ERGONOMICS, 1999, VOL. 42, NO. 9, 1216 – 1232

Significance of biomechanical and physiological variables during the determination of maximum acceptable weight of lift

MICHAEL J. JORGENSEN*†, KERMIT G. DAVIS†, BRYAN C. KIRKING‡, KAREN E. K. LEWIS† and WILLIAM S. MARRAS†

†The Biodynamics Laboratory, Ohio State University, 1971 Neil Avenue, 210 Baker Systems, Columbus, OH 43210, USA
‡Institute for Spinal Disorders, Baylor College of Medicine, Houston, TX 77030, USA

Keywords: Manual materials handling; Psychophysics; Low back disorders; Ergonomics.

The aim was to identify which biomechanical and physiological variables were associated with the decision to change the weight of lift during the determination of the maximum acceptable weight of lift (MAWL) in a psychophysical study. Fifteen male college students lifted a box of unknown weight at 4.3 lifts/min, and adjusted the weight until their MAWL was reached. Variables such as heart rate, trunk positions, velocities and accelerations were measured during the lifting, as well as estimated spinal loading in terms of moments and spinal forces in three dimensions using an EMG-assisted biomechanical model. Multiple logistic regression techniques identified variables associated with the decision to change the weights up and down prior to a subsequent lift. Results indicated that heart rate, predicted sagittal lift moment and low back disorder (LBD) risk index were associated with decreases in the weight prior to the next lift. Thus, historical measures of LBD risk (e.g. compression, shear force) were not associated with decreases in weight prior to the next lift. Additionally, the magnitudes of the predicted spinal forces and LBD risk were all very high at the MAWL when compared with literature sources of tolerance as well as observational studies on LBD risk. Our findings indicate that the psychophysical methodology may be useful for the decision to lower the weight of loads that may present extreme levels of risk of LBD; however, the psychophysical methodology does not seem to help in the decision to stop changing the weight at a safe load weight.

1. Introduction

With the elevated incidence and total cost of low back disorders (LBD) in industry as compared with other musculoskeletal disorders (Webster and Snook 1994, NIOSH 1997) an incentive exists for identifying approaches to reduce the risk of LBD. One approach has been to apply psychophysically determined 'acceptable' task parameters to the design of material handling jobs in the workplace (Snook 1978, Snook and Ciriello 1991). The psychophysical approach for determining acceptable weights of lift allows participants to select a maximum weight of the load, according to their perception of effort, by adding weight to or removing weight from a box, while avoiding overexertion or excessive fatigue (Snook 1978). The selected weight is then classified as the maximum acceptable weight of lift (MAWL). Thus, the objective of the psychophysical method is to reduce the incidence of LBD in industry

*Author for correspondence.

Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/JNLS/erg.htm
http://www.taylorandfrancis.com/JNLS/erg.htm

(Snook 1978, Snook and Ciriello 1991), with the major assumption behind the development of the MAWL for different task parameters that an individual can perceive when a lifting task will increase the risk of an LBD or physical damage (Gamberale 1990, Herrin *et al.* 1986).

The psychophysical approach has been used to assess the acceptable weights for material handling under a variety of different task characteristics as well as for different populations. Snook and Ciriello (1991) have developed a large database of MAWLs as a function of material handling task, gender, frequency of the task, start location and load travel distance. Asymmetric trunk postures during a lifting task (Garg and Badger 1986, Garg and Banaag 1988), the effects of adding handles to boxes (Garg and Saxena 1980) as well as the differences in maximum acceptable weight of lifts between experienced and inexperienced materials handlers (Mital 1987) have been assessed. Finally, the results of psychophysical studies on acceptable weights of lift have been incorporated into tools developed to assess the risk of LBD in material handling jobs (NIOSH 1981, Waters *et al.* 1993).

Some evidence suggests that the use of the psychophysical method to determine acceptable weights of lift that would accommodate a large majority of the population (75%) will reduce low back pain claims in industry by one-third (Snook *et al.* 1978). However, few epidemiological studies have addressed the psychophysical approach to assess its effectiveness as an intervention for reducing LBD incidence rates (Herrin *et al.* 1986).

Another approach used to estimate the injury potential of material handling tasks is to assess the tasks from a biomechanical perspective. Several researchers have associated the risk of LBD to biomechanical variables such as spinal compression and moment, as predicted by static biomechanical modelling techniques (Chaffin and Park 1973, Herrin *et al.* 1986). Increases in the magnitudes of biomechanical variables such as trunk velocities and awkward postures have been shown to result in increases of spinal loading as predicted by dynamic biomechanic models (Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995, Mirka and Marras 1993, Marras and Granata 1995, 1997) as well as increases in the probability that jobs that possess such motions and postures are members of a group jobs with high risk for LBD (Marras *et al.* 1993, 1995). These studies are further supported by cadaveric research (Adams and Hutton 1983, Adams *et al.* 1993, 1994) that showed that the initiation of failures to the intervertebral disc segments occurred under increases in magnitude and repetitive exposure to similar types of loading (e.g. bending moments, compression forces, etc.).

Although biomechanical variables have been shown to be important determinants of structural failure as well as of increases in risk of LBD, it is unclear if individuals are influenced by or react to biomechanical variables during a psychophysical determination of the MAWL, or if in fact individuals can perceive biomechanical variables when changing the weight of the load. For example, Thompson and Chaffin (1993), using a psychophysical lifting methodology, found no significant correlation between reported perceived exertion and the predicted compressive force at the lumbosacral joint, and they concluded that back stress is not well perceived by an individual. Chaffin and Page (1994) found that the recommended MAWLs from Snook and Ciriello (1991) for a lifting task originating at floor level resulted in compression forces on the L5/S1 intervertebral disc that were higher than the recommended NIOSH spinal loading limits (3400 N) using a biomechanical method of assessment.

It is apparent from cadaveric studies and epidemiologic research on LBD risk factors that biomechanical variables such as moments, forces and trunk motions influence the structural integrity of the spine and are associated with the reporting of LBD episodes. What is not clear, however, is the role that biomechanical variables play, if any, in the decision to change the weight of the load during the determination of the MAWL. The main objective of this research, therefore, was to identify and describe an association between biomechanical variables and the decision to change the weight during the determination of the 'acceptable' loads, given specific task parameters. Additionally, the magnitudes of the biomechanical variables that have been shown to compromise the structural integrity of the low back structures and increase the probability of high LBD risk group membership are documented at the resulting 'acceptable' loads.

2. Methods

2.1. *Subjects*

The participants for this study were of 15 male college students, with a mean (SD) age of 22.5 (2.0) years, and a mean height and weight of 109.1 (4.5) cm and 73.4 (6.6) kg, respectively. All participants were inexperienced in manual material handling and none reported a current episode of low back pain.

