ranking			Ranking			
	Joint motion	Sitting	Standing	Joint motion	Sitting	Standing	Joint motion	Standing
Wrist	Flexion	2	2	Flexion	1	1	Neutral	1
	Extension	2	2	Extenion	1	1	Moderate flexion	2
	Radial deviation	4	4	Abduction	1	1	Radial flexion	2
	Ulnar deviation	3	3	Adduction	1	1	Ulnar deviation	2
							Moderate extension	3
							Severe flexion	5
							Severe extension	6
Elbow	Flexion	1	1	Flexion	1	1	Neutral	1
	Supination	1	1	Extension	1	1	Flexion	3
	Pronation	1	1	Pronation	2	2	Extension	3
				Supination	3	3	Pronation	3
							Supination	6
Shoulder	Flexion	2	2	Flexion	1	1	Neutral	1
	Extension	3	3	Extension	2	1	Extension	7
	Adduction	4	4	Adduction	1	1	Light elevation	5
	Abduction	1	1	Abduction	1	1	Severe elevation	7
	Medial rotation	2	2				Adduction	7
	Lateral rotation	6	6					
Neck	Flexion	2	2	Flexion	1	1	Neutral	1
	Extension	2	2	Extension	2	2	Flexion	2
	Rotation	2	2	Rotation	2	2	Extension	2
	Lateral bending	2	2	Lateral bending	3	3	Rotation	2
							Lateral bending	3
Lower back	Flexion	2	2	Flexion	1	1	neutral	1
	Extension	NA	8	Extension	NA	3	flexion	3
	Rotation	2	2	Rotation	2	2	Extension	3
	Lateral bending	6	6	Lateral bending	2	2	Rotation	2
							Lateral bending	5
Hip	Flexion	8	4	Flexion	NA	4	NA	
	Extension	NA	5	Extension	NA	3		
	adduction	NA	8	Adduction	NA	2		
	Abduction	4	5	Abduction	NA	5		
	Internal rotation	5	5	Medial rotation	NA	1		
	External rotation	8	8	Lateral rotation	NA	1		
Knee	Flexion	NA	2	NA	NA		NA	
Ankle	Flexion	3	3	Flexion	2	2	NA	
	Plantar flexion	3	3	Extension	1	1		
	Adduction	3	3					
	Abduction	3	3					

NA: not available.

division. For example, the hip flexion of the sitting posture with the rank of 8 has 8 times the perceived discomfort of the elbow flexion with the lowest rank of 1.

The numerical values for the nine verbal descriptors (Table 4) were provided to associate the magnitude estimates of discomfort levels for joint motions (Tables 2 and 3), which were measured through the experiment, with easily understandable verbal categories. Hence, the values make it easy to interpret the numerical discomfort ratings in terms of plain words, that is, they help relate the magnitude continua to verbal descriptors frequently used in the traditional scaling technique.

The ranking of the seated position by the joint motions and joints was nearly identical with that of the standing posture. However, hip flexion in the seated position was found to be much more stressful than that in the standing position. It may be thought due to the increased stomach discomfort, because the stomach is

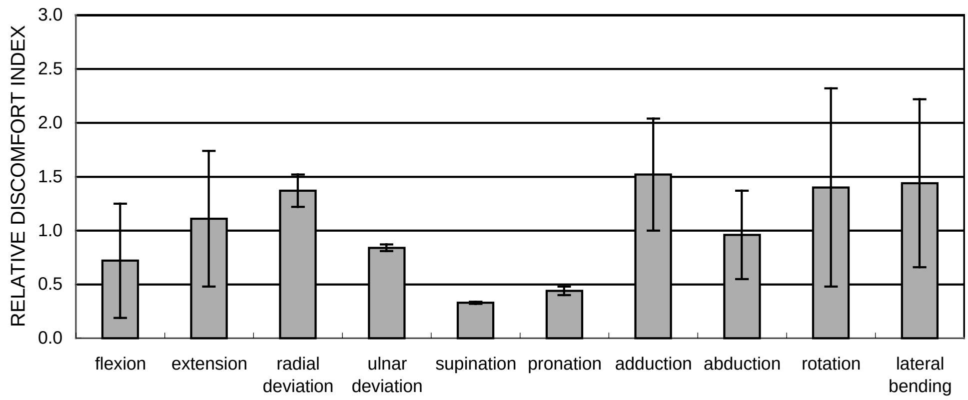

Fig. 1. Mean perceived discomfort index by the joint motions.

Table 6
Rank of stressfulness by the joints

Joint	Overall	Present study				Genaidy et al. (1995)	
		Joint	Sitting	Standing	Standing	Joint	Standing
Elbow	1	Elbow	1	Elbow	1	Neck	2
Neck	2	Neck	2	Neck	2	Wrist	3
Knee	2	Wrist	3	Knee	2	Elbow	3
Wrist	3	Ankle	3	Wrist	3	Lower back	3
Shoulder	3	Shoulder	4	Shoulder	3	Shoulder	7
Ankle	3	Lower back	4	Ankle	4		
Lower back	4	Hip	6	Lower back	4		
Hip	6			Hip	6		

compressed when the hip is flexed in the sitting posture. Due to sustaining the whole leg and foot, hip abduction has a little higher rank in the standing than in the sitting.

