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The boundaries for joint angles of isocomfort for sitting and standing males based on perceived comfort of static joint postures

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This study presents data for the joint angles of isocomfort (JAI) in sitting and standing males based on perceived comfort ratings for static joint postures maintained for 60 s. The JAI value was defined as a boundary indicating joint deviation (an angle) from neutral posture, within which the perceived comfort for different body joint postures is expected to be the same. An experiment for quantifying perceived comfort ratings was conducted using the free modulus method of magnitude estimation. Based on experimental results, regression equations were derived for each joint posture, to represent the relationships between different levels of joint deviation/joint posture and corresponding normalized comfort scores. The JAI values were developed for nine verbal categories of joint comfort. The JAIs with the *marginal* comfort levels, one of the nine verbal categories used, for most joint postures around the wrist, elbow, neck and ankle were similar to the maximum range of motion (ROM) values for these joints. However, the JAIs with the *marginal* comfort category for back and hip postures were much smaller than the maximum ROM values for these joints. There were no significant differences in JAI expressed in terms of the percentage of the corresponding maximum ROM values between sitting and standing postures. The relative 'marginal comfort index', defined as the percentage of JAIs for the *marginal* comfort relative to the corresponding maximum ROM values, for the hip was the smallest among all joints. This was followed, in an increasing order of the marginal comfort index, by the lower back and shoulder, while the marginal comfort index for the elbow joint was the largest. The results of this study suggest that static postures maintained for 60 s cause greater discomfort for the hip joint than for the other joints studied, and less discomfort for the elbow than for the other joints. The data about JAIs can be used as guidelines for enhancing postural comfort when designing a variety of human-machine tasks where static postures cannot be eliminated.

1. Introduction

1.1. *Background*

Anthropometric data including static and dynamic dimensions play an important role in workplace design. Of the two dimensions, dynamic data are considered to be

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more important than static ones, because the design of many work situations should take into account the interaction between different body segments (Sanders and McCormick 1993). For example, NASA published around 1000 anthropometric measurements from 91 worldwide surveys, most of which are static dimensions (Webb Associates 1978). A few dynamic dimensions such as range of motion (ROM) and grasping reach were also published.

Daily exposure to constrained body postures and deviations from the neutral postures over a long period may result in discomfort as well as pains and aches in the muscles, joints, tendons and other soft tissues (Grandjean and Hunting 1977, Corlett *et al.* 1979, Corlett and Manenica 1980). Minimization of perceived discomfort by eliminating physical constraints can contribute to reduction of the risk for muculoskeletal disorders (Dul *et al.* 1994, Miedema *et al.* 1997). Musculoskeletal injuries are attributable to many factors including application of high forces (Silverstein *et al*. 1986, 1987, Moore *et al.* 1991), large moments of force (Marras *et al.* 1993), and jobs that require heavy lifting (Kelsey *et al.* 1984).

Awkward, extreme and repetitive body postures have also been associated with musculoskeletal disorders in industry (Kilbom *et al.* 1986, Punnett and Keyserling 1987, Silverstein *et al.* 1987, Aaras *et al.* 1988, Keyserling *et al.* 1988, Ryan 1989, Burdorf *et al.* 1991, Moore *et al.* 1991, Punnett *et al.* 1991). Body joint angles of comfort can be used as guidelines for designing workplaces to enable workers to maintain comfortable postures during their work. However, up to now, only a few studies have been done on the comfortable range of joint postures.

Diffrient *et al.* (1985) proposed angles of comfort for vehicular seating in the *Human Scale*. These were defined as the ranges of joint angles without inducing fatigue, and, generally, lay close to the midpoint of total joint travel. Such angles were based on data from various sources determined by experimental testing and experience. Hsiao and Keyserling (1991) reviewed the related literature and classified ranges of body joint motions into three categories, depending upon joint discomfort levels:

(1) the neutral range, defined as the range of motion that presents minimal discomfort to the joint and adjacent body segments;
(2) the effort range, defined as the range of motion that can be achieved with mild discomfort to the joint and adjacent body segments; and
(3) the maximum range defined as the maximum limit of a joint's range of motion.

However, the above study was confined to only a few representative joint postures of the trunk and upper body frequently found in daily activities. Furthermore, the proposed classification of joint motion ranges was not based on experimental data, but rather on the experts' experience or knowledge.

Genaidy and Karwowski (1993) and Genaidy *et al.* (1995) provided ranking systems for the stressfulness of body deviations from neutral postures based on perceived discomfort in non-neutral postures, which showed that discomfort levels varied depending upon movements around the joints. The category scaling method with a 0–10-point scale was used to assess the degree of joint discomfort in these studies. It should be noted that (visual) discomfort scales for assessment of joint postures have been used successfully by others (Snook *et al.* 1995, Lin *et al.* 1997).

For example, Lin and Radwin (1998) demonstrated that their method for subjective ratings of discomfort for the wrist joint was relatively reliable.

1.2. *Objectives*

The present study aimed to define the joint angles of isocomfort (JAI) in sitting and standing postures under static conditions and limited exposure time. The JAI values were defined as the angles within which the perceived joint comforts were expected to be the same. The JAI values were derived using perceived joint comfort levels measured with the free modulus method of magnitude estimation. The concept of 'comfort' was adopted instead of 'discomfort', unlike previous studies, since comfort and discomfort need to be treated as different and complementary entities in ergonomic investigations (Zhang *et al.* 1996).

2. Methods

2.1. *Subjects*

Fifteen male subjects with no history of musculoskeletal disorders voluntarily participated in the experiment. Means and standard deviations of their physical characteristics were as follows. Age: 24.3 ± 3.4 years; stature: 173.2 ± 7.6 cm; and body weight: 68.2 ± 5.8 kg.

2.2. *Rating method*

A variety of psychophysical scaling methods have been developed and used to find the relationship between human sensation and physical stimuli. According to Gescheider (1988), these are classified into three types: (1) ordinal discrimination judgements of stimuli; (2) partition of sensory continuum into equal intervals; and (3) expression of perceived magnitudes of stimuli (i.e. magnitude estimation). Although the traditional category scaling methods (such as the first two types) have been widely used in the past (Genaidy and Karwowski 1993, Genaidy *et al.* 1995, Cameron 1996), they are easy to administer and they provide the frequency distribution of subjective feelings, but they have a number of serious weaknesses (Lodge 1981). First, some information can be lost due to limited resolution of the categories. For this, categorical judgement may be thought of as a qualitative rather than as a quantitative measure. Second, category scales represent only an ordinal level of measurement, thereby denying researchers legitimate access to many of the powerful statistical methods based on interval assumptions that are available for the description, prediction and modelling of relationships. Finally, by offering a fixed number of categories, the researcher is inadvertently affecting the response.

Owing to the above problems, the third type known as the magnitude estimation method has been used to evaluate human sensation to varying stimuli including physical stimuli, the social and behavioural sciences area, and the ergonomics area. In contrast to the traditional category scaling methods, the magnitude estimation method that requires an observer to make direct numerical estimations of the sensory magnitudes produced by various stimuli provides data with the characteristics of the interval or ratio scale that can be analysed by quantitative statistical techniques (Gescheider 1985).

This study aimed to quantify perceived comforts for different joint postures, which would be subject to various quantitative statistical analyses. Furthermore, since magnitude scales are almost invariably found to be superior in providing quantitative information about the intensity of people's judgements, the magnitude estimation method was employed in this study for data collection purposes. It has been experimentally proven that, given the simple instruction to match numbers to the strength of one's impressions, the average person can make proportional judgements about the intensity of most sensory continua. Only an average of 3–6% of the subjects usually fail to properly assess their sensation for some physical or psychophysical reasons (Lodge 1981).

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:

(1) a modulus method, in which the respondent is presented with an arbitrary standard stimulus for comparison, and told that the sensation it produces has a certain numerical value (modulus), such as 10. On subsequent trials, the respondent is instructed to make his/her judgements reflect how many times greater one sensation is than the value of the modulus (the ratio between the two sensations),
(2) a free modulus method, in which the respondent is required to set his/her own standard for comparison without any experimenter-defined modulus, and asked to assign numbers to his/her sensations in proportion to his/her own standard; and
(3) an absolute judgement method, in which the respondent is required to make an absolute judgement without any standard (Gescheider 1985, Han *et al.* 1998).

It should be noted that often the subject is not able to make an appropriate ratio judgement when the intensity of the stimulus is far from the standard one in the modulus method of magnitude estimation (Zwislocki and Goodman 1980), and a standard stimulus causes potential biasing effects for the response (Gescheider 1985). In addition, it is better to permit the subjects to choose their own modulus rather than to designate one for them (Gescheider 1985). It is also known that almost every observer, including children aged 4 and 5 years is readily able to establish his or her own modulus (Gescheider 1985).

Therefore, in this study, the free modulus method was adopted for assessing the intensity of stimuli, in which the subjects used their own standards without any modulus for comparison. No reference numbers or verbal anchors were given to the subjects so that they could assign a subjective number to the intensity of perceived comfort using their own scale.

A variety of dependent measures can be used in magnitude estimation experiments (Han *et al.* 1999). For example, the experimenter can make the subject express his/her perceived intensity by adjusting the loudness of sound (Zwislocki and Goodman 1980), brightness of light (Stevens 1959), vibration frequency (Stevens 1959), numeric estimates (Lodge 1981, Verrillo 1983), or the length of a line (Lodge 1981, Verrillo 1983). Of these, the numeric estimates and the line length estimates are popularly used because they are easy to administer and no special devices other than paper and pencil are required. The numeric estimate method makes the subject assign numerical values to the intensity of the given stimuli. The line length estimate method requires the subject to draw a line with an appropriate length depending upon the intensity of the stimulus. Of these two alternatives, the numeric estimate method was employed in this study.

In summary, the free modulus method of magnitude estimation, using numeric estimates as the dependent measure, was adopted to obtain subjective comfort levels for varying joint postures in this study. The subjects who participated were asked to rate numerically the intensity of joint postures' comfort with their own ratio scales without any type of anchor/standard.

2.3. *Experimental procedures*

Prior to the experiment, the subjects were informed of the purpose and procedures through a 30-min training session. Measurements of anthropometric dimensions including body stature and weight were made. The entire experiment was conducted in the laboratory with good ventilation and light, and the temperature was kept at around 20°C. The experiment consisted of four stages: (1) administering a calibration test; (2) measuring ranges of joint motions; (3) quantifying perceived joint comforts at varying postures; and (4) obtaining numerical estimations for verbal categories of joint comfort.

2.3.1. *Calibration test*: Since it is known that some subjects are not able to properly perform the magnitude estimation, a calibration test is used to screen out those subjects before conducting the magnitude estimation (Han *et al.* 1999). In addition, the test is used to make the subjects familiar with the ratio judgement tasks of magnitude estimation.

In the present study, the test required of subjects was to assign numerical values to randomly presented line length stimuli. During the test, a set of ten lines with the minimum to maximum ratio of about 1 : 100 were randomly presented to the subjects. This allowed verification that the relationship between the logarithmically transformed response values and line length stimuli was linear, i.e. that the regression coefficient between the two transformed values was 1.0 ($\alpha = 0.05$). It is known that the theoretical exponent for the power function relating subjective numeric magnitude to line length stimulus intensity is 1.0 (Stevens 1957). The slope of the regression equation should not differ statistically from the theoretical value with a 95% confidence interval (Han *et al.* 1999). All 15 subjects selected for this study passed the above test.

