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Effect of External Load at Varying Hand Positions on Perceived Discomfort

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The purpose of this study was to assess the effect of external load at varying hand positions on discomfort, and to provide a new classification of external load. An experiment was carried out in which 16 postures with an external load of 0, 1.5, 3 kg were tested. The postures were controlled by 2 independent variables of hand distance and hand height. The subjects were instructed to rate their perceived discomfort with magnitude estimation after holding a given posture for 1 min. Analysis of variance (ANOVA) exhibited that the main effects of the 3 independent variables were statistically significant for discomfort. Discomfort increased linearly with external load and hand distance. Hand height showed a quadratic relation with discomfort, which exhibited a slightly different trend from hand distance and external load. Based on the results, a new classification of external load was proposed with 3 classes grouped by perceived discomfort.

perceived discomfort postural stress external load hand position

1. INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) cause serious social problems such as wage compensation, medical expenses and reduced productivity as well as workers' physical and psychological pain [1, 2]. Winkel and Mathiassen categorized risk factors for WMSDs into individual, psychosocial and physical factors [3]. Individual factors were nonmanipulable personal characteristics including age, body size, gender, medical history, etc. Psychosocial factors were job dissatisfaction, low levels of decision latitude, task inflexibility, etc. Physical factors included awkward body posture, repetitiveness, muscle load, mechanical stress, vibration, work duration, etc.

Poor working postures have been known as a major physical factor for WMSDs along with mechanical stress. In a review of over 600 epidemiological studies, the U.S. National Institute for Occupational Safety and Health (NIOSH) reported that there was strong evidence for causal relationships between postures of the neck/shoulder and WMSDs, and that there existed some convincing epidemiological evidence for causality of awkward posture and heavy physical work for low-back musculoskeletal disorders [4]. Armstrong reported that postures in the upper extremities were related to WMSDs [5].

Cost effective quantification of the magnitude of physical exposure to poor working postures is important and necessary if the potential for injury resulting from postures is to be reduced [6]. To do this, observational methods of posture classifications such as OWAS [7], RULA [8], REBA [9] have been widely used. Not only do these methods

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classify postures of body parts into several classes (e.g., four classes of shoulder posture in RULA and REBA), but they also group force or external load, the most significant factors contributing to WMSDs, into three or four categories by considering only the weight of external load irrespective of its location. However, the effect of external load on postural stress varies depending on the location of the load (e.g., the location of a hand with an external load) or the worker's posture.

Daily exposure to constrained body postures and deviations from 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 [10, 11, 12]. Following this, many studies evaluated postural stress on the basis of discomfort [13, 14, 15, 16, 17]. Putz-Anderson and Galinsky adopted a psychophysical approach to determine work duration for limiting shoulder-girdle fatigue [17]. Genaidy and Karwowski showed that there were several distinct classes of joint deviations from neutral postures to be assigned different weights of postural stress on the basis of discomfort [16]. Genaidy, Barkawi and Christensen presented a ranking system based on discomfort to determine stress induced by non-neutral static postures around the wrist, elbow, shoulder, neck and lower back [15]. Kee and Karwowski proposed a posture classification of the upper body on the basis of discomfort caused by various joint postures [14]. Chung, Lee and Kee measured discomfort levels for various leg postures and proposed a scheme for evaluating stress attributed to different leg postures [13].

Researchers dealing with the effect of force/exertion or external load according to its location have focused on arm postures including the shoulder joint. Carey and Gallwey investigated the effect of exertion (10% and 20% of maximal voluntary contractions in neutral wrist position), pace (10 and 20 exertions per minute) and the level of simple and combined flexion/extension and radial/ulnar deviation of the wrist on discomfort in simple repetitive exertions [18]. The results revealed that exertion was the most significant factor, followed by deviation and pace. Kee measured postural discomfort for varied wrist, elbow, shoulder postures, and external load [19]. The result indicated that the effect of external load was the most important factor. Park investigated postural discomfort of varying shoulder postures and external load [20]. The study reported that two main effects of shoulder flexion/extension and external load, and the interaction of flexion/extension and external load were significant for discomfort at $\alpha = .05$, and that adduction/abduction movements did not significantly affect discomfort. Thus, exertion or external load appeared to be the factor most significantly influencing discomfort. In addition, postures of the upper body and legs have a significant effect on discomfort [19]. However, no studies considering at the same time external load, upper body postures including the trunk, arm and hand, and leg postures were found.