2.2. *Experimental design*

The experimental design consisted of a repeated measures approach, where each participant was subjected to each of the experimental conditions. To address the objective of identifying variables that may influence an individual's decision either to change or not to change the weight prior to the next lift, logistic regression techniques were used. Logistic regression techniques are appropriate in this case as it was desired to model a binary dependent variable, such as 'change' or 'no change' in weight, and the independent variables could be either categorical or continuous. The logistic regression models were restricted to the first eight trials for each lifting condition. This range was used since most of the changes of the weight were within the first eight lifts, and by not including all the no change trials (which signalled the end of the lifting condition), the resulting logistic regressions models were not artificially influenced by an excessive number of no change trials. Additionally, to reduce any confounding or masking effect of the independent variables due to the direction of the weight change (up or down), the conditions with the five highest initial weights were used to assess the down changes, and the conditions with the five lowest initial weights were used to assess the up changes of weight. This approach was also considered appropriate as most psychophysical studies are carried out by starting participants at both high and low weights, and having them adjust toward their MAWL.

The dependent variable consisted of a dichotomous change of weight variable (i.e. change up and no change for assessing the increases of the weight, and change down and no change when assessing the decreases in the weight). The independent variables consisted of the categorized and standardized predicted maximum spinal moments, the predicted maximum forces on the L5/S1 joint, the maximum trunk positions, velocities and accelerations in each of the three planes, the resulting LBD risk index and heart rate. The standardization and categorization processes are discussed below. Additionally, it was hypothesized that the initial weight and lifting trial number might be confounders, as they might be associated with the decision to change or not to change the weight, as well as with the resulting magnitudes of the independent variables. Therefore, all logistic regression models were generated while controlling for initial weight and lifting trial effects. Since multiple observations were obtained from each participant, the participant effect was also controlled for when building the logistic regression models.

2.3. *Experimental task*

The study was carried out using a modified psychophysical procedure. Ten lifting conditions were performed by each participant, with each condition beginning at a different initial weight. Five of the lifting conditions began with loads greater than the estimated MAWL while the remaining five lifting conditions began at loads less than the estimated MAWL (Ciriello *et al.* 1990, 1993). The participants were permitted to add or remove as much weight from the box as desired between lift trials, and continued to lift the box until the weight was unchanged for eight consecutive lift trials. Since electromyography (EMG) was being used in this study, the use of this modified psychophysical approach reduced the chance for fatigue, which, if present, would alter the EMG signal. For the purposes of this study, this weight was defined as the MAWL. The participants, however, were not aware of this criterion for ending the lifting condition. To simulate a manual material-handling task, the subjects lifted a box from knee height, carried it for 5 feet and placed it on a shelf at elbow height. The lift rate was 4.3 lifts/min, which has been used in previous psychophysical studies (Snook and Ciriello 1991, Ciriello *et al.* 1993).

2.4. *Apparatus*

Participants moved a box of dimensions 25.4 × 42.5 × 32.4 cm (height × width × depth). Handles were 20.3 cm from the bottom of the box. Weights consisted of 42 kg of metal filings separated into 0.91 kg packages of similar size and shape. The box was similar in size to the large box used in the Snook and Ciriello (1991) studies.

A lumbar motion monitor (LMM), which is essentially an exoskeleton of the spine, was used to collect the three-dimensional kinematic trunk variables (Marras *et al.* 1992, 1993). Horizontal moment – arm distances between the approximate location of the L5/S1 disc and the hands were measured by a tape measure during the lifting and lowering phases of the task. The moment – arm was then combined with the weight of the box to estimate the maximum static moment for input into the LBD risk model developed by Marras *et al.* (1993, 1995).

Participant heart rate was obtained by use of a Polar Favor Heart Rate Monitor (Polar CIC, Inc., Port Washington, NY, USA). The monitor transmitted the heart rate to a digital readout on a wrist receiver.

Electromyographic (EMG) activity was collected through the use of bipolar silver – silver chloride surface electrodes spaced ~3 cm apart over 10 trunk muscles (right and left erector spinae; right and left latissimus dorsi; right and left internal obliques; right and left external obliques; and right and left rectus abdominis) (Mirka and Marras 1993).

The EMG-assisted biomechanical model used to estimate spinal loading (Marras and Sommerich 1991a,b, Granata and Marras 1993, 1995, Marras and Granata 1995, 1997) requires calibration exertions using a force plate (Bertec 4060A, Worthington, OH, USA) and an L5/S1 locator (Fathallah *et al.* 1997) to determine participant-specific muscle gain. Using methods developed by Fathallah *et al.* (1997), the participant-specific muscle gain was determined. The magnitude of the muscle gain represents the force output of the muscle per cross-sectional unit area for that particular participant. This gain factor was then used to calculate the internal moments and forces for the experimental task to allow the participants to move without being restricted to a force plate.

All signals from the above equipment (except heart rate, as noted below) were collected simultaneously through customized Windows™-based software developed in-house. The signals were collected at 100 Hz and recorded on a 486 portable computer via an analogue-to-digital conversion board.

2.5. *Experimental procedure*

Surface electrodes were applied to the trunk muscles specified above using standard placement procedures (Marras 1990). The heart rate transmitter was placed across the participant's chest at the level of the xyphoid process. The participant was then placed in a structure that allowed maximum voluntary contractions (MVCs) of the trunk to be performed in six directions (Mirka and Marras 1993). All subsequent EMG data for the calibration exertions and the experimental tasks were normalized to these MVCs. To reduce fatigue effects, a 2-min rest was given after every MVC (Caldwell *et al*. 1974).

The LMM was then placed on the participant's back and calibration exertions were performed with the participant standing on the force plate. These sagittally symmetric exertions required the participant to lift a 22.7 kg (50 lb) box from knee height to elbow height. Five calibration exertions were performed at the beginning, at the midpoint (after five lifting conditions) and at the end of the experiment.

After completing the first set of calibration exertions, the participant read the experimental instructions (see Appendix), which were also repeated verbally to ensure comprehension. A computer-generated tone signalled the subject to perform each lift. The box was returned to the starting position by an experimenter and the participant was permitted to make any desired changes in the weight of the box until the next tone sounded. The heart rate was recorded at the completion of each lift, as well as the amount of weight in the box, which was measured by a force plate.

Each of the 10 lifting conditions began at a different weight. Initial weights of 9.1, 11.8, 14.5, 17.2, 20.0, 29.9, 32.7, 35.4, 38.1 and 41.7 kg were presented in random order to each participant. Participants were required to attempt to lift each weight, even if a lift or placement on the shelf could not be completed. After the attempt, the participant was allowed to change the weight.