2.3.2. *Range of motion*: For the subjects who passed the calibration test, the maximum range of motion (ROM) values for all joints listed in table 1 were measured with a manual goniometer (Jarmar, Jackson, MI, USA). The definitions of joint postures were adopted from previous studies. Definitions for wrist, elbow, neck, knee and ankle postures were taken from Murrell (1969), those for shoulder postures from Chaffin and Andersson (1991), Hsiao and Keyserling (1991) and Kroemer *et al.* (1994), and those for back postures from Hsiao and Keyserling (1991) and Kee (1996). The joint postures employed are shown in figure 1.

Before measuring ranges of joint motion, subjects were asked to participate in a warm-up exercise for five or more minutes using an ergometer (Aerometer, Lafayette, Instrument, Layfayette, IN, USA) to enhance mobility of their body joints. The landmarks representing points of measurement were attached to estimated centres of the subjects' body joints (figure 2). The range of joint motion was measured for all the joints shown in table 1. The reference arms were aligned with the long axes of adjoining body segments, with the centre of the goniometer on the attached mark of the corresponding joint. When measuring range of joint

Table 1. Joint postures measured in the study.

Joint	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	Dorsi flexion Plantar Adduction Abduction	Dorsi flexion Plantar flexion Adduction Abduction

motion, the subjects were asked to place all joints except the measured one in their neutral positions, and to voluntarily move through the entire range of motion toward the prescribed directions (figure 2).

Neutral position was defined as the posture where no joint motion was present, i.e. the angle of joint motion was 0°. Measurements were conducted on a special purpose board with a height of 20 cm. This allowed, for example, the measurement of the ankle plantar flexion. The seat, with adjustable height and without arm-rests, was used when measuring range of joint motion in seated positions (figure 2). The seat height was adjusted for the subjects to allow them to adopt a sitting posture with knee flexion of 90° and with the feet placed on the floor. The range of motion was measured and recorded when the subject notified the experimenter that he had reached the maximum position for a given joint motion. It was assumed that the

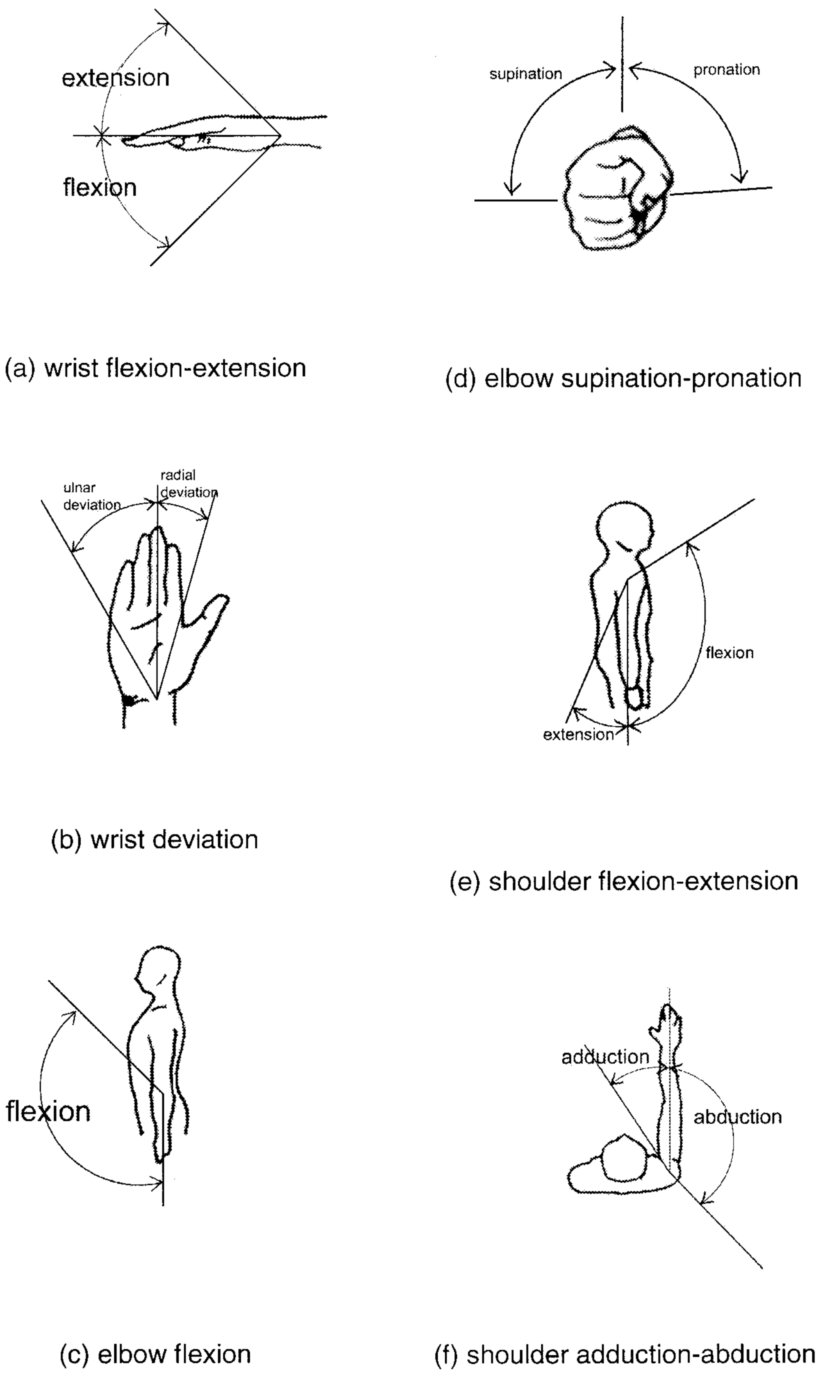


Figure 1. Joint postures measured in the study.

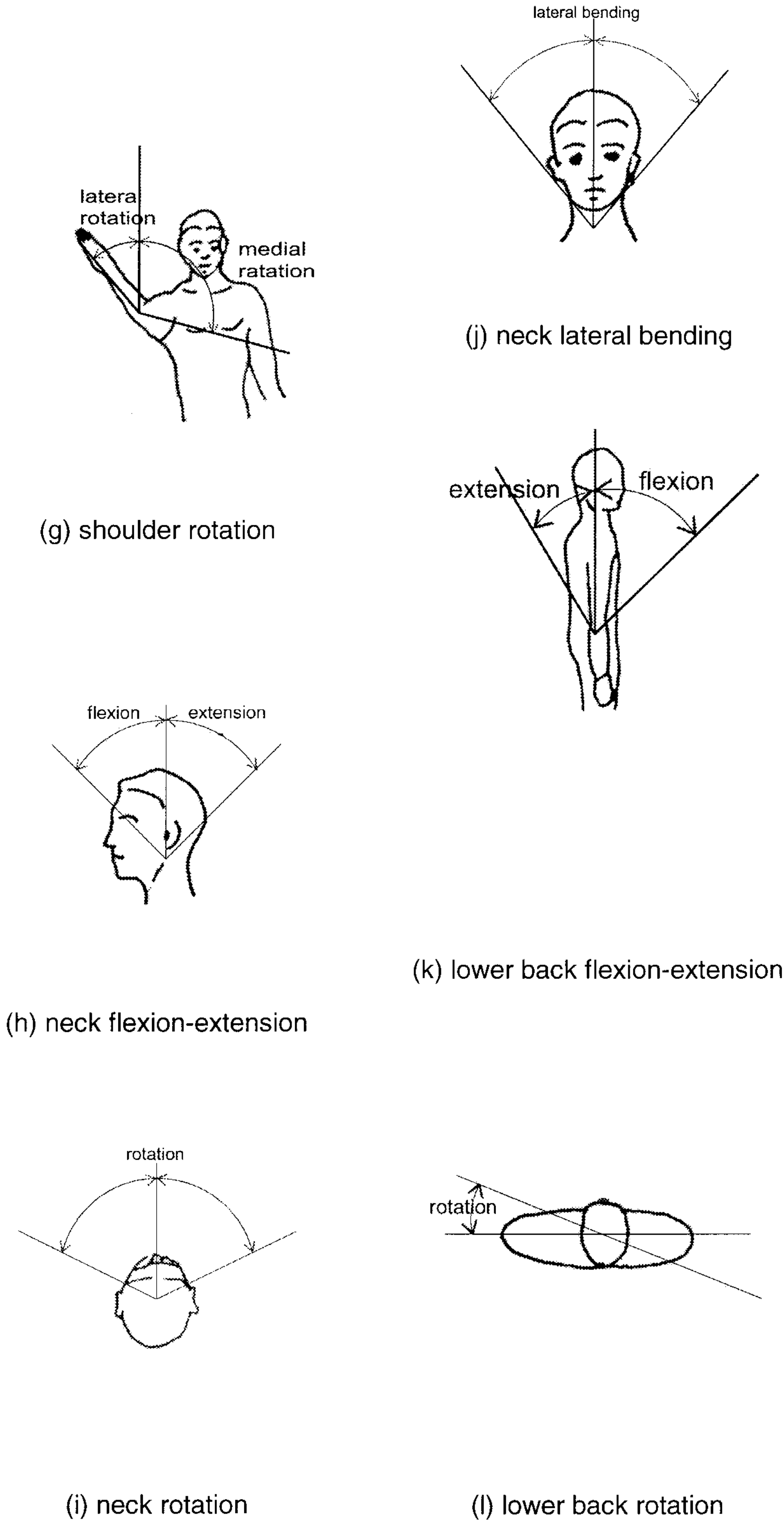


Figure 1. Joint postures measured in the study (continued).