For an observational method to be practical and to assess postural stress more precisely, it is necessary to classify external load considering its location, because (a) most workers do their work with hand tools or objects and (b) the locations of the hand tools or objects differ depending on the task. The purpose of this study was to examine and quantify the effect of weight and location of external load on perceived discomfort and to propose a new classification of external load, based on experimental results. The location of external load is controlled by hand positions, which are determined by the trunk, arm, hand and leg postures. It would be useful to develop an observational method more properly reflecting the effect of external load.

2. METHOD

2.1. Subjects

Eight healthy male graduate students with no history of musculoskeletal disorders voluntarily participated in the experiment. Before the experiment, the subjects were informed of the experimental protocol and possible risks. Means and standard deviations of the subjects' demographic data were as follows:

height	178.3 ± 4.62 cm
weight	79.1 ± 9.66 kg
age	25 ± 1.31 years
shoulder height (SH)	144.4 ± 4.54 cm
arm reach (AR)	73.6 ± 3.83 cm

All subjects were right-handed.

2.2. Experimental Variables and Postures

Hand height, hand distance and external load weight were the independent variables. All experimental postures were defined by horizontal and vertical distances of hand position with respect to feet in the upright position [21]. The hand positions were determined by two relative parameters adopted from Miedema, Douwes and Dul [21]: the percentage of AR (i.e., hand distance) and the percentage of SH (i.e., hand height). AR was defined as the maximum horizontal distance from the tip of the middle finger to the wall when the subject stood upright with his back against the wall. SH was defined as the vertical distance from the floor to the acromion in the upright position (Figure 1).

In this study, four levels of hand distance (AR 100%, AR 70%, AR 40%, AR 0%) and four levels of hand height (SH 120%, SH 100%, SH 70%, SH 40%) were chosen (Figure 1).

AR 100%	full arm length
AR 70%	70% of full arm length
AR 40%	forearm length
SH 120%	forehead level
SH 100%	shoulder level
SH 70%	waist level
SH 40%	knee level

These hand positions were designed to include almost all work spaces found in real workshops. In addition, three levels of external load weight (0, 1.5, 3 kg) were employed. This was based on a survey for 575 workers working at an assembly line of a large automobile manufacturing company in Korea. The survey showed that 84% of workers handled tools or parts of 3 kg or under, and that only 43 workers (7%) handled tools of 6 kg or over [22]. Armstrong, Punnett and Ketner also reported that tools in automobile tasks weighed under 3 kg [23]. Two dumbbells of 1.5 and 3 kg were the external load.

Whole-body discomfort was the dependent variable. Discomfort was measured with the modulus method of magnitude estimation. In this method, respondents are presented with an arbitrary standard stimulus for comparison and are told that the sensation it produces has a certain

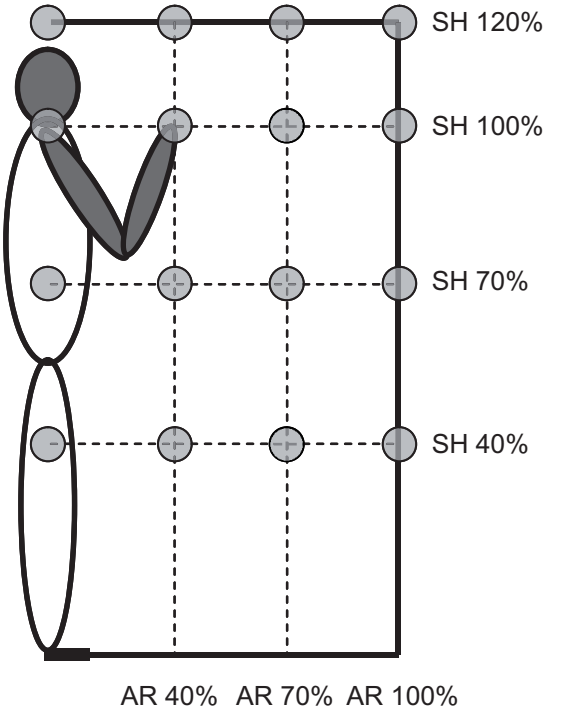

Figure 1. Definitions and levels of hand distance and hand height. *Notes.* SH = shoulder height, AR = arm reach.

numerical value (modulus), e.g., 10 [24, 25]. On subsequent trials, the respondents are instructed to numerically make their judgements reflect how many times greater a sensation is than the value of the modulus (the ratio between the two sensations). The rating is on a ratio scale, so that addition, subtraction, multiplication and division are possible. The rating ranges from 0 to 100 with the verbal anchors of 0 = *extremely comfortable*, 100 = *extremely uncomfortable and unable to maintain the posture*.