2.6. *Data analyses*

Voltages were collected from the LMM, which were converted into trunk angles, velocities and accelerations through customized conversion software. The 'probability of high risk group membership' (here after referred to as 'LBD risk index') was calculated using the multiple logistic regression equation developed by Marras *et al.* (1993). The EMG and kinematic data were imported into an EMG-assisted spinal loading model to predict spinal forces and moments in three planes on the L5/S1 joint.

2.7. *Statistical analysis*

Descriptive statistics were generated to describe the kinematics (trunk position, velocities and accelerations), LBD risk index, heart rate and the spinal loading (moments and forces) for each of the 10 lifting conditions across the last eight lifts of each condition. This identifies the magnitude of each variable at the MAWL.

For the logistic regression analysis each independent variable was categorized by identifying cut-off values that best separated the trials with no changes from the trials with changes (acceptable and unacceptable categories). To identify a common cut-off value that would be independent of intersubject variability for each independent variable, the data for each independent variable were standardized to the mean and variance of the trials of the respective independent variable at the MAWL. This standardization was also performed to allow the data to be interpreted in reference to a common point, the participant's MAWL.

Thus, for each participant, each independent variable was standardized by the following equation:

$$X_s = \frac{X_{ij} - X_{\mathrm{mawl}}}{S_{\mathrm{mawl}}}, \qquad (1)$$

where X_s is the participant-specific standardized independent variable; X_{ij} is the measured independent variable from each participant for lifting condition i and lifting trial j; X_{mawl} is the mean of the variable across the MAWL trials for each participant; and S_{mawl} is the standard deviation of the variable across the MAWL trials for each participant.

The standardized variables were then interpreted as follows: zero values correspond to the mean of the variable at the MAWL trials, while + 1.0 represents values that are 1 SD (of the MAWL trials) greater than the mean of the MAWL trials. Similarly, − 1.0 represents values that are 1 SD (of the MAWL trials) less than the mean of the MAWL trials. Each independent variable was then categorized by selecting a cut-off value and assigning all standardized values greater than the cut-off a value of 1, and all standardized values less than the cut-off a value of zero. The nine cut-offs for each independent variable were determined by selecting a value ranging from − 2.0 to + 2.0 SD around the MAWL mean in 0.5 SD increments.

Initially, univariate logistic regression was performed to assess the individual associations in terms of the odds' ratios of changing the weight up or down, independently, versus not changing the weight. Multiple logistic regression was performed on several theoretical models for evaluating the up changes as well as the down changes in the weight. Stepwise logistic regression was used to determine which cut-off value was to be used for each independent variable. Wald χ^2-tests assessed the significance of each independent variable for the univariate logistic regression models, with a significance level of $\alpha = 0.05$. Wald χ^2-tests and χ^2-tests on the deviance were used to assess the significance of additional variables entered into the multiple logistic regression models. The fit of the model was assessed by the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989). Additionally, the predictive ability of the final model was determined by evaluating the Goodman – Kruskal γ statistic. All statistical analyses were performed using the SAS (1982) statistical software.

3. Results

3.1. *Descriptive statistics at the MAWL*

The resulting spinal loading and LBD risk values at the MAWL are shown for each lifting condition in table 1. Generally, the final average MAWL across all 15 participants were very similar for all 10 conditions, ranging from 24.3 to 28.9 kg. The predicted sagittal moment was also very similar across the 10 conditions. The average of the maximum spinal forces ranged from 561.5 N (9.1 kg initial weight) to

Table 1. Mean (SD) MAWL, heart rate, spinal loading and probability of high-risk group membership for each initial weight (averaged across 15 subjects) at the eight MAWL trials.

			Spinal loading				
Condition initial weight (kg)	MAWL (kg)	Heart rate (bpm)	Sagittal moment (Nm)	Lateral shear force (N)	A/P shear force (N)	Compression force (N)	LBD risk index
9.1	24.9	123	239.7	561.5	1091.1	5174.4	0.57
	(7.3)	(16)	(101.2)	(366.6)	(683.5)	(2226.2)	(0.20)
11.8	26.9	120	265.2	590.0	1188.1	5697.2	0.63
	(7.4)	(17)	(108.1)	(398.8)	(639.9)	(2307.5)	(0.17)
14.5	24.3	122	253.0	645.1	1161.0	5482.9	0.56
	(7.4)	(17)	(120.0)	(497.7)	(712.2)	(2556.1)	(0.23)
17.4	25.3	121	249.3	600.7	1158.9	5367.6	0.58
	(6.6)	(16)	(106.0)	(427.4)	(606.4)	(2229.8)	(0.19)
20.0	27.0	119	269.7	756.3	1499.3	5958.8	0.61
	(7.5)	(19)	(111.1)	(624.0)	(1315.9)	(2675.2)	(0.21)
29.9	26.1	122	257.7	809.9	1185.5	5592.4	0.58
	(7.1)	(16)	(112.3)	(656.8)	(695.2)	(2396.6)	(0.19)
32.7	27.2	119	270.1	761.5	1300.2	5947.2	0.61
	(6.9)	(15)	(111.2)	(518.5)	(756.9)	(2340.0)	(0.19)
35.4	28.9	121	264.7	693.1	1181.5	5712.1	0.62
	(8.6)	(17)	(105.3)	(440.1)	(582.1)	(2324.4)	(0.24)
38.1	28.6	124	265.3	667.9	1196.4	5693.1	0.62
	(8.0)	(16)	(99.6)	(446.8)	(602.1)	(2060.2)	(0.18)
41.7	27.1	125	259.0	623.3	1136.1	5563.0	0.63
	(9.6)	(17)	(95.8)	(424.9)	(428.5)	(1966.4)	(0.21)

809.9 N (29.9 kg initial weight) for lateral shear, 1091.1 N (9.1 kg initial weight) to 1499.3 N (20.0 kg initial weight) for anterior/posterior (A/P) shear, and 5174.4 N (9.1 kg initial weight) to 5958.8 N (20.0 kg initial weight) for compressive force on the L5/S1 intervertebral disc. Additionally, the LBD risk index remained relatively stable across all 10 conditions, ranging from 56% (14.5 kg initial weight) to 63% (11.8 and 41.7 kg initial weights). Heart rate was very consistent across all the conditions, ranging from 119 to 125 bpm.