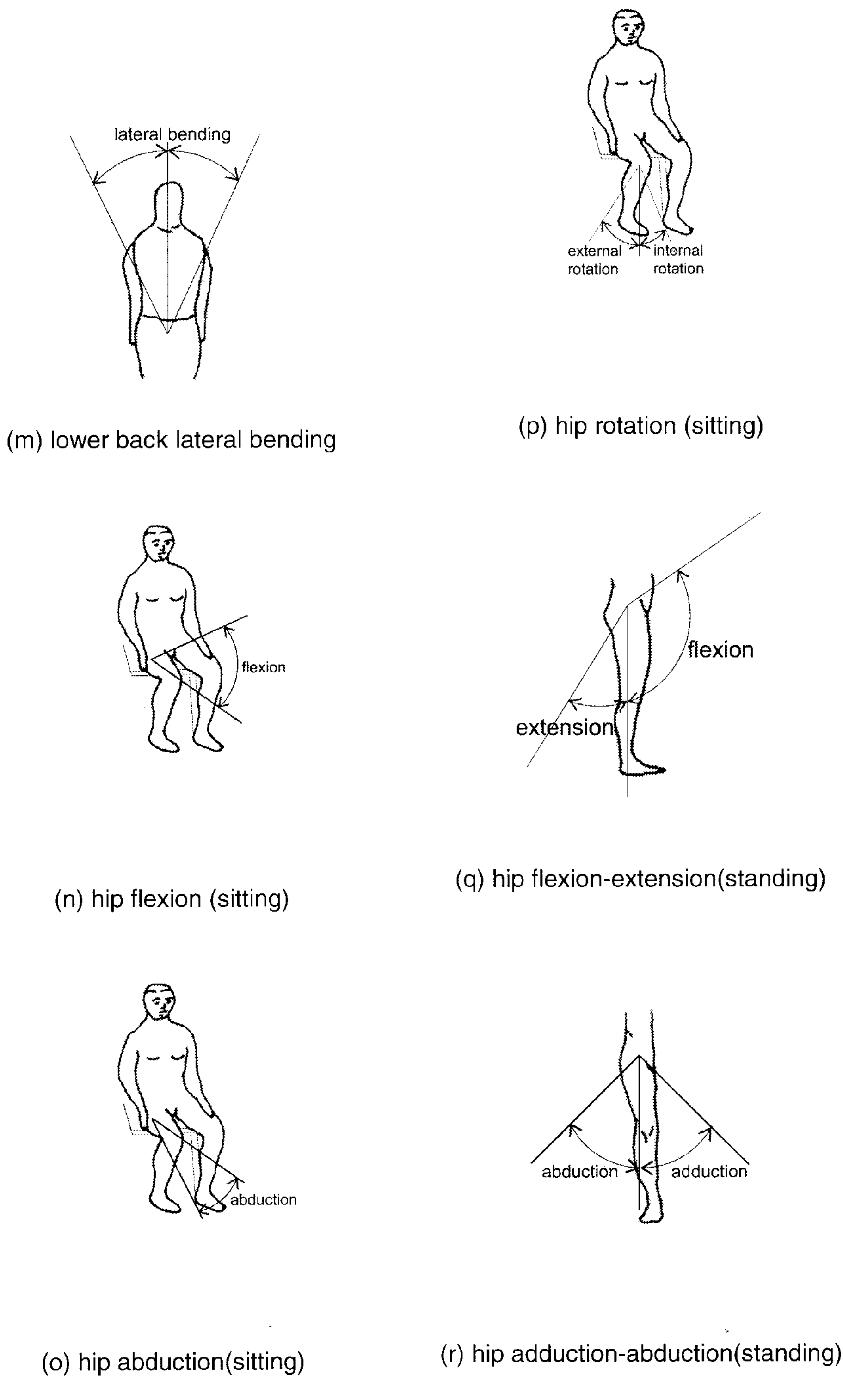
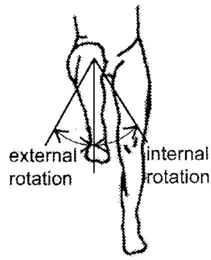
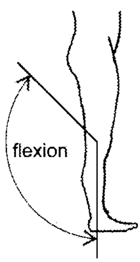


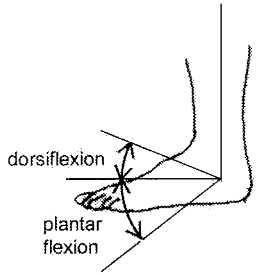
Figure 1. Joint postures measured in the study (continued).



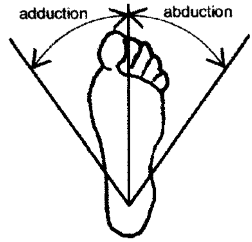
(s) hip rotation(standing)



(t) knee flexion

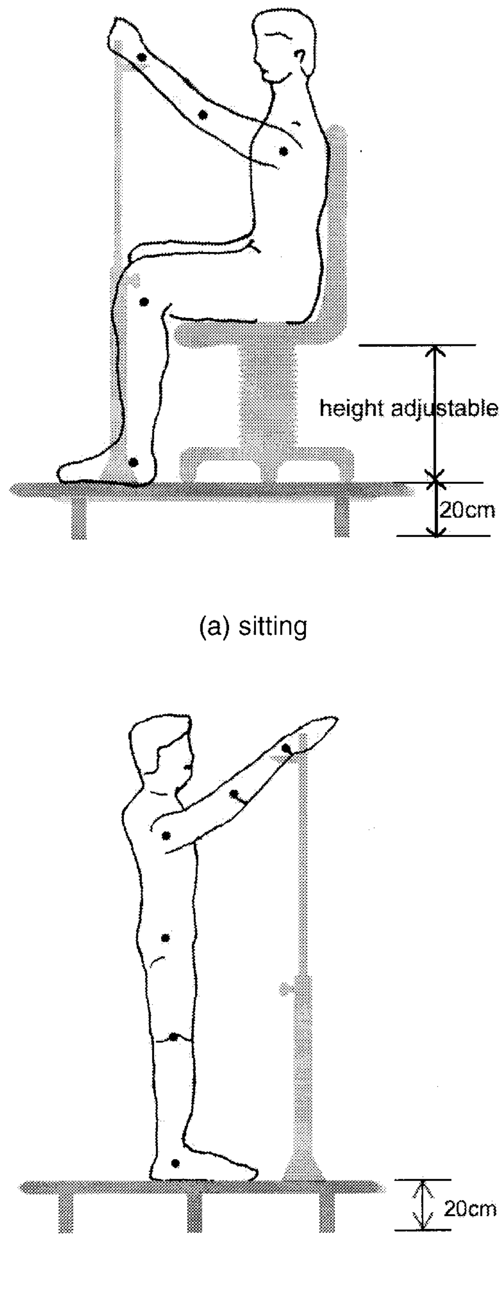


(u) ankle flexion



(v) ankle adduction-abduction

Figure 1. Joint postures measured in the study (continued).



(b) standing

Figure 2. Experimental standing scenes in sitting and standing postures.

virtual hip joint was located at the L5/S1 intervertebral level, as proposed in the study by Hsiao and Keyserling (1991).

2.3.3. *Main experiment*: In the main experiment, subjects were instructed to rate the perceived comfort level for a given posture (defined by the joint deviation) with a ratio scale. The subjects were required to adopt specific postures according to experimental treatment with the aid and instruction of the experimenter. The goniometer and pointers of iron bars were used to ensure that the subjects assumed the posture designated according to the experimental treatments (figure 2). As mentioned above, the free modulus method of magnitude estimation that uses numerical estimates as the dependent variable was adopted to quantify the joint comfort levels at varying postures. The instructions for the subjects, originally proposed by Stevens (1975), were adapted as follows:

> In this experiment we would like to determine the comfort of various joint postures. For this purpose, you will be presented with a series of joint postures in a random order. Your task will be to tell us how comfortable they seem to you by assigning numbers to them. Assign the first joint posture any number that seems appropriate to you. Then assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers that you may use. You may use whole numbers, decimals, or fractions. Try to make each number match the intensity as you perceive it.

The joints and joint postures included in the study are shown in table 1. The ROM value for each joint posture was equally divided into five levels for the purpose of measuring the perceived comfort: 0% (neutral), 25%, 50%, 75% and 100%. Each subject was asked to hold the given posture for 60 s. The rest of the joints were in the neutral positions while the joint under study was deviated.

The posture holding time of 60 s was adopted based on the following two facts: (1) it was used for evaluating joint motion discomforts in a previous study (Genaidy *et al.* 1995); and (2) Grandjean (1988) reported that if a high force is exerted, static muscle actions should be less than 10 s, for a moderate force less that 1 min, and for a low force less than 4 min. On the basis of this finding, the posture score in RULA (McAtamney and Corlett 1993) is increased by 1 if the posture is mainly static, that is, held for longer than 60 s.

The overall sitting and standing postures were the same as those used for measuring joint ROMs. A rest of 60 s was given following each measurement. The subjects rated their perceived comfort level for the given posture during the 60 s rest period. 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 a 5 min warm-up using an ergometer followed by 10 practice trials and 35 experimental trials, lasted for about 110–120 min. During the warm-up period, subjects were asked to ride a stationary bicycle at their own pace for 5 min.

If the neutral postures, i.e. 0% ROM postures of several joint postures for a joint were the same, only one neutral joint posture was included in the experiment. For example, there are four joint postures in the wrist, including flexion, extension, radial deviation and ulnar deviation, but the neutral postures of the four joint postures are all the same. Then, the perceived comfort level in the neutral posture of wrist flexion was measured and used as the comfort values for the three unmeasured neutral joint postures. The practice trials were performed to make the subjects familiar with the experimental task and environment before each experimental session. The subjects were asked to rate perceived comforts for ten joint postures randomly selected among joint postures performed in the past sessions.

2.3.4. *Numerical estimations for verbal categories*: In order to develop the JAI boundaries according to a verbal scale of perceived comfort, instead of the continuous numerical comfort values for joint postures, the numerical estimates for nine verbal categories were obtained from all subjects. The estimates for nine verbal categories were needed to associate the numerical comfort levels for joint postures measured in the main experiment with the plain words of verbal categories frequently used in the psychophysics (Han *et al.* 1998). This was done immediately after the main experiment measuring perceived comfort levels.

The following verbal categories of joint comfort were used: *extremely poor*, *very poor*, *somewhat poor*, *marginal*, *moderate*, *good*, *very good*, and *extremely good.* The subjects were required to make numerical estimations for each of these categories using the same scales as they had utilized during the main experiment (i.e. the one that measured their perceived joint comfort levels for varying joint postures). The nine verbal categories were presented in English, because all subjects were college-age students who had excellent knowledge of the English language.

The numerical estimations for the verbal descriptors make it easy to interpret the numerical magnitude estimates for perceived comfort levels in terms of plain words. Such estimations provide a basis for subdividing the ROMs of joint postures into several JAI boundaries according to the verbal categories.

3. Results

3.1. *Data normalization*

Since all subjects in this study utilized their own scale to rate the intensity of stimuli (perceived comforts in given postures) according to the free modulus of the magnitude estimation (Han *et al.* 1999), data normalization procedure was applied. Such normalization allows comparison across subjects and statistical data treatment such as regression analysis. In general, two normalization methods can be used for conducting statistical tests: (1) normalization using the minimum and maximum (min-max) values of each subject for the interval scale; and (2) normalization using a geometric mean for the ratio scale. In this study, the min-max normalization procedure suggested by Hwang and Yoon (1981) was applied to each subject's ratings

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

where $i = i^{\text{th}}$ level of posture;
$t = j^{\text{th}}$ joint posture;
$k = k^{\text{th}}$ subject;
raw data$_{ijk}$ = comfort at the i^{th} level of the j^{th} joint posture in the k^{th} subject;
max comfort$_k$ = maximum comfort in the k^{th} subject among all his ratings;
min comfort$_k$ = minimum comfort in the k^{th} subject among all his ratings;
normalized comfort score$_k$ = normalized comfort score at the i^{th} level of the j^{th} joint posture in the k^{th} subject.

In the magnitude estimation, the data from several observers may best be combined by calculating the median or geometric mean of the judgements for each stimulus. This is because the arithmetic mean may be greatly affected by a few unrepresentative high judgements (Gescheider 1985). In addition, it has been recommended that the data for different observers be combined by computing the geometric mean for each stimulus value, when no modulus is designated (Stevens 1971). Following these recommendations, in this study the geometric means of the transformed data for all 15 subjects in each experimental treatment were calculated and used as representative values for perceived comfort levels for further analysis. The geometric mean values of the normalized comfort scores at each level of joint postures across all subjects are summarized in tables 2 and 3, for the sitting and standing postures respectively.

3.2. *Relationships between joint postures and perceived comforts*

Regression analysis was used to determine quantitative relationships between the levels of joint deviation/joint posture (in degrees of an angle) and perceived comfort in each joint posture and the results are given in table 4. The level of joint deviation angle was treated as an independent variable, and the geometric mean of the normalized comfort score as the dependent variable. For the purpose of regression analysis and for ease of application to design, the percentages of the individual ROMs, which were used as the independent variable in the main experiment, were replaced by the mean corresponding joint angle values across all subjects at each level of joint posture.