A calibration test was conducted to make the subjects familiar with magnitude estimation and to screen out the subjects who did not have the ability to make ratio judgements [24, 25]. In the calibration test, the subjects were asked to estimate the length of lines numerically in the numeric estimation test and to draw lines which corresponded to the presented numbers in the line production test. Each subject was presented, in random order, 10 lines in the numeric estimation test and 10 numbers in the line production test. Simple regression analyses were performed on two sets of logarithmically transformed stimuli and response data obtained in the tests. The slope

of the regression equation should not be significantly different from 1.0 ($\alpha = .05$). All subjects passed these tests.

2.3. Pre-Test

As the human body has redundant degrees of freedom in motion, there are infinite feasible postures the upper body and legs can assume to reach a hand position. To conduct an experiment under controlled conditions, a representative posture at each hand position was necessary. Prior to the main experiment, a pre-test was conducted to determine the representative postures. All the subjects participated in it. The subjects' anthropometric data, including the SH and AR, were measured before the test. The subjects were asked to assume the most comfortable posture while holding a 1.5-kg dumbbell in 16 hand positions. The subjects were requested to position their right hand in given hand positions, which were on the sagittal plane with respect to the shoulder joint. An iron bar pointer attached to an iron stick was used to indicate hand positions (see Figure 4). The subjects were also instructed to minimize trunk rotation and lateral bending while assuming postures. The left hand was held naturally at the subjects' left side. Pictures were taken with a digital camera after the subjects assumed comfortable postures. The postures were analysed and those most subjects took were selected as representative.

2.4. Main Experiment

There were 16 experimental postures; each of them had three levels of external load (0, 1.5, 3 kg), which resulted in 48 experimental treatment conditions. The within-subject design was applied and the experimental treatment conditions were randomized for each subject. In the experiment, the subjects were asked to assume and maintain experimental postures for 60 s. After 60 s, the subjects were required to rate their perceived whole-body discomfort for the given experimental treatment with the magnitude estimation method. The iron bar pointer was used to ensure that the subjects put their right hand on the hand position designated for the given experimental treatment condition (Figure 4). A posture holding time of 60 s was adopted based on three facts: (a) previous studies also used the 60-s interval for assessing joint motion discomfort [14, 15, 16]; (b) Grandjean reported that if a high force was exerted, static muscle actions had to be under 10 s, for a moderate force under 1 min, and for a low force under 4 min [26] (on that basis, the posture score in RULA is increased by 1 if the posture is mainly static, i.e., held for over 60 s [8]); and (c) such conditions often occur in contemporary jobs in the office environment, construction industry and agriculture [4]. All subjects were allowed enough rest periods of at least 3 min between the experimental trials. To reduce the fatigue effect, each subject attended two consecutive sessions on two separate days. Each experimental session consisted of 25 and 23 experimental treatments in the two days. Each session followed two to four warm-up tests, in which postures not used in the experimental conditions were adopted.

3. RESULTS

3.1. ANOVA and Post Hoc Analysis

Analysis of variance (ANOVA) was performed to grasp the effect of independent variables on whole-body discomfort. The ANOVA results in Table 1 showed that the main effect on perceived discomfort was significant in all three independent variables: hand height, hand distance and external load ($p < .001$). The effect was greatest in external load, followed by hand distance and hand height. Two-way interactions between hand distance and hand height, between hand distance and external load, and between hand height and external load were all significant ($p < .001$). A three-way interaction among hand distance, hand height and external load was also significant at $\alpha = .05$.

The two-way interaction effects exhibited the following trends: (a) perceived discomfort increased as hand distance increased, except for SH 40%; for SH 40%, perceived discomfort levels in AR 0%–70% remained the same (Figure 2a); (b) perceived discomfort increased as external load and hand distance increased; without exter-

nal load, however, discomfort remained the same at hand distances of AR 0%, 40% and 70% (Figure 2b); and (c) perceived discomfort increased in a similar pattern as external load increased for hand heights of SH 70%, 100% and 120%, except for hand height of SH 40% (Figure 2c). In the absence of external load, perceived discomfort was highest at SH 40%.

Student–Newman–Keuls (SNK) tests were conducted for post hoc analyses ($\alpha = .05$) [27]. The effects of hand distance were grouped into three classes on the basis of perceived discomfort: AR 0% and 40%, AR 70%, and AR 100%. Perceived discomfort appeared to be linearly related to hand distance in a positive direction (Figure 3a). Discomfort increased as hand height

TABLE 1. Analysis of Variance (ANOVA) Results

Source		*DF*	*SS*	*MS*	*F*	*p*
HD		3	41333	13778	112.82	<.001
HH		3	14955	4985	40.82	<.001
EL		2	145052	72526	593.89	<.001
HD × HH		9	6971	775	6.34	<.001
HD × EL		6	8644	1441	11.80	<.001
HH × EL		6	5002	834	6.83	<.001
HD × HH × EL		18	3632	202	1.65	.046
	error	336	41033	122		
	total	383	266620			

Notes. HD = hand distance, HH = hand height, EL = external load.