3.2. *Univariate logistic regression results in predicting changes in weight*

Table 2 shows the results of the univariate logistic regression for the odds' ratio of *changing the weight up versus no change in the weight* while controlling for participant, lifting trial and initial weight effects. Only the lateral shear force, sagittal velocity and heart rate were non-significant at the $\alpha = 0.05$ level. Significant odds' ratios (ORs) > 1.0 are interpreted as an increase in the odds of increasing the weight versus not changing the weight, when the standardized magnitude of the variable is greater than the cut-off value (number of SD above the mean at the MAWL trials). For example, the participant is 2.66 times more likely to change the weight up versus not change the weight before the next lift if the sagittal acceleration is 1.5 SD above the mean sagittal acceleration for the participant at the MAWL. OR < 1.0 are interpreted as a decrease in the odds that the participant changes the weight up versus not changing the weight. OR < 1.0 can also be interpreted as an increase in the odds of not changing the weight versus changing the weight up.

Table 2. Univariate logistic regression model parameters for the odds of *changing up* versus the odds of no change of weight, while controlling for participant, lifting trial and initial weight effects.

Variable	Cut-off value*	Parameter (β)	Standard error	p	Odds' ratio[+]
Lateral shear (N)	1.5	– 0.6550	0.4993	0.1900	0.52
A/P shear (N)	– 1.5	– 1.1910	0.5043	0.0200	0.30
Compression (N)	– 1.0	– 0.8997	0.2491	0.0003	0.41
Sagittal moment (Nm)	– 1.5	– 1.3807	0.3171	0.0001	0.25
Lateral moment (Nm)	– 1.5	– 1.2863	0.4738	0.0100	0.28
Twisting moment (Nm)	– 1.5	– 1.5553	0.5094	0.0020	0.21
Resultant moment (Nm)	– 1.5	– 1.3839	0.3430	0.0001	0.25
Sagittal position (deg)	1.5	0.8554	0.3970	0.0300	2.35
Lateral position (deg)	– 1.5	– 1.2733	0.4462	0.0040	0.28
Twist position (deg)	– 1.5	– 1.2200	0.4169	0.0030	0.30
Sagittal velocity (deg/s)	2.0	0.6678	0.4279	0.1200	1.95
Lateral velocity (deg/s)	– 1.5	– 1.0629	0.4507	0.0200	0.35
Twist velocity (deg/s)	– 1.5	– 1.3345	0.5476	0.0100	0.26
Sagittal acceleration (deg/s^2)	1.5	0.9770	0.3714	0.0100	2.66
Lateral acceleration (deg/s^2)	– 0.5	– 1.2656	0.5250	0.0200	3.55
Twist acceleration (deg/s^2)	– 0.5	– 1.0607	0.5115	0.0300	2.89
LBD risk index (%)	– 1.0	– 1.0969	0.2330	0.0001	0.33
Heart rate (bpm)	1.0	– 1.2782	0.8016	0.1100	0.28

*Number of SD above or below the average at the MAWL.

[+] The odds' ratio refers to the odds of changing the weight up versus the odds of not changing the weight for the next lift. Odds' ratio > 1.0 indicates an increased likelihood for increasing the weight before the next lift, and one < 1.0 indicates a decreased likelihood for increasing the weight before the next lift.

Table 3 shows the results of the univariate logistic regression for the ORs of *changing the weight down versus no change in the weight*. All independent variables except lateral position, lateral velocity, twist velocity, sagittal acceleration and twist acceleration were significant at the $\alpha = 0.05$ level. The model variables should be interpreted in the same way as in table 2, except that the ORs represent the likelihood of making a change *down* versus not changing the weight before the next lift, given the levels of the independent variables.

3.3. *Multiple logistic regression models predicting changes of weights*

As shown in table 4, the final multiple logistic regression model for predicting the *up changes* of weight includes the maximum twisting velocity and the A/P shear force. The cut-off value defining the best separation between up changes and no changes for maximum twist velocity was at 1.5 SD below the mean of the MAWL trials. This indicates that when the maximum twist velocity > 1.5 SD below the mean maximum twist velocity at the MAWL, there was a decrease in the odds of changing the weight up, or equivalently, more than a 4-fold increase in the likelihood of not changing the weight versus changing the weight up on the next lift. For the A/P shear force, the cut-off value corresponded to the mean of the MAWL trials, which indicates that when the A/P shear force of the lifting trials exceeded the mean of the A/P shear force at the MAWL, there was a decrease in the likelihood of changing the weight up versus not changing the weight. Equivalently, participants were almost twice as likely

Table 3. Univariate logistic regression model parameters for the odds of *changing down* versus the odds of no change of weight, while controlling for participant, lifting trial and initial weight effects.

Variable	Cut-off value*	Parameter (β)	Standard error	p	Odds' ratio[+]
Lateral shear (N)	1.0	0.5475	0.2354	0.0200	1.73
A/P shear (N)	1.0	1.1839	0.2304	0.0001	3.27
Compression (N)	1.5	1.2670	0.2305	0.0001	3.55
Sagittal moment (Nm)	1.5	1.5894	0.2295	0.0001	4.90
Lateral moment (Nm)	− 1.0	0.8765	0.2985	0.0030	2.40
Twisting moment (Nm)	0.0	0.6222	0.1922	0.0010	1.86
Resultant moment (Nm)	1.0	1.2152	0.2067	0.0001	3.37
Sagittal position (deg)	− 1.5	1.1292	0.4993	0.0200	3.09
Lateral position (deg)	1.0	0.2295	0.2153	0.2865	1.26
Twist position (deg)	1.5	− 0.7815	0.3003	0.0100	0.46
Sagittal velocity (deg/s)	− 2.0	− 1.5193	0.6773	0.0200	0.22
Lateral velocity (deg/s)	− 0.5	− 0.2998	0.2085	0.1500	0.74
Twist velocity (deg/s)	2.0	− 0.7520	0.4484	0.0900	0.47
Sagittal acceleration (deg/s^2)	− 1.5	− 0.6607	0.3653	0.0700	0.52
Lateral acceleration (deg/s^2)	− 0.5	− 2.0259	0.7428	0.0060	0.13
Twist acceleration (deg/s^2)	0.5	− 0.4513	0.2419	0.0600	0.64
LBD risk index (%)	1.5	1.9481	0.2359	0.0001	7.02
Heart rate (bpm)	1.0	1.6421	0.3015	0.0001	5.17

*Number of SD above or below the average at the MAWL.

[+] The odds' ratio refers to the odds of changing the weight down versus the odds of not changing the weight for the next lift. Odds' ratio > 1.0 indicate an increased likelihood for decreasing the weight before the next lift, and one < 1.0 indicates a decreased likelihood for decreasing the weight before the next lift.

not to change the weight than change the weight up when the A/P shear force exceeded the mean A/P shear force at the MAWL.