All the relationships were well fitted with either a linear or a quadratic equation, with the determination coefficient (R^2) over 90%, except for the neck rotation for which $R^2 = 88\%$. All regression models were also statistically significant at $\alpha = 0.05$. The regression equations for sitting and standing postures were different because the perceived comfort levels were measured separately in the two postures, and some joint postures (including the shoulder and lower back) were constrained by the seat only in the sitting posture. Furthermore, the definitions of joint postures for the hip differed for the two postures (figure 1). However, perceived comfort levels for joint postures (except for the lower back and hip) were not statistically different at $\alpha = 0.10$ between the sitting and standing postures. Overall, the results revealed that perceived comfort decreased as joints moved away from their neutral positions.

3.3. *Numerical estimations for verbal categories*

As mentioned above, the numerical estimates for verbal categories of perceived comfort were used to model the JAIs depending upon the joint postures. The comfort levels for nine verbal categories are shown in table 5 and figure 3. The data presented are the geometric mean values of subjects' normalized ratings.

3.4. *Joint angles of isocomfort (JAI)*

The joint angles of isocomfort (JAI) with a specific comfort level for each joint posture can be derived using the equations shown in table 4 and the numerical values of corresponding verbal categories of comfort (table 5). For example, the JAI of shoulder flexion with the *marginal* comfort level in sitting posture can be obtained by inversely calculating the independent variable of the relevant equation in table 4 corresponding to the dependent variable of the *marginal* comfort level (66.4 in table 5). This results in an angle of 112° for the independent variable of shoulder flexion.

The JAI values corresponding to the *marginal* and *good* categories were calculated using the regression equations in table 4. These were summarized in tables 6 and 7 along with the values of maximum range of joint motions in sitting and standing postures, respectively.

Table 2. Geometric means of the normalized comfort scores in sitting posture.

Joint	Posture level (%)	Normalized comfort score					
		Flexion	Extension	Radial deviation	Ulnar deviation		
Wrist	0	91.6	91.6	91.6	91.6		
	25	87.7	86.6	88.4	85.4		
	50	84.9	82.7	83.4	82.4		
	75	78.6	75.9	77.2	77.7		
	100	95.9	62.1	64.1	67.4		
		Flexion	Supination	Pronation			
Elbow	0	96.1	91.6	91.6			
	25	88.2	88.8	90.4			
	50	85.2	85.8	84.4			
	75	82.9	82.5	78.3			
	100	72.9	64.0	64.9			
		Flexion	Extension	Adduction	Abduction	Medial rotation	Lateral rotation
Shoulder	0	97.9	97.9	84.8	84.8	80.6	80.7
	25	78.9	79.5	76.3	74.5	75.7	72.1
	50	67.5	68.6	70.6	67.3	74.3	63.3
	75	62.4	53.1	60.2	59.5	64.7	55.4
	100	44.4	35.8	35.7	35.5	50.4	43.7
		Flexion	Extension	Rotation	Lateral bending		
Neck	0	96.7	96.7	96.7	96.7		
	25	85.7	85.3	90.1	89.8		
	50	82.0	69.4	85.1	83.1		
	75	75.8	61.6	81.6	74.9		
	100	65.0	39.4	58.5	52.5		
		Flexion	Rotation	Lateral bending			
Lower back	0	95.9	95.9	95.9			
	25	81.4	86.9	81.4			
	50	69.3	76.5	58.3			
	75	61.4	65.3	50.3			
	100	47.0	44.8	33.9			
		Flexion	Abduction	Internal rotation	External rotation		
Hip	0	96.4	96.4	96.4	96.4		
	25	54.7	66.3	67.7	66.1		
	50	47.6	50.2	62.3	54.8		
	75	36.5	37.0	48.2	38.3		
	100	15.8	22.8	36.4	21.9		
		Dorsi flexion	Plantar flexion	Adduction	Adbuction		
Ankle	0	97.9	97.9	97.9	97.9		
	25	91.4	90.0	89.7	90.0		
	50	86.0	83.2	86.4	86.9		
	75	81.1	75.0	78.4	79.1		
	100	65.5	65.3	64.8	69.3		

The JAI values with the *marginal* comfort index (MCI) for most joint postures around the wrist, elbow, neck and ankle were similar to the maximum ROM values. The JAIs with the *marginal* comfort category for back and hip postures were much

Table 3. Geometric means of the normalized comfort scores in standing posture.

Joint	Posture level (%)	Normalized comfort score					
		Flexion	Extension	Radial deviation	Ulnar deviation		
Wrist	0	92.4	92.4	92.4	92.4		
	25	87.3	86.5	89.7	86.2		
	50	84.3	84.6	83.4	83.0		
	75	79.3	82.0	79.2	78.0		
	100	69.1	61.4	71.8	66.6		
		Flexion	Supination	Pronation			
Elbow	0	98.5	91.6	91.6			
	25	88.6	86.4	87.1			
	50	85.6	84.5	86.0			
	75	82.5	82.4	81.5			
	100	72.9	68.6	70.7			
		Flexion	Extension	Adduction	Abduction	Medial rotation	Lateral rotation
Shoulder	0	96.6	96.6	88.3	88.3	86.3	86.3
	25	86.3	88.1	83.8	81.9	83.4	79.8
	50	82.1	80.8	78.8	77.6	79.9	75.8
	75	74.8	72.1	76.3	72.3	73.1	69.2
	100	58.4	59.1	60.1	59.8	62.1	57.0
		Flexion	Extension	Rotation	Lateral bending		
Neck	0	96.5	96.5	96.5	96.5		
	25	87.6	86.4	89.7	90.0		
	50	82.6	76.9	84.5	85.7		
	75	77.6	66.4	82.1	77.9		
	100	69.0	53.0	60.9	61.6		
		Flexion	Extension	Rotation	Lateral bending		
Lower back	0	96.5	96.5	96.5	96.5		
	25	78.5	73.9	86.2	78.6		
	50	68.8	57.7	81.3	68.8		
	75	60.1	37.6	72.0	52.8		
	100	38.9	18.6	52.2	35.0		
		Flexion	Extension	Adduction	Abduction	Internal rotation	External rotation
Hip	0	96.5	96.5	96.5	96.5	85.0	85.0
	25	71.5	65.9	78.3	64.8	61.1	55.3
	50	56.1	59.8	72.6	45.7	57.2	47.7
	75	34.2	45.1	61.3	35.6	47.8	32.6
	100	14.4	30.1	45.7	18.9	32.8	19.4
		Dorsi flexion	Plantar flexion	Adduction	Adbuction	Flexion (knee)	
Ankle	0	87.9	87.9	87.9	87.9	96.5	
	25	83.0	84.8	85.8	85.9	75.1	
	50	83.5	80.4	79.3	82.9	71.3	
	75	77.7	73.3	73.4	77.8	64.3	
	100	66.3	66.8	61.0	65.8	46.3	

Table 4. Regression equations for perceived joint comfort based on the joint postures.

		Sitting posture		Standing posture	
Joint	Joint posture	Equation	R^2	Equation	R^2
Wrist	Flexion	$y = -0.005x^2 + 0.033x + 90.784$	0.98	$y = -0.003x^2 - 0.083x + 91.611$	0.97
	Extension	$y = -0.005x^2 - 0.115x + 91.006$	0.99	$y = -0.008x^2 + 0.088x + 90.512$	0.92
	Radial deviation	$y = -0.034x^2 + 0.089x + 91.054$	0.98	$y = -0.015x^2 - 0.278x + 92.489$	0.99
	Ulnar deviation	$y = -0.005x^2 - 0.222x + 90.787$	0.97	$y = -0.006x^2 - 0.196x + 91.507$	0.97
Elbow	Flexion	$y = -0.140x + 95.505$	0.93	$y = -0.156x + 97.223$	0.93
	Supination	$y = -0.003x^2 + 0.095x + 90.288$	0.95	$y = -0.001x^2 - 0.004x + 90.214$	0.92
	Pronation	$y = -0.004x^2 + 0.067x + 91.249$	0.98	$y = -0.003x^2 + 0.017x + 90.502$	0.94
Shoulder	Flexion	$y = -0.255x + 95.041$	0.97	$y = -0.181x + 97.264$	0.94
	Extension	$y = -0.842x + 97.092$	0.99	$y = -0.509x + 97.553$	0.99
	Adduction	$y = -0.023x^2 + 0.002x + 82.920$	0.97	$y = -0.013x^2 + 0.005x + 87.171$	0.93
	Abduction	$y = -0.002x^2 + 0.075x + 82.900$	0.96	$y = -0.001x^2 - 0.071x + 87.346$	0.97
	Medial rotation	$y = -0.002x^2 + 0.015x + 79.651$	0.98	$y = -0.002x^2 - 0.013x + 85.945$	0.99
	Lateral rotation	$y = -1.111x + 81.704$	0.98	$y = -0.019x^2 - 0.240x + 85.382$	0.97
Neck	Flexion	$y = -0.423x + 95.849$	0.97	$y = -0.376x + 95.797$	0.98
	Extension	$y = -0.593x + 97.965$	0.98	$y = -0.458x + 97.099$	0.99
	Rotation	$y = -0.007x^2 + 0.079x + 94.817$	0.90	$y = -0.006x^2 + 0.016x + 94.792$	0.88
	Lateral bending	$y = -0.015x^2 + 0.130x + 94.849$	0.94	$y = -0.011x^2 + 0.049x + 94.968$	0.94
Lower back	Flexion	$y = -0.501x + 94.641$	0.99	$y = -0.479x + 93.360$	0.98
	Extension	NA		$y = -2.157x + 95.258$	0.99
	Rotation	$y = -0.721x + 98.498$	0.97	$y = -0.003x^2 - 0.143x + 94.846$	0.97
	Lateral bending	$y = -1.765x + 96.404$	0.97	$y = -1.571x + 96.815$	0.98

(Continued)

Table 4. Regression equations for perceived joint comfort based on the joint postures. (continued)

Joint	Joint posture	Sitting posture: Equation	Sitting posture: R^2	Standing posture: Equation	Standing posture: R^2
Hip	Flexion	$y = 0.022x^2 - 2.607x + 91.440$	0.94	$y = -1.013x94.652$	0.99
	Extension	NA		$y = -1.201x + 90.460$	0.95
	Adduction	NA		$y = -1.725x94.316$	0.98
	Abductuion	$y = 0.004x^2 - 1.246x + 94.941$	0.98	$y = 0.010x^2 - 1.783x + 94.969$	0.98
	Internal rotation	$y = 0.016x^2 - 2.004x + 93.990$	0.97	$y = -0.964x + 80.119$	0.94
	External rotation	$y = -2.152x + 90.358$	0.97	$y = -1.399x + 78.782$	0.96
Knee	Flexion	NA		$y = -0.384x + 92.940$	0.93
Ankle	Dorsi flexion	$y = -0.009x^2 - 0.539x + 97.308$	0.99	$y = -0.013x^2 - 0.118x + 87.021$	0.97
	Plantar flexion	$y = -0.826x + 98.962$	0.97	$y = -0.013x^2 - 0.073x + 87.647$	0.99
	Adduction	$y = -0.013x^2 - 0.335x + 96.787$	0.98	$y = -0.016x^2 - 0.070x + 87.816$	0.98
	Abduction	$y = -0.006x^2 - 0.386x + 96.794$	0.98	$y = -0.016x^2 + 0.132x + 87.282$	0.98

x: level of joint posture (°), $0 \leq x \leq$ ROM, y: geometric mean of normalized comfort score. NA: not available

Table 5. Geometric mean normalized comfort scores corresponding to verbal categories.