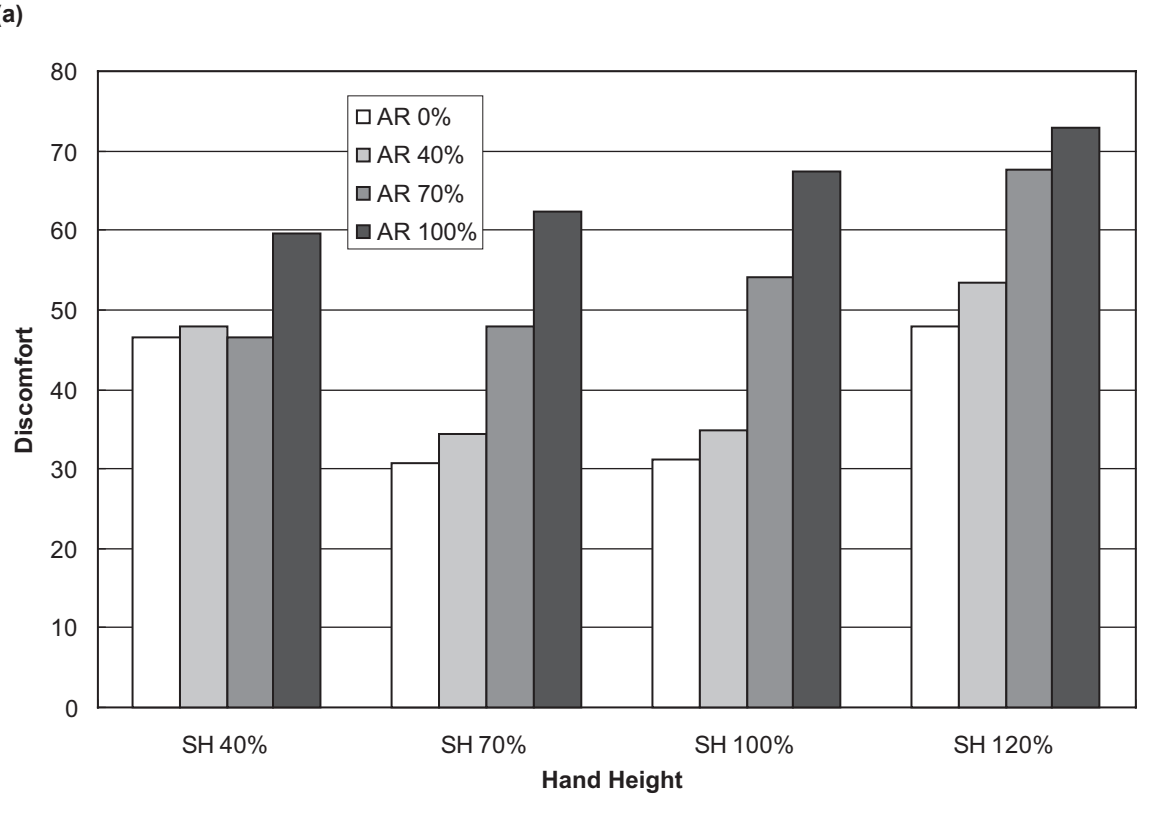

Figure 2. Interaction effects among independent variables: (a) hand distance and hand height, (b) hand distance and external load, (c) hand height and external load. *Notes.* SH = shoulder height, AR = arm reach.