The rankings reported in this study differed from those reported by Genaidy and Karwowski (1993), and Genaidy et al. (1995). These differences may be partly because of different definitions and measurement methods for the joint motions, data gathering method, and statistical analysis method. It should also be noted that Genaidy and Karwowski (1993) developed their ranking systems based on the discomfort ratings of joint motions only at the limit of range of motion, instead of a full range of motion as in this study. Second, Genaidy et al. (1995) calculated the joint discomfort rating index (JDRI) for non-neutral postures relative to neutral postures around the joints. However, this study showed that the discomfort ratings for neutral postures were different depending upon the joints involved. Therefore, the ranking by the joints based on the JDRI values might be inadequate. Furthermore, the amount of traveled motions in each joint motion was not considered when the ranking or JDRI was obtained and/or calculated in the previous studies (Genaidy et al., 1995). Based on the results of this study, it is recommended to use the unit discomfort rating values for developing more accurate ranking systems on the basis of the size of ROMs of the specific joint motions.

It is expected that these ranking systems may be used as a valuable tool when safely designing/redesigning the working postures in industry, or properly evaluating the stressfulness of the postures. For example, practitioners of health and safety in industrial sites can safely design/redesign the working postures for workers to enable to take the joint motions with lower ranks/stresses with reference to the ranking systems developed, because it is already known that minimization of discomfort can reduce the risk of musculoskeletal disorders (Dul et al., 1994; Milner, 1985; Nag, 1991; Putz-Anderson and Galinsky, 1993; Zhang et al., 1996). Using the rankings after observing working postures in industrial sites, posture-related stresses can also be roughly evaluated by adding corresponding ranks for each observed joint motions without any published postural classification scheme. Genaidy and Karwowski (1993), and Genaidy et al. (1995) suggested that the ranking systems be needed to better understand potentially adverse effects of poor working postures on the health and well-being of the industrial population. In addition, the developed ranking systems can be used as a cost function to accurately predict the human postures, since it is generally hypothesized that human body control utilizes a cost function attached to each joint, which defines a cost value (i.e., discomfort value) for each joint angle, and a posture configuration is chosen based on the minimum total cost (Cruse et al., 1990; Jung et al., 1994).

References

Chaffin, D.B., Andersson, G.B.J., 1991. Occupational Biomechanics, 2nd Edition. Wiley, New York.

Corlett, E.N., Bishop, R.P., 1976. A technique for assessing postural discomfort. Ergonomics 19, 175–182.

Cruse, H., Wischmeyer, E., Bruwer, M., Brockfeld, P., Dress, A., 1990. On the cost functions for the control of the human arm movement. Biol. Cybernet. 62, 519–528.

Dul, J., Douwes, M., Smitt, P., 1994. Ergonomics guidelines for the prevention of discomfort of static postures can be based on endurance data. Ergonomics 37, 807–815.

Genaidy, A.M., Al-Shedi, A.A., Karwowski, W., 1994. Postural stress analysis in industry. Appl. Ergon. 25, 77–87.

Genaidy, A.M., Barkawi, H., Christensen, D., 1995. Ranking of static non-neutral postures around the joints of the upper extremity and the spine. Ergonomics 38, 1851–1858.

Genaidy, A.M., Karwowski, W., 1993. The effects of neutral posture deviation on perceived joint discomfort ratings in sitting and standing postures. Ergonomics 36, 785–792.

Gescheider, G.A., 1985. Psychophysics: Method, Theory, and Application, 2nd Edition. Lawrence Erlbaum Associates, London.

Han, S.H., Jung, E.S., Jung, M., Kwahk, J., Park, S., 1998. Psychophysical methods and passenger preferences of interior designs. Appl. Ergon. 29, 499–506.

Hsiao, H., Keyserling, W.M., 1991. Evaluating posture behavior during seated tasks. Int. J. Ind. Ergon. 8, 313–334.

Hwang, C.L., Yoon, K., 1981. Multiple Attribute Decision Making: Method and Application. Spring, New York.

Jung, E.S., Choe, J., Kim, S.H., 1994. Psychophysical cost function of joint movement for arm reach posture prediction. In: Proceedings of the Human Factors Society 36th Annual Meeting, Nashville, TN, 24–28 October, pp. 636–640.

Juul-Kristensen, B., Fallentin, N., Ekdahl, C., 1997. Criteria for classification of posture in repetitive work by observation methods: a review. Int. J. Ind. Ergon. 19, 397–411.

Karhu, O., Kansi, P., Kuorinka, I., 1977. Correcting working postures in industry: a practical method for analysis. Appl. Ergon. 8, 199–201.

Kee, D., 1996. Measurement on range of two degrees of freedom motion for analytic generation of workspace. J. Ergon. Soc. Korea 15, 15–24.

Kroemer, K., Kroemer, H., Kroemer-Elbert, K., 1994. Ergonomics: How to Design for Ease & Efficiency. Prentice-Hall, Englewood Cliffs, NJ.

Lodge, M., 1981. Magnitude Scaling: quantitative Measurement of Opinions. Sage Publications, London.

Milner, N., 1985. Modeling fatigue and recovery in static postural exercise. Ph.D. Thesis, University of Nottingham, Nottingham.

Murrell, K., 1969. Ergonomics. Chapman&Hall, London.

Nag, P.K., 1991. Endurance limits in different models of load holding. Appl. Ergon. 22, 185–188.

Putz-Anderson, V., Galinsky, T.L., 1993. Psychophysically determined work durations for limiting shoulder girdle fatigue from elevated manual work. Int. J. Ind. Ergon. 11, 19–28.

Zhang, L., Helander, M.G., Drury, C.G., 1996. Identifying factors of comfort and discomfort in sitting. Human Factors 38, 377–389.

Zwislocki, J.J., Goodman, D.A., 1980. Absolute scaling and sensory magnitude: a validation. Percept. Psychophys. 28, 28–38.