Category	Geometric mean normalized comfort scores
Extremely good	100.0
Very good	94.1
Good	86.4
Moderate	75.8
Marginal	66.4
Somewhat poor	52.1
Poor	37.4
Very poor	20.5
Extremely poor	0.0

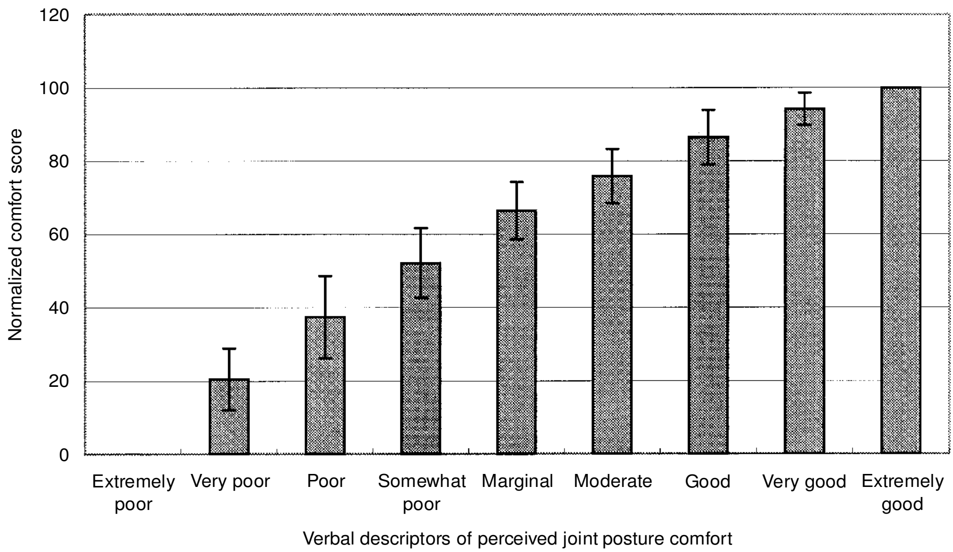


Figure 3. Comfort scores corresponding to verbal categories of perceived postural comfort.

smaller than the corresponding maximum ROM values. The pair-wise *t*-test showed that there were no significant differences at $\alpha = 0.05$ in percentages of JAIs in terms of the corresponding maximum ROM values or in JAI values between sitting and standing postures.

A relative *marginal comfort index (RMCI)*; (tables 6 and 7) was defined by taking the JAI for the *marginal* comfort category as a percentage of the corresponding maximum ROM value. The relative marginal comfort index for the hip was the smallest among all joints. This was followed by the lower back and shoulder, while the value for the elbow was the largest. On the basis of these findings, it can be concluded that hip postures are less comfortable than any other joint posture in static postures held for 60 s, while elbow postures are the most comfortable. The *relative good comfort index* (RGCI), which was defined in a similar way to the *marginal comfort index* (tables 6 and 7), exhibited much smaller values than the relative RMCI, with most percentage values of less than 40.0%.

Table 6. JAIs (^{0}) corresponding to the comfort levels of *marginal* and *good* in sitting posture.

Joint	Joint posture	Range of motion*	Marginal	Marginal index†	Good	Good index‡
Wrist	Flexion	72 (6.4)§	72 (2.1)¶	100	33	46
	Extension	65 (8.1)	59 (1.4)	91	20	31
	Radial deviation	29 (4.4)	29 (1.9)	100	13	45
	Ulnar deviation	50 (4.7)	50 (2.0)	100	14	28
Elbow	Flexion	145 (9.7)	145 (2.6)	100	65	45
	Supination	119 (14.6)	106 (3.4)	89	55	46
	Pronation	87 (9.4)	87 (1.8)	100	44	51
Shoulder	Flexion	194 (5.1)	112 (4.1)	58	33	17
	Extension	72 (6.4)	36 (1.9)	50	13	18
	Adduction	44 (5.1)	25 (4.5)	57	0	0
	Abduction	132 (12.3)	73 (5.2)	55	0	0
	Medial rotation	116 (6.7)	85 (2.2)	73	0	0
	Lateral rotation	32 (6.0)	14 (2.2)	44	0	0
Neck	Flexion	69 (6.8)	69 (2.3)	100	22	32
	Extension	94 (9.5)	53 (3.3)	56	19	20
	Rotation	72 (9.1)	69 (6.8)	96	41	57
	Lateral bending	55 (9.1)	48 (5.8)	87	28	51
Lower back	Flexion	94 (4.0)	56 (2.0)	60	17	18
	Extension		NA			
	Rotation	69 (8.9)	45 (3.7)	65	17	25
	Lateral bending	34 (4.4)	17 (4.5)	50	6	18
Hip	Flexion	45 (6.5)	10 (3.1)	22	2	4
	Extension		NA			
	Adduction		NA			
	Abduction	76 (9.7)	25 (4.5)	33	7	9
	Internal rotation	42 (3.4)	16 (5.5)	38	4	10
	External rotation	33 (4.8)	11 (5.5)	33	2	6
Knee	Flexion		NA			
Ankle	Dorsi flexion	36 (4.6)	35 (1.2)	97	15	42
	Plantar flexion	37 (6.0)	37 (2.5)	100	15	41
	Adduction	38 (4.9)	37 (2.5)	97	18	47
	Abduction	41 (6.3)	41 (2.0)	100	20	49

NA: not available. *Maximum range of motion, which is mean value of maximum range of motion for 15 subjects. †Relative *marginal* comfort index, which is JAI at the *marginal* comfort level as a percentage of the corresponding range of motion. ‡Relative *good* comfort index, which is JAI at the *good* comfort level as a percentage of the corresponding range of motion. §Standard deviation. ¶Standard error of regression equation, and the standard errors for *marginal* and *good* comfort indexes are the same because both the values were obtained from the same regression equation.

The JAIs for the other seven verbal categories (except for 'marginal' and 'good' categories) are presented in tables 8 and 9. It should be noted that some of the JAI values, with certain comfort categories calculated by using the regression equations in table 4, may be negative or may exceed the ROM values of the corresponding joint postures'. Therefore, the JAI values were set to 0 in the cases where the calculated JAI values were less than 0, and the JAIs were set to upper limits of corresponding joints' ROMs when the calculated JAIs exceeded their corresponding joints' ROM values.

Table 7. JAIs (°) corresponding to the comfort levels of *marginal* and *good* in standing posture.

Joint	Joint posture	Range of motion*	Marginal	Marginal index†	Good	Good index‡
Wrist	Flexion	72 (6.4)§	72 (1.9)¶	100	30	42
	Extension	65 (8.3)	61 (4.5)	94	29	45
	Radial deviation	29 (4.5)	29 (0.9)	100	13	45
	Ulnar deviation	50 (4.7)	50 (2.2)	100	17	34
Elbow	Flexion	145 (9.7)	145 (2.7)	100	69	48
	Supination	119 (13.6)	119 (3.3)	100	60	50
	Pronation	87 (9.4)	87 (2.7)	100	40	46
Shoulder	Flexion	194 (4.8)	171 (3.7)	88	60	31
	Extension	72 (6.4)	66 (1.7)	92	22	31
	Adduction	44 (4.5)	40 (3.7)	91	8	18
	Abduction	132 (12.3)	113 (2.5)	86	11	8
	Medial rotation	116 (6.7)	95 (0.7)	82	0	0
	Lateral rotation	32 (5.4)	26 (2.7)	81	0	0
Neck	Flexion	69 (6.8)	69 (1.4)	100	25	36
	Extension	94 (10.5)	67 (1.0)	71	23	24
	Rotation	72 (8.0)	70 (6.5)	97	39	54
	Lateral bending	55 (9.1)	53 (4.3)	96	30	55
Lower back	Flexion	115 (15.4)	56 (2.9)	49	15	13
	Extension	36 (6.5)	13 (1.9)	36	4	11
	Rotation	95 (9.6)	76 (3.7)	80	34	36
	Lateral bending	37 (5.1)	19 (3.7)	51	7	19
Hip	Flexion	80 (6.1)	28 (2.1)	35	8	10
	Extension	51 (5.5)	20 (6.3)	39	3	6
	Adduction	28 (3.0)	16 (2.8)	57	5	18
	Abduction	66 (8.3)	18 (4.3)	27	5	8
	Internal rotation	49 (6.2)	14 (5.3)	29	0	0
	External rotation	44 (6.3)	9 (4.0)	20	0	0
Knee	Flexion	116 (9.1)	69 (5.3)	59	17	15
Ankle	Dorsi flexion	36 (4.6)	30 (2.1)	83	0	0
	Plantar flexion	37 (5.9)	37 (1.0)	100	7	19
	Adduction	38 (4.0)	34 (1.4)	89	7	18
	Abduction	41 (6.3)	41 (1.5)	100	13	32

NA: not available. *Maximum range of motion, which is mean value of maximum range of motion for 15 subjects. †Relative *marginal* comfort index, which is JAI at the *marginal* comfort level as a percentage of the corresponding range of motion. ‡Relative *good* comfort index, which is JAI at the *good* comfort level as a percentage of the corresponding range of motion. §Standard deviation. ¶Standard error of regression equation, and the standard errors for *marginal* and *good* comfort indexes are the same because both the values were obtained from the same regression equation.

As shown in tables 8 and 9, the JAIs with the *extremely good* and *extremely poor* categories in all joints were less than 0 or larger than their ROMs' limits, respectively. In addition, the JAIs with the comfort categories of *very good*, *somewhat poor* and *very poor* in almost every joint were also outside their ROM values, while those with the *good*, *moderate*, and *marginal* categories were within ROM values in all joint postures. The JAI values, for each joint that can be defined

Table 8. JAI values (°) corresponding to the *extremely good*, *very good*, *moderate*, *somewhat poor*, *poor*, *very poor* and *extremely poor* comfort levels in sitting posture.

Joint	Joint posture	Extremely good	Very good	Moderate	Somewhat poor	Poor	Very poor	Extremely poor
Wrist	Flexion	0	0	58	72	72	72	72
	Extension	0	0	45	65	65	65	65
	Radial deviation	0	0	23	29	29	29	29
	Ulnar deviation	0	0	37	50	50	50	50
Elbow	Flexion	0	10	141	145	145	145	145
	Supination	0	0	87	119	119	119	119
	Pronation	0	0	71	87	87	87	87
Shoulder	Flexion	0	4	75	168	194	194	194
	Extension	0	4	25	53	71	72	72
	Adduction	0	0	17	37	44	44	44
	Abduction	0	0	44	107	132	132	132
	Medial rotation	0	0	48	116	116	116	116
	Lateral rotation	0	0	5	27	32	32	32
Neck	Flexion	0	4	47	69	69	69	69
	Extension	0	7	37	77	94	94	94
	Rotation	0	0	17	58	72	72	72
	Lateral bending	0	13	40	55	55	55	55
Lower	Flexion	0	1	38	85	94	94	94
Back	Extension				NA			
	Rotation	0	6	31	64	69	69	69
	Lateral bending	0	1	12	25	33	34	34
Hip	Flexion	0	0	6	18	27	42	45
	Extension				NA			
	Adduction				NA			
	Abduction	0	1	16	39	56	76	76
	Internal rotation	0	0	10	27	42	42	42
	External rotation	0	0	7	18	25	32	33
Knee	Flexion				NA			
Ankle	Dorsi flexion	0	5	27	36	36	36	36
	Plantar flexion	0	6	28	37	37	37	37
	Adduction	0	6	29	38	38	38	38
	Abduction	0	6	35	41	41	41	41

NA: not available.

within its ROM, are illustrated in figures 4 and 5. The JAI values that were close to those with adjacent comfort categories were not included to preserve the clarity of presentation. Figures 4 and 5 show that the JAI values are very different depending upon the joints and joint postures.