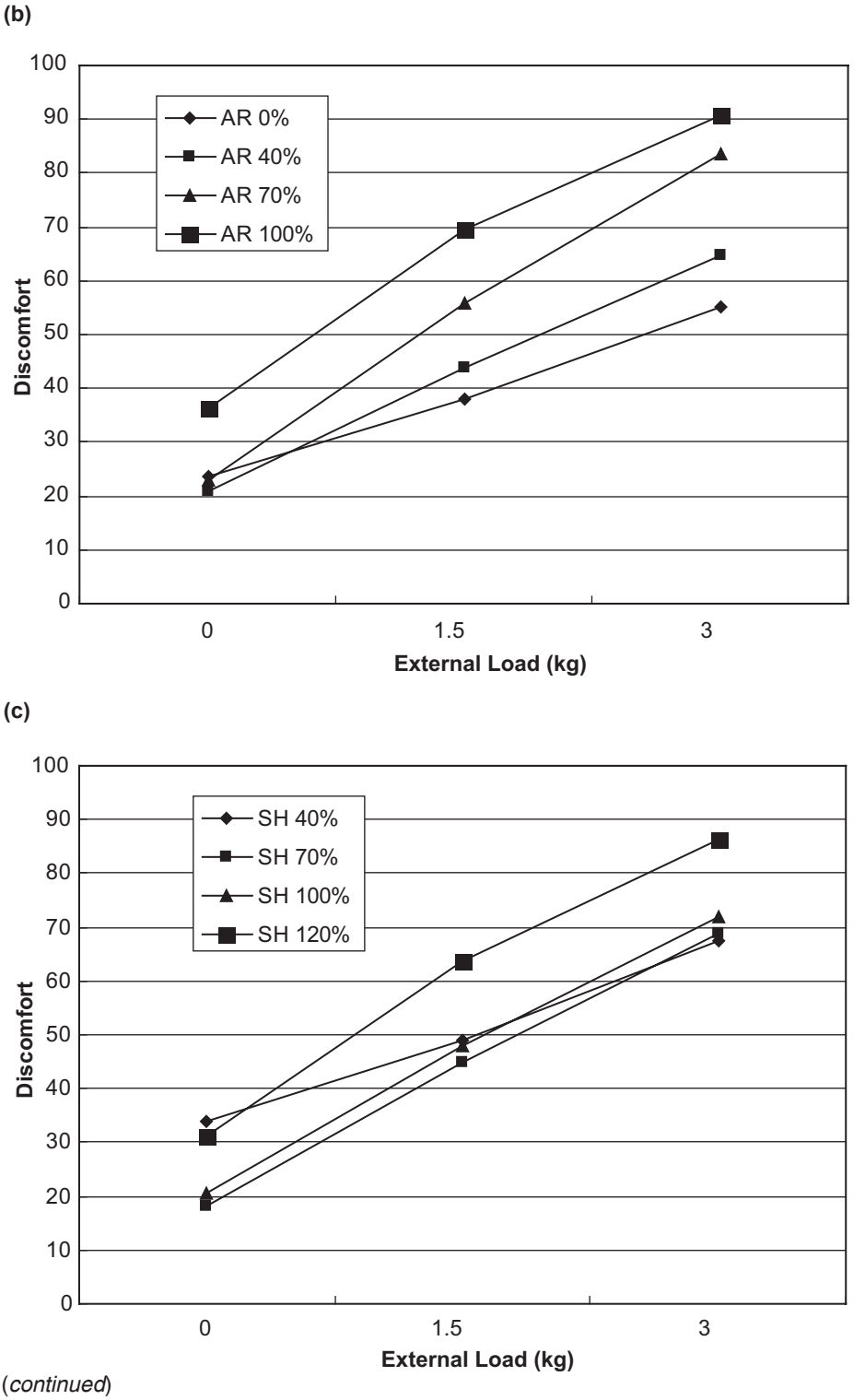

Figure 2. (*continued*)

increased from SH 70% to 120%, while discomfort decreased in the interval of hand height from SH 40% to 70%. Discomfort according to hand height were classified into three groups: SH 40%, 70% and 100%; SH 120% or 40%; and SH 100%, 70% and 120% (Figure 3b). In general, discomfort was seen to be quadratically related to hand height, whereas discomfort increased monotonically with external load (Figure 3c). Discomfort scores for external load had three distinct groups: 0, 1.5 and 3 kg.