The final multiple logistic regression model for predicting the *down changes* of weight included the maximum sagittal moment, heart rate and LBD risk index (table 5). The cut-off value defining the best separation between down changes and no changes for maximum sagittal moment and LBD risk index occurred at 1.5 SD above the mean of the MAWL trials. Likewise, the cut-off value defining the best separation between down changes and no changes of weight for the heart rate occurred at 1.0 SD above the mean heart rate at the MAWL. Thus, when either the maximum sagittal moment or the LBD risk > 1.5 SD above the respective mean values at the MAWL, there was an increase in the odds of changing the weight down versus not changing the weight before the next lift. Equivalently, when heart rate > 1.0 SD above the mean heart rate at the MAWL, there was almost a 5-fold increase in the likelihood of changing the weight down versus not changing the weight before the next lift.

Table 4. Multiple logisitc regression model parameters for odds of *changing up* versus odds of no change of weight during the first eight lifts.

Variable	Cut-off value*	Parameter (β)	Standard error	p	Odds' ratio[+]	95% CI for odds' ratio
Intercept	—	8.981	0.892	0.0001	—	—
Participant	—	– 0.190	0.029	0.0001	0.83	0.78 – 0.87
Initial weight	—	– 0.191	0.031	0.0001	0.83	0.78 – 0.88
Lift trial	—	– 0.661	0.060	0.0001	0.52	0.46 – 0.58
Maximum twist velocity (deg/s)	– 1.5	– 1.538	0.557	0.0058	0.22	0.07 – 0.64
A/P shear force (N)	0.0	– 0.653	0.249	0.0088	0.52	0.32 – 0.85

*Number of SD above or below the average of the variable at the MAWL.

[+] The odds' ratio refers to the odds of changing the weight up versus the odds of not changing the weight for the next lift. Odds' ratio > 1.0 indicate an increased likelihood for increasing the weight before the next lift, and one < 1.0 indicates a decreased likelihood for increasing the weight before the next lift.

Table 5. Multiple logistic regression model parameters for odds of *changing down* versus odds of no change of weight during the first eight lifts.

Variable	Cut-off value*	Parameter (β)	Standard error	p	Odds' ratio[+]	95% CI for odds' ratio
Intercept	—	– 1.134	0.954	0.2349	—	—
Participant	—	– 0.055	0.025	0.0296	0.95	0.90 – 0.99
Initial weight	—	0.076	0.026	0.0041	1.08	1.02 – 1.14
Lift trial	—	– 0.515	0.056	0.0001	0.60	0.54 – 0.67
Sagittal moment (Nm)	+ 1.5	0.907	0.267	0.0007	2.48	1.47 – 4.18
Heart rate (bpm)	+ 1.0	1.593	0.341	0.0001	4.92	2.52 – 9.56
LBD risk index (%)	+ 1.5	1.547	0.263	0.0001	4.70	2.81 – 7.87

*Number of SD above or below the average of the variable at the MAWL.

[+] The odds' ratio refers to the odds of changing the weight down versus the odds of not changing the weight for the next lift. Odds' ratio > 1.0 indicate an increased likelihood for decreasing the weight before the next lift, and one < 1.0 indicates a decreased likelihood for decreasing the weight before the next lift.

The performance and internal validity of the two multiple logistic regression models were evaluated using the Goodman – Kruskal γ, as well a goodness-of-fit test to assess the predictive ability of the model. As shown in table 6, both the up-change ($\gamma = 0.76$) and down-change ($\gamma = 0.70$) logistic regression models resulted in similar γ's, indicating that the both models resulted in similar predictability of changes and no changes. However, addition of the biomechanical variables for the up-change model resulted in very little additional predictability (increase of 3%), as compared with the down-change model after the biomechanical variables and heart rate were added to the model (increase of 32%). Finally, the internal validity of both multiple logistic regression models was deemed adequate using the Hosmer – Lemeshow goodness-of-fit test (Hosmer and Lemeshow 1989).

4. Discussion

This work has facilitated the understanding of the biomechanical variables associated with changes of weight during a psychophysical experiment. It also illustrates the magnitudes of the variables that have historically been used to estimate risk of LBD. Very little difference existed between the up-change and down-change prediction models (Goodman – Kruskal $\gamma = 0.76$ for the up-change model, and $\gamma = 0.70$ for the down-change model). However, the increase in predictive ability after controlling for participant and experimental effects (i.e. initial weight and lifting trial) was quite different between the two models. Even though the up-change model had significant ORs for the A/P shear force and maximum twist velocity, inclusion of these variables only increased the predictive value of the model from 0.736 to 0.76, or an increase of 3% above participant, initial weight and lifting trial. Thus, it appears that adding biomechanical variables, although significant in the model, provides very

Table 6. Goodman – Kruskal γ values for predictability of the models for both the up-change and down-change multiple logistic regression models.

Model	Model variables	Goodman – Kruskal γ
Up-changes	Participant Lift condition Lift trial	0.732
	Participant Lift condition Lift trial A/P shear force Twist velocity	0.76
Down changes	Participant Lift condition Lift trial	0.532
	Participant Lift condition Lift trial Sagittal moment LBD risk index Heart rate	0.70

little additional predictive ability for changing up versus not changing the weight for the next lift.

The prediction of down-changes of weight appeared more dependent on the exposure variables (biomechanical variables and heart rate) than in the up-change model, as the independent variables accounted for a higher percentage of the predictability (increase of 32%, from a baseline of $\gamma = 0.532 - 0.700$) as compared with the up-change model. This suggests that for this study the participants may have based their decision to decrease the weight in part on biomechanical variables.

The presence of sagittal moment in the down-change model is consistent with the observation that some form of moment is also included in other models for biomechanical based risk analyses. For example, the horizontal distance factor, which is part of moment, is present in the NIOSH lifting equations (NIOSH 1981, Waters *et al.* 1993). Chaffin and Park (1973) essentially calculated the maximum moment when identifying the most stressful part of a person's task to calculate the lifting strength ratio; and the maximum moment of a person's task was found to be the single greatest predictor of the LBD risk index in repetitive material handling jobs (Marras *et al.* 1993, 1995). Furthermore, differences between MAWLs from different psychophysical studies were reduced after correcting for differences in the lifting moment (Davis *et al.* 1997), indicating the importance that the lifting moment plays in MAWL determination. The presence of sagittal moment in the logistic regression models of this study, as well as its presence in existing risk analysis methods, indicates 'consensus' validity in that it has been consistently identified as an important factor associated with LBD.