4. Discussion

Previous studies on comfortable ranges of joint postures focused on: (1) the comfort zone (CZ) values (Diffrient *et al.* 1985); and (2) the neutral range (NR) and effort range (ER) values (Hsiao and Keyserling 1991). Three comfort-related joint ranges including the JAI values for the *marginal*, *moderate* and *good* comfort levels for sitting posture derived in the present study are presented in table 10. A comparison of these three different concepts revealed the following. The CZ values for shoulder extension-flexion and neck motions, such as extension-flexion, rotation and lateral bending, were not very different from the corresponding JAIs associated with the

Table 9. JAI values (°) corresponding to the *extremely good*, *very good*, *moderate*, *somewhat poor*, *poor*, *very poor* and *extremely poor* comfort levels in standing posture.

Joint	Joint posture	Extremely good	Very good	Moderate	Somewhat poor	Poor	Very poor	Extremely poor
Wrist	Flexion	0	0	60	72	72	72	72
	Extension	0	0	49	65	65	65	65
	Radial deviation	0	0	25	29	29	29	29
	Ulnar deviation	0	0	37	50	50	50	50
Elbow	Flexion	0	20	137	145	145	145	145
	Supination	0	0	118	119	119	119	119
	Pronation	0	0	73	87	87	87	87
Shoulder	Flexion	0	17	119	194	194	194	194
	Extension	0	5	46	72	72	72	72
	Adduction	0	0	30	44	44	44	44
	Abduction	0	0	78	132	132	132	132
	Medial rotation	0	0	68	116	116	116	116
	Lateral rotation	0	0	17	32	32	32	32
Neck	Flexion	0	5	53	69	69	69	69
	Extension	0	7	47	94	94	94	94
	Rotation	0	12	58	72	72	72	72
	Lateral bending	0	11	44	55	55	55	55
Lower	Flexion	0	0	37	86	115	115	115
Back	Extension	0	0	9	20	27	34	36
	Rotation	0	5	59	95	95	95	95
	Lateral bending	0	0	13	28	37	37	37
Hip	Flexion	0	0	19	42	57	73	80
	Extension	0	0	12	32	44	51	51
	Adduction	0	0	11	24	28	28	28
	Abduction	0	0	11	29	42	66	66
	Internal rotation	0	0	4	29	44	49	49
	External rotation	0	0	2	19	30	42	44
Knee	Flexion	0	0	45	106	116	116	116
Ankle	Dorsi flexion	0	0	18	36	36	36	36
	Plantar flexion	0	6	28	37	37	37	37
	Adduction	0	6	25	38	38	38	38
	Abduction	0	6	31	41	41	41	41

good levels of comfort. The NR values for wrist extension-flexion, wrist ulnar deviation-radial deviation, back rotation and neck lateral bending were somewhat similar to the corresponding JAIs with the *good* comfort level. The NR values for shoulder adduction-abduction, shoulder rotation, neck extension-flexion, and back flexion were very similar to the corresponding JAIs for the *moderate* comfort category. The NR for back lateral bending was almost the same as its JAI of the *marginal* category. The ER and JAI of the marginal category for wrist ulnar deviation-radial deviation, elbow flexion, and shoulder extension-flexion were similar. Finally, the ER for neck rotation was nearly identical to JAI with the *good* comfort level.

According to the definitions of the comfort zone and the neutral range, these two values should be closer to JAIs corresponding to the *marginal* comfort category. Also, the effort range values should be similar to JAIs with the *somewhat poor* or *poor* comfort categories. It should be noted that the published comfort zones, and

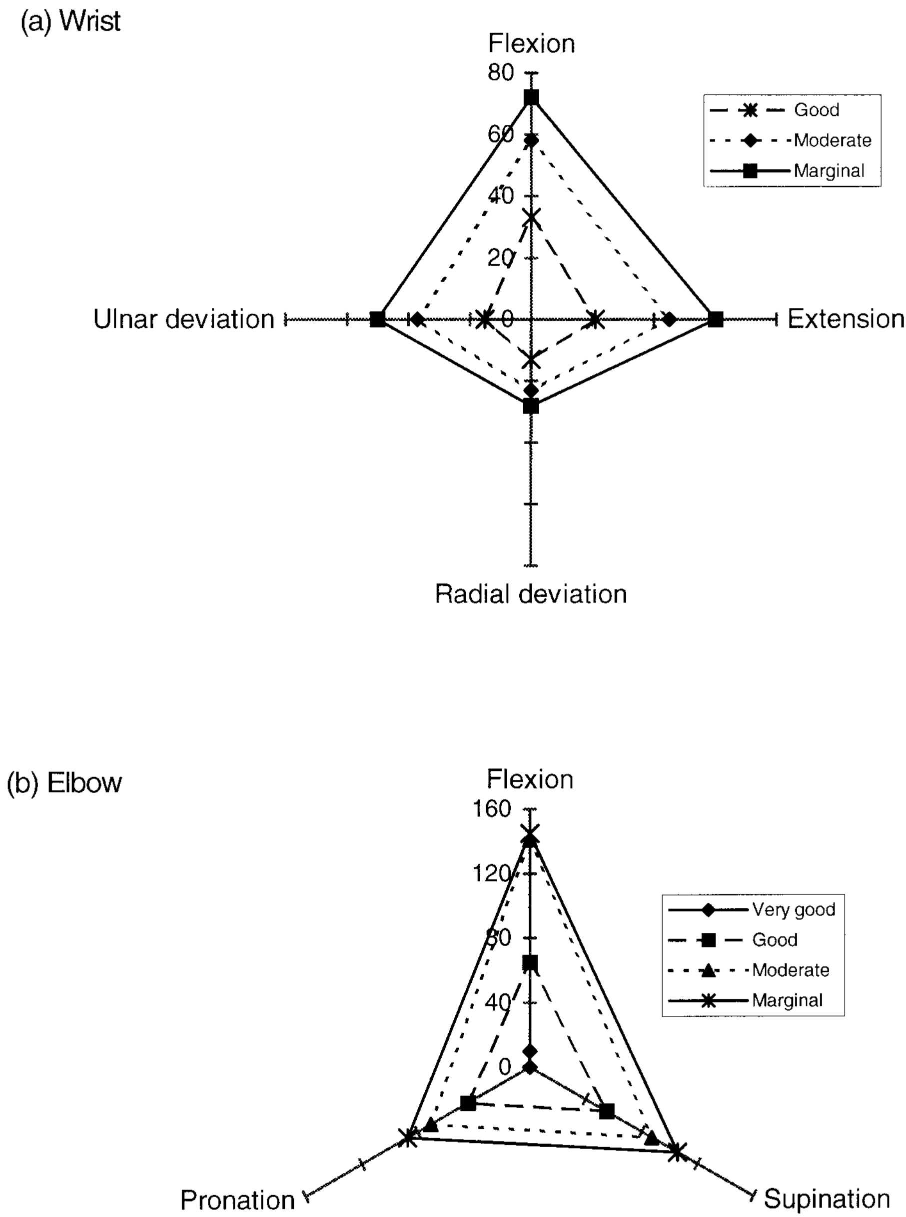
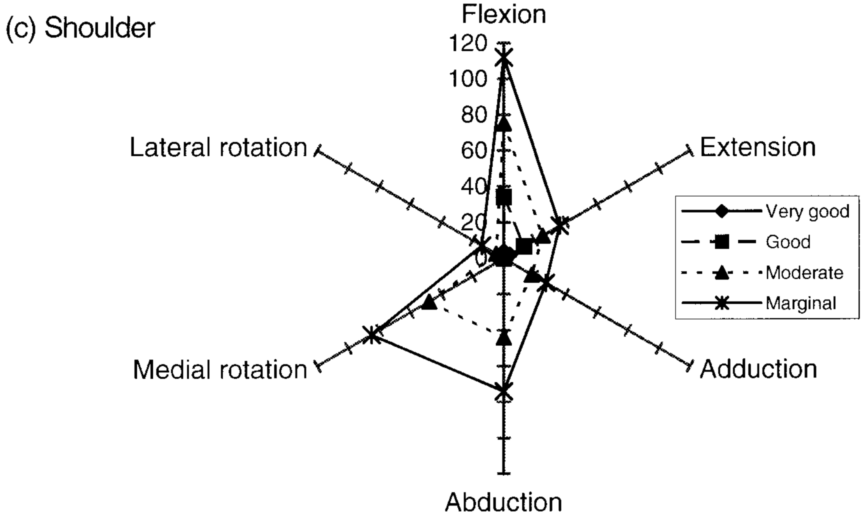


Figure 4. JAIs for joints in sitting posture

the neutral and effort ranges for joint postures, are smaller than the corresponding JAIs derived in this study, i.e. the former are underestimated compared to the latter. This may be partly due to differences in definitions of joint postures and motions, different measurement techniques as well as data gathering methods used, and differences in subject populations. As such, the results of the above comparisons between the existing comfort-related joint ranges and the JAIs proposed in this study should be used very cautiously in real design situations. Potential users should keep



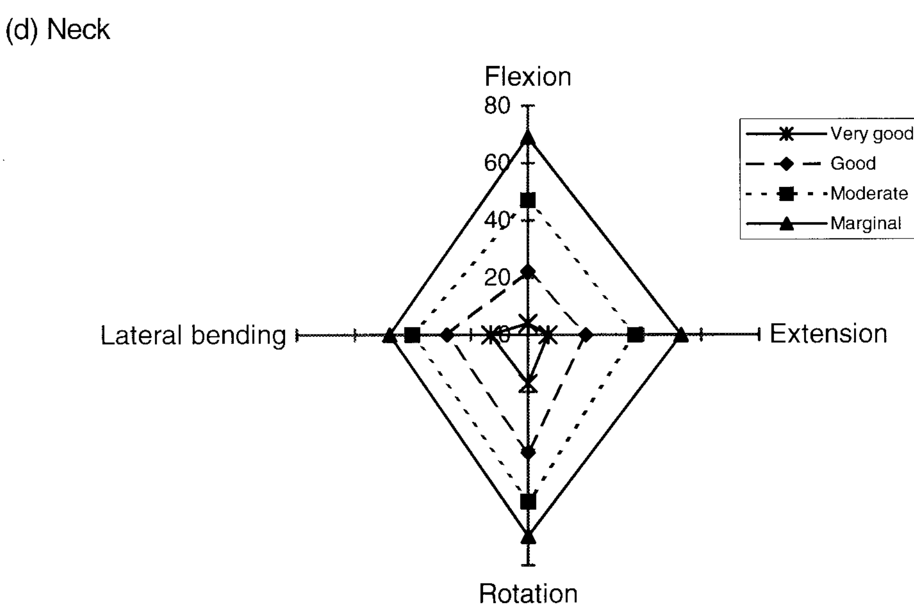


Figure 4. JAIs for joints in sitting posture (continued).

in mind that: (1) the CZ and JAI were based on the concept of comfort, while the NR and ER were based on discomfort levels; and (2) the indices of comfort and discomfort are not two opposites on a continuous scale, but rather complementary entities (Zhang *et al.* 1996).