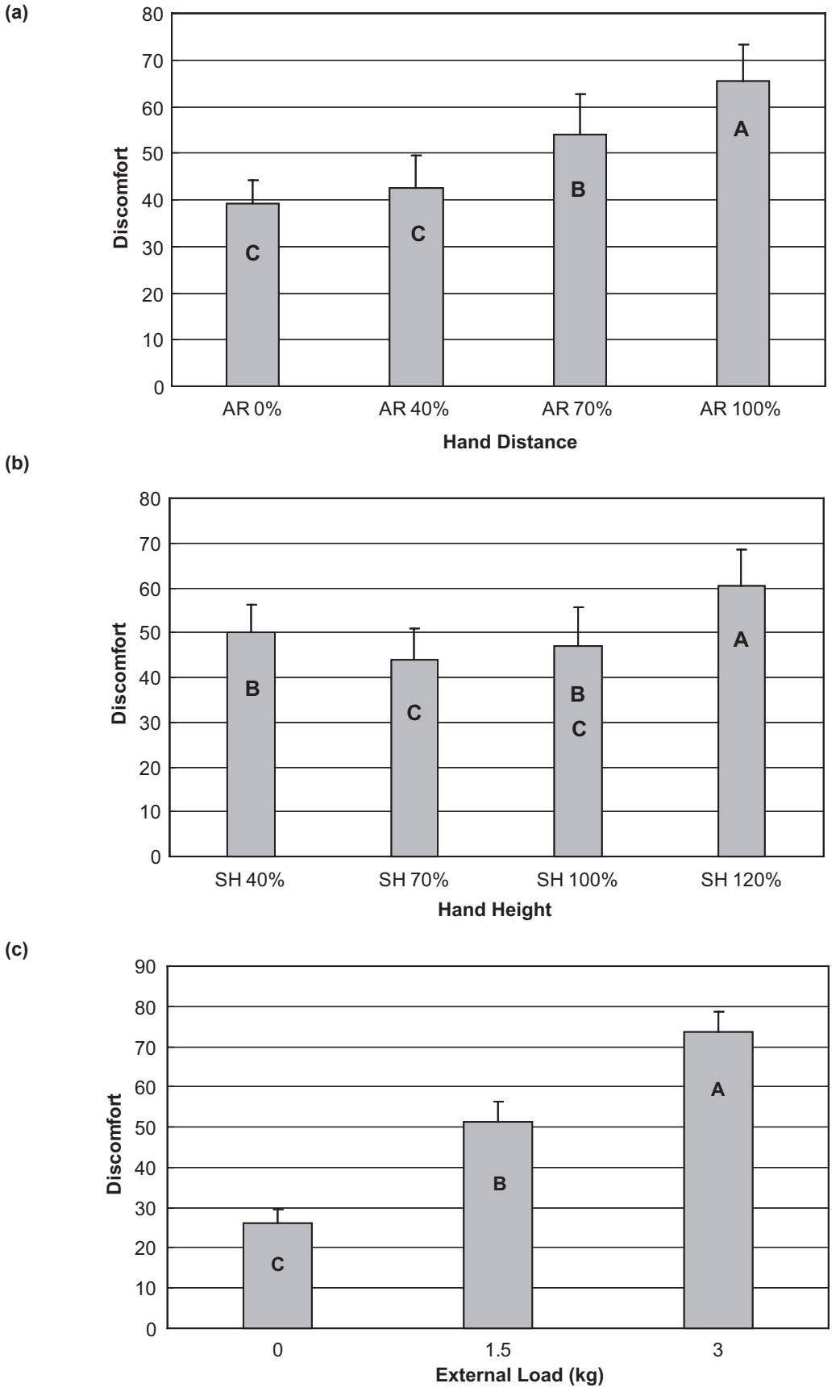

Figure 3. Discomfort by independent variables: (a) hand distance, (b) hand height, (c) external load. *Notes.* SH = shoulder height, AR = arm reach. Discomfort means with the same letter are not significantly different.

3.2. Regression Analysis

A significant three-way interaction in ANOVA means that the effect of external load varies according to hand positions. To investigate this effect, simple linear regression analyses were performed for each of the 16 experimental hand positions. External load weight was the independent variable and the average discomfort ratings of each posture for the 8 subjects were the dependent variable. The slope of the regression line indicated the relative effect of external load on perceived discomfort (i.e., discomfort/kilogram) at the 16 hand positions. Table 2 summarizes the 16 regression equations.

Tests for the null hypothesis, i.e., H_0: the slope is 0, showed that all slopes were nonzero at $\alpha = .05$. The coefficients of simple determination R^2 were at least .64, except for AR 0%, SH 40% ($R^2 = .22$), and AR 40%, SH 40% ($R^2 = .34$). ANOVA was conducted to examine the effect of hand positions, which were determined by hand height and hand distance, on the slope values (i.e., the effect of external load). The analysis showed that the main effects of hand distance and hand height were statistically significant at $\alpha = .05$. The interaction effect of hand distance and hand height was also statistically significant at $\alpha = .05$.

3.3. Classification of Effect of External Load

To group the slope values of the regression equations or the effects of external load, the SNK test was carried out for the slope values. Based on the SNK test, the 16 postures or hand positions were divided into three groups, each with a similar degree of discomfort (Table 3). Group A corresponded to postures with the smallest slope values at hand height of SH 40%, 70% and 100%, the slopes of which ranged from 7.04 to 10.83, with the average of 8.5. The characteristics of these postures are that horizontal hand distance from the shoulder joints is shorter than forearm length and the hand is below the shoulder (SH 100%).

Group B included postures with midrange slope values at SH 40%, 70%, 100%, and the smallest slope values at SH 120%. The slopes in group B were 14.17–16.65, with the average of 15.2. These postures were differentiated by the fact that hand distance was between AR 40% and 70% (the middle of forearm length and arm length), and that the hand was not above SH. Some cases showed that hand distance was the same as arm length (i.e., AR 100%, SH 40%) or that the hand was above the shoulder (i.e., AR 0%, SH 120%).