The LBD risk index, as calculated by Marras *et al.* (1993), also appears to be an important variable when assessing what individuals may be responding to. Although the LBD risk index represents a combination of biomechanical variables (maximum static moment, lift rate, lateral and twist velocities, and maximum sagittal position), and participants may not necessarily be able to perceive this index by itself, it did have the highest OR in the univariate case (= 7.02), and remained significant in the final model. This may indicate that the decision process may be very complex in nature, drawing on several cues.

The most surprising result in the down-change model was the inclusion of heart rate and the magnitude of its OR. The heart rate resulted in the second highest univariate OR (= 5.17) and remained virtually unchanged when included in the final model (OR = 4.92). This indicates that heart rate was associated to the down-changes almost independently of the sagittal moment and the LBD risk index. The presence of the heart rate in this study may be reflective of the high rate of lifting (4.3 lifts/min). Although no other rates of lifting were investigated in this study, previous research has suggested that psychophysical tests at frequencies > 4.3 lifts/min will result in higher MAWLs than weight limits based on physiological criteria such as oxygen consumption and heart rate (Ciriello *et al.* 1990).

The finding that both biomechanical variables and heart rate are important predictors of down-changes in weight during the determination of MAWL is consistent with the findings of Karwowski and Ayoub (1984) in that the psychophysical methodology appears to integrate both biomechanical and physiological attributes. Heart rate has typically been used as a surrogate measure of physiological stress (Garg and Ayoub 1980, Mital 1985, 1986, Kumar and Mital 1992). However, evidence is lacking that elevated levels of physiological stress are associated specifically with LBD incidence (Leamon 1994). Thus, the findings of this study, while consistent with previous assertions that biomechanical and physiological indices may be integrated, suggest that the psychophysical methodology might not identify loads that result in a reduction of risk specific to LBD, but may in fact be more effective in the reduction of other stresses such as physiological stress that may lead to whole-body fatigue. This may be a result of the instructions given to the participant before the psychophysical study is initiated, which do not mention specifically to make adjustments based on perceived fatigue, strain or overexertion to the low back area (Snook and Ciriello 1974, 1991, Ciriello and Snook 1983).

Finally, the absence of spinal forces (e.g. compression and shear forces) in the final logistic regression model for decreasing the weight prior to the next lift was not a complete surprise. Reviews of the literature by Cavanaugh (1995) suggest controversy about the presence of free nerve endings (nociceptors) within and around the intervertebral disc. While early research found no presence of innervation of nociceptors in the intervertebral disc, more recent researchers have found nociceptors within the superficial layers of the posterior annulus of normal discs (Cavanaugh 1995). One possible hypothesis for the absence of spinal loading variables in the down-change model might be that the forces generated about the disc during the experimental task, although they approached the estimates for spine load tolerance, were not of sufficient magnitude to create enough pressure inside the intervertebral disc to stress the outer most layers of the annulus fibrosis. Adams *et al.* (1996) have found that under uniform compression forces on cadaver intervertebral motion segments, the peak stresses were highest in the nucleus and inner portions of the posterior annulus fibrosis, but were virtually non-existent at the outer layers of the posterior annulus fibrosis. Following this line of reasoning, if nociceptors penetrated further into the annulus, under high levels of spinal loading, the participants might key on feedback from pain stimuli. Free nerve endings (nociceptors) have been found to be present within the annulus of abnormal discs, to as much as one-half the depth of the annulus (Yoshizawa *et al.* 1980). Since the participants in this study were young healthy males with no reported history of back pain, it is likely that the presence of any nociceptors was limited to the outer layers of their intervertebral discs.

While the logistic regression models indicated that certain biomechanical variables were important determinants of whether a person changed the weight of the load, the magnitudes of commonly used LBD risk indicators at the MAWL were all quite high as compared with previous literature sources. The predicted spinal compression forces ranged from 5174 to 5959 N, and shear forces ranged from 561 to 1499 N, which are comparable with previously reported tolerances from the literature. Jager and Luttmann (1991) describe the average lumbar compressive strength of 20–30-year-old males to be ~7500 N, with older populations having even lower tolerance limits to compression. According to NIOSH (1981), microfractures of the vertebral endplates would be expected in 50% of the working population at compressions of 6400 N. McGill (1996) estimates the shear force tolerance of L5/S1 as 1000 N; similarly, Farfan (1989) estimates the shear force tolerance of L5/S1 as 900 N. Similar findings of large forces at the MAWL have been reported by Chaffin and Page (1994), who found compressive forces as high as 8000 N (mean of ~5500 N) during lifts originating at the floor, using a two-dimensional static model. Thus, based on published spinal tolerance data, the estimated spinal forces in this study are very high at the MAWL, and even though these weights were deemed acceptable by the subjects, these MAWLs would be labelled as having high risk for LBD.

The resulting LBD risk index values at the MAWL (ranged between 0.56 and 0.63) also indicate that this experimental task would be identified as having high risk of LBD. Marras *et al*. (1998) indicate that probability values > 0.60 consisted mostly of high risk jobs (93.3%), which were jobs that had incidence rates for low back injuries of at least 12.0/100 persons/year (mean of 26.3). Additionally, the most conservative estimate of the MAWL from this study (24.3 kg) is 2.3 times greater than the mean maximum weight handled for the high-risk jobs studied by Marras *et al*. (1993).

Other methods for assessing risk of LBD using the resulting MAWL and experimental task parameters also indicate that high risk of LBD exists. Application of the 1991 NIOSH lifting equation (Waters *et al*. 1993) resulted in 100% of the MAWL lifting trials having a lifting index (LI) > 1.0, and 97.6% with LI > 3.0, where the average lifting index was 7.07. NIOSH considers any LI > 1.0 to indicate an elevated risk of LBD. Similarly, using the NIOSH Work Practice Guide (NIOSH 1981), 97.6% of the MAWL lifting trials were above the action limit (AL) and 19.1% above the maximum permissible limit (MPL). Thus, based on all the methods of risk evaluation mentioned above, it is apparent that these participants chose MAWLs using psychophysical methods that would be considered to have an elevated risk of LBD.

Several limitations must be considered when interpreting the results of this study. First, the methodology for determining the MAWL in this experiment was slightly different than in previous psychophysical experiments. Whereas other studies have set a time limit for the weight adjustment period (ranging from 20 min to 8 h), this experiment defined the MAWL as the weight lifted for eight consecutive no changes. The protocol used here was based on a pilot study that indicated most changes occurred in the first few lifts of the adjustment period, followed by minor oscillatory changes. Additionally, this protocol was also used to reduce the effects that fatigue could have on an EMG signal. Thus, it is possible that the MAWLs in this experiment could have been different than those from previous studies, which allow more time for adjustment. However, the MAWLs determined in this study were consistent with those from other studies (Ciriello *et al*. 1990).