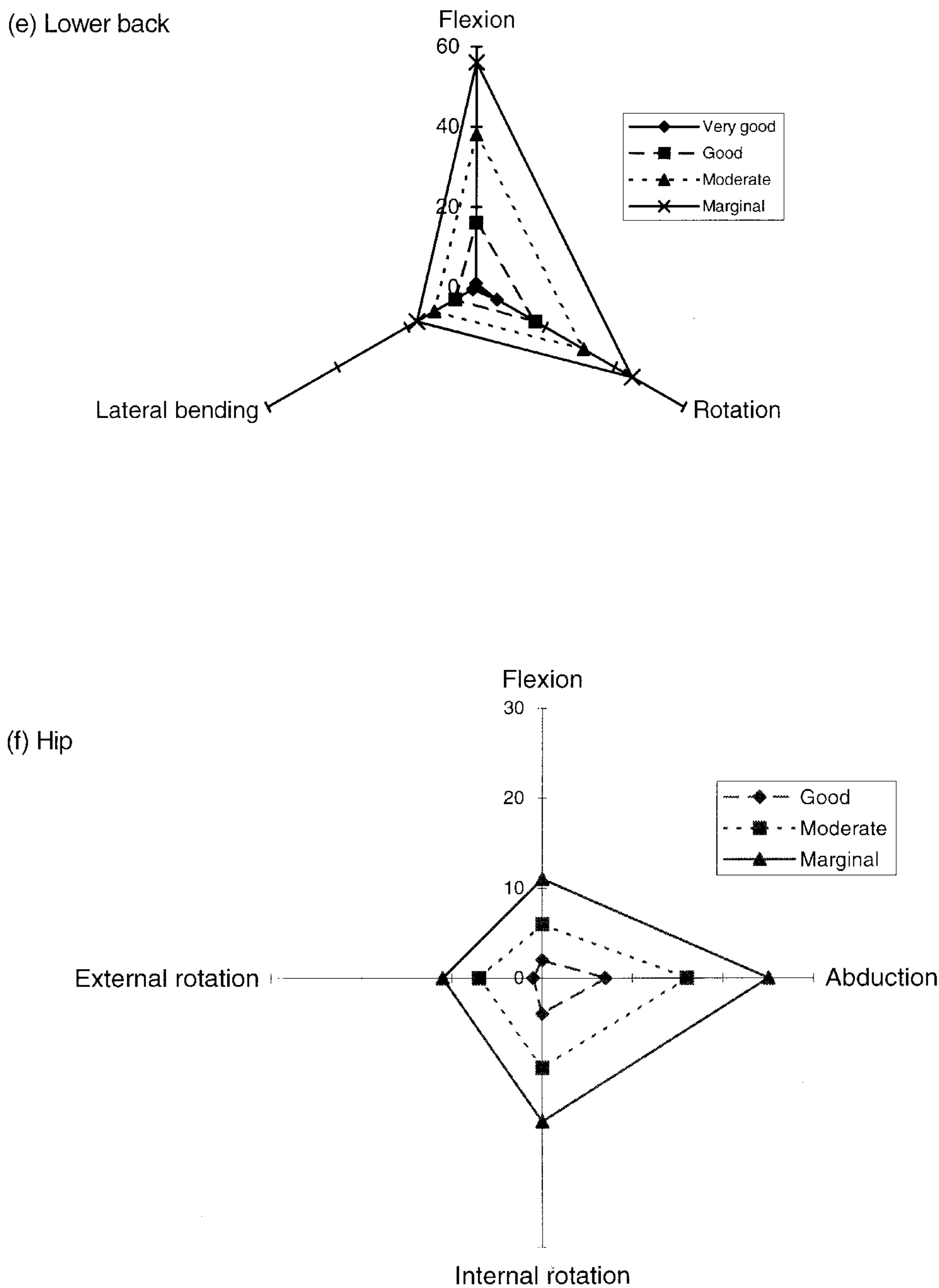


Figure 4. JAIs for joints in sitting posture (continued).

Previously reported values of comfort zone and those of neutral and effort ranges were determined based on several independent studies, which were performed under different experimental conditions. As such, they lack consistent criteria in the definition of joint (motion) comfort. Furthermore, most of the previously published

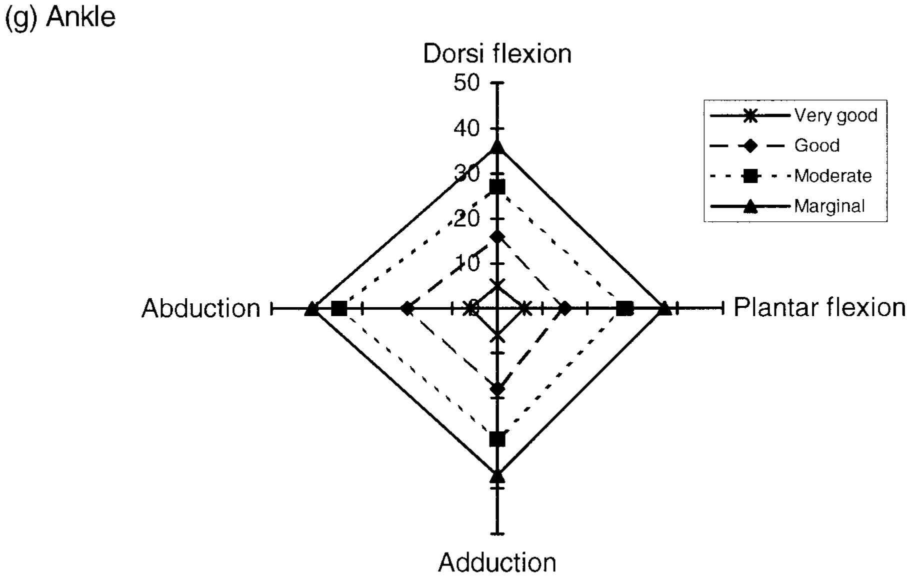
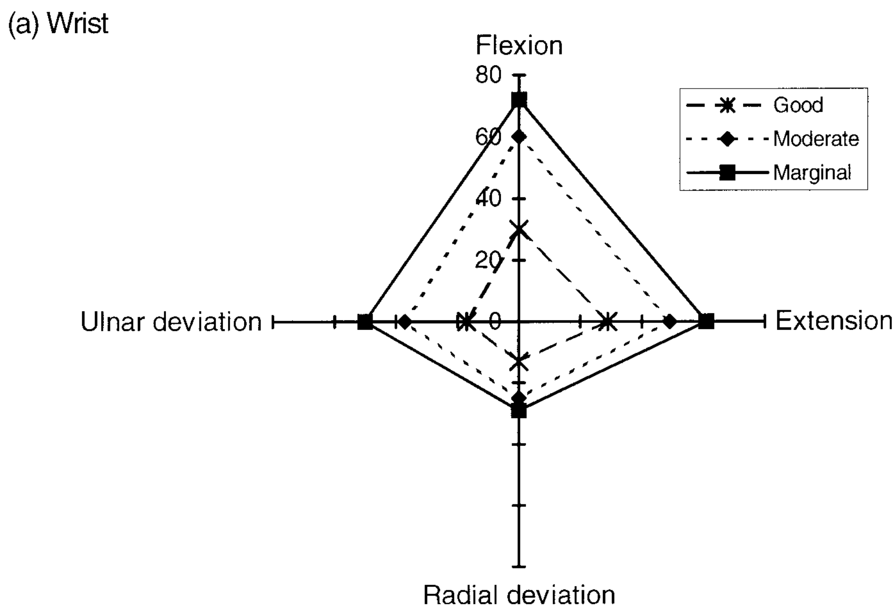


Figure 4. JAIs for joints in sitting posture (continued).

data on postural comfort relied mainly on the experts' experience and/or assessments. In the present study, the joint angles of isocomfort for all joint postures were obtained based on perceived comfort levels derived experimentally using the magnitude estimation method. When considering these facts, it is expected that the JAIs will be more appropriate for workplace design compared to the comfort-related joint ranges or zones.

Although the results of this study have specific advantages (as discussed above) compared to the previous comfort-related zones, there are also limitations. The main limitations are as follows: (1) only static postures held for 60 s were investigated, and no other factors, such as the external load (force), repetitiveness (frequency) or longer exposure times were considered; (2) joint postures and motions were expressed using a single degree of freedom, even though a real posture is actually defined by combining multiple degrees of freedom; and (3) the experiment was conducted in the laboratory rather than in the industrial setting. Therefore, further research is needed to resolve the above problems.

Finally, it is noted that application of the free modulus method of magnitude estimation did not lead to any special problems or difficulties, except that it took more time to perform the experiment, and data analysis including data normalization, statistical analysis, etc. was more time consuming as well. These disadvantages can be justified considering the fact that only a limited number of statistical analyses are possible if the traditional category scaling methods are used. Furthermore, Gescheider (1985) reported that almost every subject has the ability to properly perform the free modulus method of magnitude estimation. The free modulus method of magnitude estimation has been used in many previous studies for example by Stevens and Marks (1971), Jung and Choe (1996), and Han *et al.* (1998), for obtaining the relationship between intensity and area for warmth sensations, for measuring joint discomfort, and for measuring preference of a high



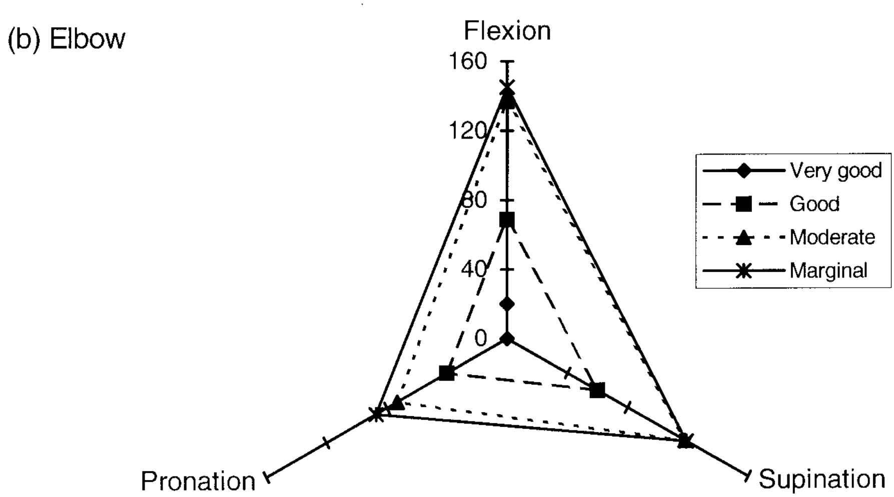
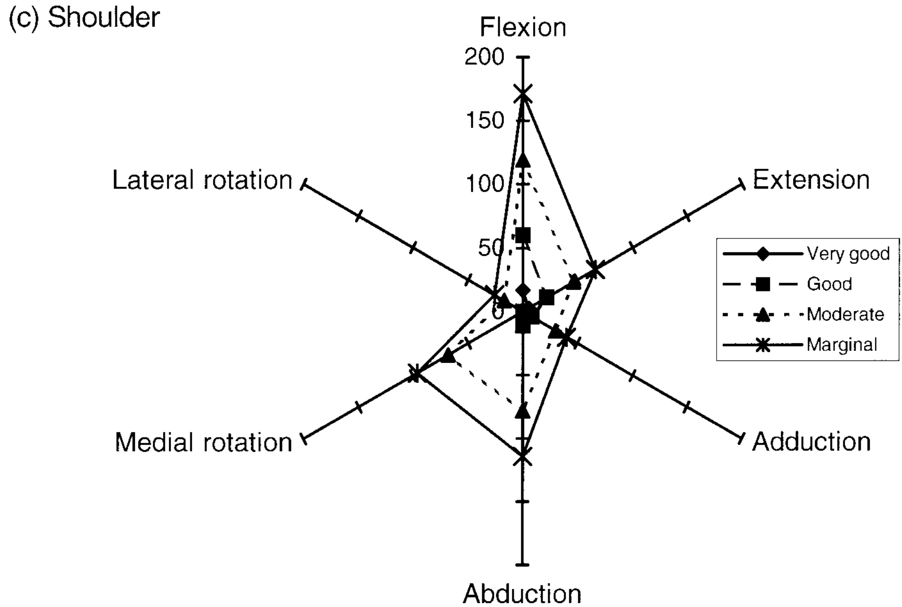


Figure 5. JAIs for the joints in standing posture.

speed train's interior design. Taking into consideration these facts, it is recommended that the free modulus method of magnitude estimation is used to quantify the relationship between human sensation and physical stimuli for varying quantitative statistical analyses, provided that the subjects are carefully selected and are able to rate the intensity of stimulus with the ratio scale.