Group C consisted of the remaining postures, whose slopes were 17.83–24.67, with the average

TABLE 2. Summary of Regression Equations

	AR 0%		AR 40%		AR 70%		AR 100%	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
SH 40%	7.04	.22	7.63	.34	14.17	.75	15.58	.73
SH 70%	10.83	.69	16.75	.86	21.67	.94	18.08	.84
SH 100%	8.50	.64	14.17	.70	24.46	.89	21.17	.87
SH 120%	15.54	.77	19.88	.90	20.42	.91	17.83	.69

Notes. SH = shoulder height, AR = arm reach.

TABLE 3. Student–Newman–Keuls Grouping Test Results for the Slope of Each Posture (α = .05)

Group (Slope)	AR 0%	AR 40%	AR 70%	AR 100%
SH 40%	A (7.04)	A (7.63)	B (14.17)	B (15.58)
SH 70%	A (10.83)	B (16.75)	C (21.67)	C (18.08)
SH 100%	A (8.50)	B (14.17)	C (24.67)	C (21.17)
SH 120%	B (15.54)	C (19.88)	C (20.42)	C (17.83)

Notes. SH = shoulder height, AR = arm reach.

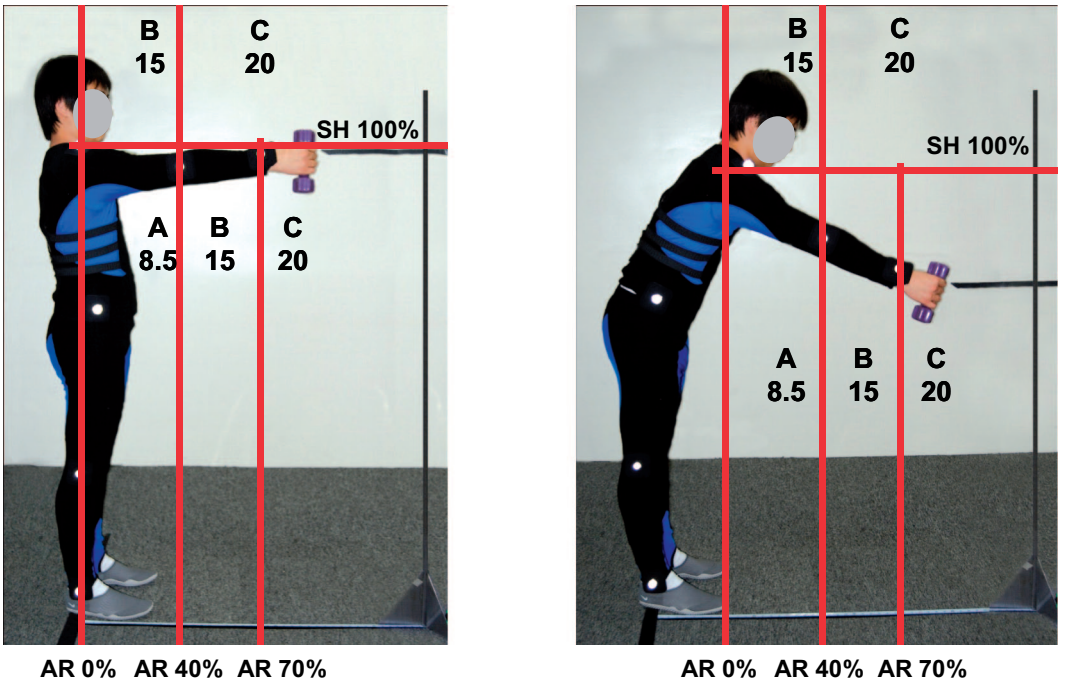

Figure 4. Schematization of the effect of external load on discomfort. *Notes.* A, B and C represent groups with a similar degree of discomfort.

of 20.5. The postures in group C were distinguished by the fact that hand distance was not shorter than AR 70%, and the hand was not above the shoulder, or that hand distance was longer than forearm length, and the hand was above the shoulder. Figure 4 shows the characteristics of the three groups.

On the basis of this classification, hand positions were categorized into three classes: light, moderate and severe. Next, each class was assigned a numerical relative discomfort score on the basis of a normalized value of discomfort for the light hand position, which was the least stressful of the three hand positions investigated (Table 4). A relative discomfort score of 1.0 was assigned to the light hand position as a reference score, thereby higher scores indicating that the hand position group was exposed to more stressful postures.