Second, the participants in this experiment were young college males inexperienced with material handling. This may have influenced the magnitude of the final MAWLs. Thus, the variables in the models based on this participant population may not be applicable to other populations that may use a different decision process to make changes in the weight of the loads (e.g. experienced material handlers, female or older populations).

Finally, the variables in the multiple logistic regression models are most applicable to tasks that are comparable. The variables associated with changes in weight for the determination of the MAWL most likely will be different for different tasks. For example, the decision to decrease the weight during a sagittally symmetric lifting task with a slower lift rate may result in the exclusion of heart rate or the LBD risk index from the down-change model. Additionally, this experimental task did not involve significant asymmetric postures (e.g. subjects were allowed to move their feet and, thus, very little trunk twisting occurred); therefore, the findings may not be generalized to tasks where large magnitudes of twisting are present.

5. Conclusion

The variables associated with changes of weight during a psychophysical study indicate that the decision process for changing the weight may partially incorporate multiple channels of sensory inputs (biomechanical and physiological). When the participants in this study decided to decrease the weight of the load lifted, these changes were highly associated with the magnitudes of heart rate, the sagittal moment and a LBD risk index. When increasing the weight towards the MAWL, their decisions were associated with the A/P shear force and twist velocity; however, the addition of these two variables to the model based on only participant, initial weight and lifting trial provided little extra predictive ability. While the biomechanical variables included in the models have been associated specifically with LBD, insufficient evidence exists that relates measures of physiological stress (i.e. heart rate) to LBD. Thus, the psychophysical methodology may be addressing more of a whole-body injury prevention rather than one specific to the low back, consistent with the objectives of the NIOSH Work Practices Guide for Manual Lifting (NIOSH 1981). Additionally, based on the acceptable weights chosen by the participants, there appears a high probability that a similar industrial task would have a high rate of LBD based on the resulting magnitudes of LBD risk, estimated spinal forces as compared with tolerance data and the risk indices as developed by NIOSH. Thus, the psychophysical methodology may be useful for the decision to lower the weight of loads that may present extreme levels of risk of LBD, but the psychophysical methodology does not seem to help in the decision to stop changing the weight at a safe load weight.

Acknowledgements

We thank Delia Treaster for her contribution to the design of the study and data collection.

References

Adams, M. A. and Hutton, W. C. 1983, The effect of fatigue on the lumbar intervertebral disc, *Journal of Bone and Joint Surgery*, **65-B,** 199 – 203.

Adams, M. A., Green, T. P. and Dolan, P. 1994, The strength in anterior bending of lumbar intervertebral discs, *Spine*, **19,** 2197 – 2203.

Adams, M. A., McNally, D. S. and Dolan, P. 1996, 'Stress' distributions inside intervertebral discs: the effects of age and degeneration, *Journal of Bone and Joint Surgery*, **78-B,** 965 – 972.

Adams, M. A., McNally, D. S., Wagstaff, J. and Goodship, A. E. 1993, Abnormal stress concentration in lumbar intervertebral discs following damage to the vertebral bodies: a cause of disc failure? *European Spine Journal*, **1,** 214 – 221.

Caldwell, L. S., Chaffin, D. B., Dukes-Dobos, F. N., Kroemer, K. H. E., Laubach, L. L., Snook, S. H. and Wasserman, D. E. 1974, A proposed standard procedure for static muscle strength testing, *American Industrial Hygiene Association Journal*, **35,** 201 – 206.

Cavanaugh, J. M. 1995, Neural mechanisms of lumbar pain, *Spine*, **20,** 1804 – 1809.

Chaffin, D. B. and Page, G. B. 1994, Postural effect on biomechanical and psychophysical weight-lifting limits, *Ergonomics*, **37,** 663 – 676.

Chaffin, D. B. and Park, K. S. 1973, A longitudinal study of low-back pain as associated with occupational weight lifting factors, *American Industrial Hygiene Association Journal*, **34,** 513 – 525.

Ciriello, V. M. and Snook, S. H. 1983, A study of size, distance, height, and frequency effects on manual handling tasks, *Human Factors*, **25,** 473 – 483.

Ciriello, V. M., Snook, S. H., Blick, A. C. and Wilkinson, P. L. 1990, The effects of task duration on psychophysically-determined maximum acceptable weights and forces, *Ergonomics*, **33,** 187 – 200.

Ciriello, V. M., Snook, S. H. and Hughes, G. J. 1993, Further studies of psychophysically determined maximum acceptable weights and forces, *Human Factors*, **35,** 175 – 186.

Davis, K. G., Kirking, B. C., Gaudes, L. L., Yang, J. and Marras, W. S. 1997, Influence of lift moment in determining MAWL, *Human Factors*, **39,** 312–322.

Farfan, H. F. 1988, Biomechanics of the lumbar spine, in W.H. Kirkaldy-Willis (ed.), *Managing Low Back Pain*, 2nd edn (New York: Churchill Livingstone).

Fathallah, F. A., Marras, W. S., Parnianpour, M. and Granata, K. P. 1997, A method for measuring external spinal loads during unconstrained free-dynamic lifting, *Journal of Biomechanics*, **30,** 975–978.

Gamberale, F. 1990, Perception of effort in manual material handling, *Scandinavian Journal of Work and Environmental Health*, **16 (suppl. 1),** 59–66.

Garg, A. and Ayoub, M. M. 1980, What criteria exist for determining how much load can be lifted safely? *Human Factors*, **22,** 475–486.

Garg, A. and Badger, D. 1986, Maximum acceptable weights and maximum voluntary isometric strengths for asymmetric lifting, *Ergonomics*, **29,** 879–892.

Garg, A. and Banaag, J. 1988, Maximum acceptable weights, heart rates, and RPE's for one hour's repetitive asymmetric lifting, *Ergonomics*, **31,** 77–96.

Garg, A. and Saxena, U. 1980, Container characteristics and maximum acceptable weight of lift, *Human Factors*, **22,** 487–495.

Granata, K. P. and Marras, W. S. 1993, An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions, *Journal of Biomechanics*, **26,** 1429–1438.

Granata, K. P. and Marras, W. S. 1995, An EMG-assisted model of trunk loading during free-dynamic lifting, *Journal of Biomechanics*, **28,** 1309–1317.

Herrin, G. A., Jaraiedi, M. and Anderson, C. K. 1986, Prediction of overexertion injuries using biomechanical and psychophysical models, *American Industrial Hygiene Association Journal*, **47,** 322–330.