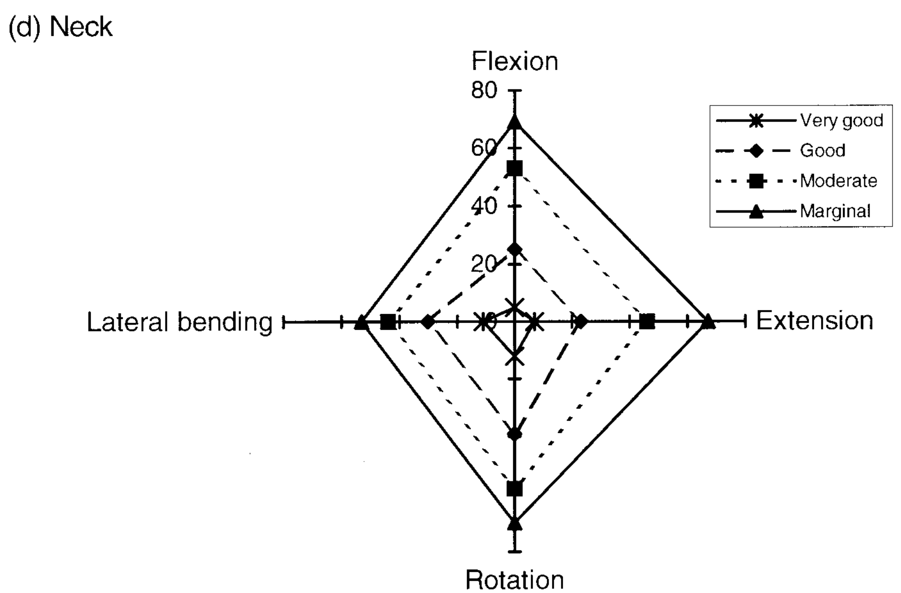
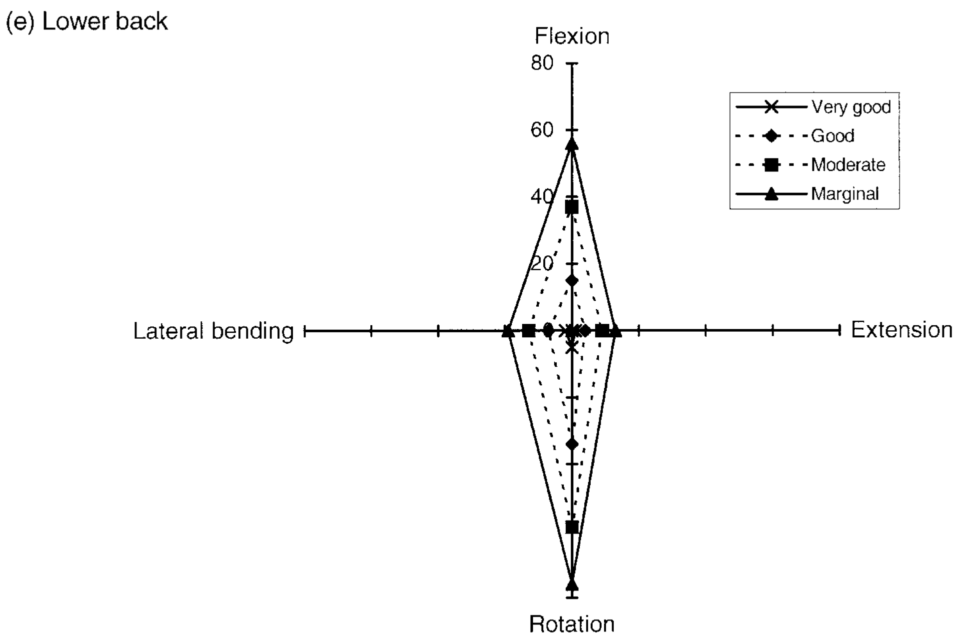


Figure 5. JAIs for the joints in standing posture (continued).



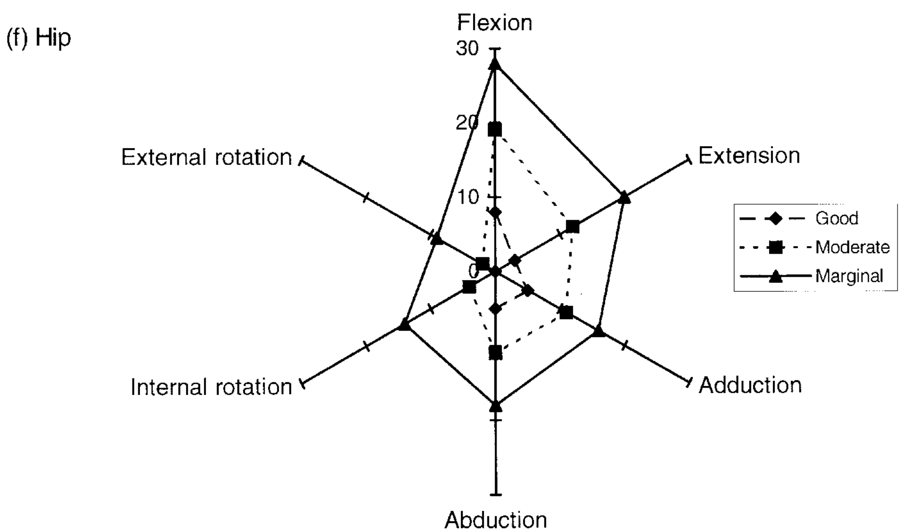
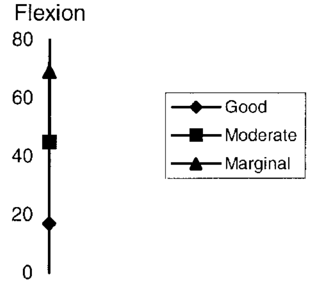


Figure 5. JAIs for the joints in standing posture (continued).

(g) Knee



(h) Ankle

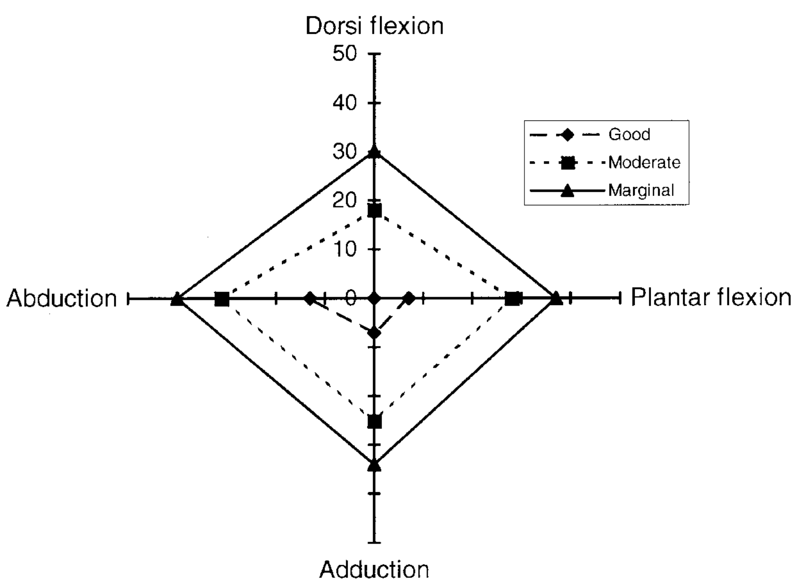


Figure 5. JAIs for the joints in standing posture (continued).

5. Conclusions

This study investigated the joint angles of isocomfort for the spine and upper and lower extremities in sitting and standing postures of male subjects under static conditions. The JAI values were based on perceived joint posture comfort levels, which were derived using the magnitude estimation method. The results of this study suggest that static postures maintained for 60 s cause greater discomfort for the hip joint than for the other joints studied, and less discomfort for the elbow than for the other joints. The derived JAI values were different from the comfort zone or the neutral and effort ranges reported by previous studies. The high values of R^2 for the regression models which were developed imply that the posture may be one of the most significant factors affecting perceived joint comfort levels under static

Table 10. Comparison of the results of previous studies and the present study.

Joint posture	Previous studies: Comfort zone (CZ)*	Previous studies: Neutral range† (NR)	Previous studies: Effort range† (ER)	Present study: JAI values for comfort levels: Good	Present study: JAI values for comfort levels: Moderate	Present study: JAI values for comfort levels: Marginal
Wrist extension flexion	−25°–45°	−15°–15°	−45°–45°	−20°–33°	−45°–58°	−59°–72°
Wrist ulnar deviation–radial deviation		−15°–5°	−40°–25°	−14°–13°	−37°–23°	−50°–29°
Elbow flexion	15°–100°	45°–110°	20°–130°	0°–65°	0°–140°	0°–145°
Elbow supination–pronation		−90°–−30°	−120°–30°	−55°–44°	−87°–71°	−106°–87°
Shoulder extension–flexion	−15°–35°	−27°–45°	−45°–90°	−13°–33°	−25°–75°	−36°–112°
Shoulder adduction–abduction	−25°–0°	−20°–45°	−45°–90°	0°	−17°–43°	−25°–73°
Shoulder rotation		−20°–45°		0°	−5°–48°	−14°–85°
Neck extension–flexion	−30°–30°	−45°–45°		−19°–22°	−37°–47°	−53°–69°
Neck rotation	−45°–45°	−20°–20°	−45°–45°	−41°–41°	−58°–58°	−69°–69°
Neck lateral bending	−20°–20°	−20°–20°		−28°–28°	−40°–40°	−48°–48°
Back flexion–extension		0°–30°		0°–17°	0°–38°	0°–56°
Back rotation		−20°–20°		−17°–17°	−31°–31°	−45°–45°
Back lateral bending		−20°–20°		−6°–6°	−12°–12°	−17°–17°

*Diffrient *et al.* 1985. †Hsiao and Keyserling 1991.

conditions. There were independent of other possible influencing factors, such as the strength and endurance of individuals. It is expected that the reported data on JAIs can be used as partial guidelines for enhancing postural comfort when designing a variety of human-machine tasks where static postures cannot be eliminated, including, for example, office environment, working with computers, or design of car interiors and aircraft cockpits.

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