TABLE 4. Classification of External Load Effect

Hand Position	Description	Discomfort Score
Light	HH ≤ SH HD < FL	1.0 × load (kg)
Moderate	HH ≤ SH HD > FL HD < AR 70% or HH > SH HD < Fl	2.0 × load (kg)
Severe	HH ≤ SH HD ≥ AR 70% or HH > SH HD > FL	2.4 × load (kg)

Notes. HH = hand height, SH = shoulder height, HD = hand distance, FL forearm length, AR = arm reach.

4. DISCUSSION

Postural discomfort for 48 experimental treatments (16 postures with external load of 0, 1.5, 3 kg) was measured to quantify the effect of external load on varying hand positions. The hand positions were controlled by two independent variables: hand distance and hand height. ANOVA revealed that the main effects of the three independent variables on perceived discomfort were all significant (Table 1). This is in agreement with Boussenna, Corlett and Pheasant

[28], who reported that changes in postures were significantly correlated with changes in discomfort. Since the 16 experimental postures were largely affected by flexion of the elbow, shoulder, trunk and knee, the results of this study in part agree with the findings of Kee [19, 29] and Park [20]. Those studies also exhibited that elbow and shoulder flexion significantly affected perceived discomfort.The classification of external load newly developed in this study was based on subjectively perceived discomfort. Its weakness consists in not using objective measures such as biomechanical loading, psychophysical data, etc. However, the following facts justify this: (a) according to Corlett and Bishop [10] and Corlett and Manenica [11], an acceptable level of discomfort is a limit to posture holding time, and discomfort is a valid measure of postural load; (b) according to Boussenna et al., body-part discomfort is related to a more objective measure, e.g., the torque at the joint just distal to the site of discomfort [28]; (c) minimization of discomfort can contribute to reduced risk for musculoskeletal disorders [30] (d) discomfort can be considered as an independent evaluation criterion for static postures [30] and (e) warning provided by discomfort often indicates the inadequacy of the match between a person and that person's work [10].

Observational techniques including OWAS [7], RULA [8], REBA [9], etc., have been widely used to quantify postural loading. Although these techniques are equipped with three or four categories of load/force for assessing postural stress due to external load, they have some limitations. First, the categories of load/force are not based on objective and consistent grounds such as experimental data, but rather on subjective evaluations by workers, ergonomists, occupational physiotherapists, etc. [7, 8, 9, 14]. Second, although those methods were developed for specific industrial work and, accordingly, may be applicable to different tasks, the interval of the categories of load/force is too wide to assess exactly the effect of external load. For example, OWAS has three classes of load/force with intervals of 10 kg (0–10, >10–20, >20 kg). Third, the observational methods assign scores of the ordinal scale to each category for load/force without considering the hand or load/force positions. For example, OWAS assigns 1 to force/load of 0–10 kg, 2 to >10–20 kg and 3 to >20 kg. However, ANOVA for the slopes (i.e., the effect of external load on discomfort) in this study suggested that stress levels caused by external load differed depending on hand position. Based on this finding, this study presented a new classification of external load, considering at the same time its real weight and hand position. Furthermore, the category score based on the magnitude estimation method is a ratio scale that can be used with addition, subtraction, multiplication and division.

The new classification of external load has overcome the shortcomings discussed here, but it still has some limitations. First, external load was confined to 3 kg or under. So, the external load classification cannot be generalized to hand load exceeding 3 kg. However, much larger ranges of hand load are used in real-world tasks. Second, only posture held for 60 s and external load were investigated as independent variables among factors such as repetitiveness (frequency) and duration, which are known to affect perceived discomfort and mechanical exposure to musculoskeletal injury [3, 31]. Third, perceived discomfort was obtained only on static joint motions held for 60 s rather than on dynamic motions, which are more frequent in real work situations. Fourth, only young male graduate students participated in the experiment investigating the effect of external load. To generalize this study's findings, data on discomfort should be gathered for both female and male subjects from a wide range of age groups. Due to these limitations, caution is required when applying the developed external load classification scheme.

5. CONCLUSIONS

This study assessed the effect of hand positions and external load on 16 postures. Its results were as follows: (a) of the three independent variables, external load had the greatest effect on postural discomfort, followed by hand distance and hand height; (b) the effect of external load was significantly different depending on hand position

controlled by hand distance and height; (c) a new external load classification scheme was proposed on the basis of the experimental results.

In this study, maximum external load was limited to 3 kg or under, and the direction of external load was vertically downward, which is the same as the direction of gravity. Further studies investigating the effect of external load exceeding 3 kg and other force directions such as pressing, pushing, pulling, etc., are necessary.

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