Hosmer, D. W. and Lemeshow, S. 1989, *Applied Logistic Regression* (New York: Wiley).

Jager, M. and Luttmann, A. 1991, Compressive strength of lumbar spine elements related to age, gender, and other influencing factors, *Journal of Electromyographical Kinesiology*, **1,** 291–294.

Karwowski, W. and Ayoub, M. M. 1984, Fuzzy modeling of stresses in manual lifting tasks, *Ergonomics*, **27,** 641–649.

Kumar, S. and Mital, A. 1992, Margin of safety for the human back: a probable consensus based on published studies, *Ergonomics*, **35,** 769–781.

Leamon, T. B. 1994, Research to reality: a critical review of the validity of various criteria for the prevention of occupationally induced low back pain disability, *Ergonomics*, **37,** 1959–1974.

Marras, W. S. 1990, Industrial electromyography, *International Journal of Industrial Ergonomics*, **6,** 89–93.

Marras, W. S. and Granata, K. P. 1995, A biomechanical assessment and model of axial twisting in the thoraco-lumbar spine, *Spine*, **20,** 1440–1451.

Marras, W. S. and Granata, K. P. 1997, Spine loading during trunk lateral bending motions, *Journal of Biomechanics*, **30,** 697–703.

Marras, W. S. and Sommerich, C. M. 1991a, A three-dimensional motion model of loads on the lumbar spine: I. Model structure, *Human Factors*, **33,** 123–137.

Marras, W. S. and Sommerich, C. M. 1991b, A three-dimensional motion model of loads on the lumbar spine: II. Model validation, *Human Factors*, **33,** 139–149.

Marras, W. S., Allread, W. G. and Reid, R. G. 1999, Occupational low back disorder risk assessment using the lumbar motion monitor, in W. Karwowski and W. S. Marras (eds), *The Occupational Ergonomics Handbook* (Boca Raton: CRC Press).

Marras, W. S., Fathallah, F. A., Miller, R. J., Davis, S. W. and Mirka, G. A. 1992, Accuracy of a three-dimensional lumbar motion monitor for recording dynamic trunk motion characteristics, *International Journal of Industrial Ergonomics*, **9,** 75–87.

Marras, W. S., Lavendar, S. A., Leurgans, S. E., Fathallah, F. A., Ferguson, S. A., Allread, W. G. and Rajulu, S. L. 1995, Biomechanical risk factors for occupationally related low back disorders, *Ergonomics*, **38,** 377–410.

Marras, W. S., Lavender, S. A., Leurgans, S. E., Rajulu, S. L., Allread, W. G., Fathallah, F. A. and Ferguson, S. A. 1993, The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders, *Spine*, **18,** 617–628.

McGill, S. M. 1996 Searching for the safe biomechanical envelope for maintaining healthy tissue. Pre-ISSLS Workshop: The Contribution of Biomechanics to the Prevention and Treatment of Low Back Pain, University of Vermont, June 25, 1996.

Mirka, G. A. and Marras, W. S. 1993, A stochastic model of trunk muscle coactivation during trunk bending, *Spine*, **18,** 1396 – 1409.

Mital, A. 1985, Models for predicting maximum acceptable weight of lift and heart rate and oxygen uptake at that weight, *Journal of Occupational Accidents*, **7,** 75 – 82.

Mital, A. 1986, Prediction models for psychophysical lifting capabilities and the resulting physiological responses for work shifts of varied durations, *Journal of Safety Research*, **17,** 155 – 163.

Mital, A. 1987, Pattern of differences between the maximum weights of lift acceptable to experienced and inexperienced materials handlers, *Ergonomics*, **30,** 1137 – 1147.

National Institute for Occupational Safety and Health 1981, *Work Practices Guide for Manual Lifting*. Technical Report DHHS (NIOSH) Publication No. 81-122 (Cincinnati, OH: NIOSH).

National Institute for Occupational Safety and Health 1997, Musculoskeletal Disorders and Work Factors. Technical Report DHHS (NIOSH) Publication No. 97-141 (Cincinnati, OH: NIOSH).

SAS Institute, Inc. 1982, *SAS User's Guide* (Cary, NC: SAS Institute).

Snook, S. H. 1978, The design of manual handling tasks. *Ergonomics*, **21,** 963 – 985.

Snook, S. H., Campanelli, R. A. and Hart, J. W. 1978, A study of three preventive approaches to low back injury, *Journal of Occupational Medicine*, **20,** 478 – 481.

Snook, S. H. and Ciriello, V. M. 1974, Maximum weights and work loads acceptable to female workers, *Journal of Occupational Medicine*, **16,** 527 – 534.

Snook, S. H. and Ciriello, V. M. 1991, The design of manual handling tasks: revised tables of maximum acceptable weights and forces, *Ergonomics*, **34,** 1197 – 1213.

Thompson, D. D. and Chaffin, D. B. 1993, Can biomechanically determined stress be perceived? Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, 11 – 15 October 1993, Seattle, 789 – 792.

Waters, T. A., Putz-Anderson, V., Garg, A. and Fine, L. J. 1993, Revised NIOSH equation of the design and evaluation of manual lifting tasks, *Ergonomics*, **36,** 749 – 776.

Webster, B. S. and Snook, S. H. 1994, The cost of 1989 workers' compensation low back pain claims, *Spine*, **19,** 1111 – 1116.

Yoshizawa, H., O'Brien, J. P., Smith. W. T. and Trumper, M. 1980, The neuropathology of intervertebral discs removed for low back pain. *Journal of Pathology*, **132,** 95 – 104.

Appendix

We want you to imagine that you are working on a job where you are getting paid for bulk. The job would be conducted over an 8-hour shift that allows you to go home not feeling exhausted. We want you to work as hard as you can *without straining yourself, or without becoming unusually tired, overheated, or out of breath.*

The task will consist of one lifting frequency of four lifts per minute. You will be lifting a box at knee height to a position marked at about elbow height. The load will be returned to the original position by one of the experimenters.

YOU WILL ADJUST YOUR OWN WORKLOAD AS YOU FEEL APPROPRIATE. You will lift when the computer-generated tone signals the start of the lift. Your job will be to adjust the load according to how you feel. This part of the task will not be easy. Remember, only you know how you feel. You will be able to adjust the weight by adding or removing masses from the box.

If you feel you are working too hard, reduce the load. But we don't want you loafing either. If you feel you can work harder, as you might on piece work, increase the load. Don't hurry your lift. Feel free to adjust the load as many times as necessary. Remember, we are not interested in how much you are capable of lifting but rather the maximum amount that you would like to handle if you were actually performing the task at work.