

A BIOMECHANICAL INTERPRETATION OF THE PSYCHOPHYSICAL DETERMINATION OF WORK CAPACITY

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This study compares major trunk muscle activity during lifting tasks at weight levels below, at, and above the maximum acceptable weight of lift. The increase in peak and average muscle activity for the latissimus dorsi muscle pairs, and in average activity for the erector spinae muscle pairs, is greater from the medium to the high weight condition than from the low to medium weight condition ($p \leq 0.05$). This study shows that the increase in muscle activity, relative to external load increases, is non-linear, and there are critical thresholds at which the worker judges the task to be unacceptable based upon biomechanical factors.

INTRODUCTION

Musculoskeletal disorders and low back pain are a major problem in industry, and the cost in terms of money and human suffering is substantial. According to the National Safety Council (1987), the direct and indirect costs of back injuries to U.S. industries total six billion to eight billion dollars annually. Andersson (1981) states that factors which affect absence from work because of low back pain symptoms include heavy physical work, frequent bending, lifting, forceful movements, and repetitive work. Thus, any information that can be gained regarding how the body is affected by these factors could contribute to a reduction in the number of back injuries in the workplace and, consequently, a reduction in costs due to back injuries.

Work capacity evaluation plays an important role in the reduction of back injuries by either assisting in the redesign of job tasks or by assuring that only people with sufficient strength are employed. According to Ayoub, et al. (1980), the psychophysical methodology has been successful in determining load handling capacities of individuals or groups of individuals. However, these models fail to render information regarding the body's internal loads, such as spinal compression and muscle forces, which may influence a person's determination of the Maximum Acceptable Weight of

Lift (MAWL). Conversely, biomechanical models provide insight as to how the body functions as a system and can be useful in determining internal forces of the body, but these models are not adept at determining work capacity.

It is desirable to find a link between these two bodies of research so that a more comprehensive understanding of occupational low back disorders can be achieved. In order to accomplish this objective, this study will examine the influence of muscle usage on the psychophysical determination of lifting strength. With the aid of electromyography (EMG), muscle activity during lifting tasks can be determined for major trunk muscles. If the muscle activity is compared for lifting tasks with load levels below the MAWL, at the MAWL, and above the MAWL, then insight may be gained as to the role of muscle activity in the determination of an individual's lifting capacity.

METHOD

Subjects

Five normal, healthy, college aged male volunteers were used. None of the subjects had a history of low back pain. A description of the subjects is given in Table 1.

Table 1. Description of Subjects.

	age (yrs.)	weight (kg)	stature (cm)
mean	27.8	88.9	185.9
s.d.	3.7	19.6	9.5

Experimental Design

Weight of lift and frequency of lift were the independent variables in this study. The frequency of lift consisted of two levels: 1 lift per minute and 4 lifts per minute. These levels were chosen because of the prevalence of lifting tasks in industry that are performed within this frequency range. Recent surveys by Ciriello, et al., 1990, found that 94% of industrial lifting tasks are performed at a frequency below 4.3 lifts per minute. The weight of lift consisted of three levels: the MAWL minus twenty-five percent of the MAWL, the MAWL, and the MAWL plus twenty-five percent of the MAWL. The MAWL was determined using a standard psychophysical methodology.

The dependent variables examined were the integrated EMG (IEMG) of the left and right erector spinae (es) muscle group, the IEMG of the left and right rectus abdominis (ra) muscle group, and the IEMG of the left and right latissimus dorsi (ld) muscle group. It must be noted that these EMG values were not used as predictors of muscle force, but rather as a measure of relative muscle activity, which gives an indication of "muscular effort".

Several nuisance variables were controlled so that they would not affect the results of the study. The same box was used throughout the study and

the subjects lifted the box to a constant height of 76 cm. The subjects were allowed to use any type of lift they wished; however, the lifting technique was kept constant within a subject for all conditions. Four subjects used the cantilever type lift, and one subject used a squat lift.

Apparatus

The apparatus consisted of six basic components: the box that was lifted, the weights in the box, an event marker, the EMG processing system, the analog to digital data collection system, and the computer.

The box was constructed of sturdy plywood and was 30.0 cm wide, 30.0 cm deep, and 26.8 cm high. Handles that were 2.54 cm in diameter were placed horizontally on either side of the box and were 43 cm apart. The weights were in the form of lead pellets approximately 2 to 5 cm long and 0.3 to 0.6 cm wide.

An event marker, which consisted of a bounceless switch that output a 5 volt signal when "on" and output a 0.1 volt signal when "off" was used to mark the beginning and end of a lift. The marker was attached to the data acquisition system and was digitized and stored in the computer.

The EMG apparatus consisted, in part, of bipolar surface electrodes that were attached to the skin above the muscle to be sampled. Each pair of electrodes was attached to a preamplifier that was attached to a belt around the subject's waist. The preamplifier was attached to the main EMG system via a coaxial cable. The EMG signal was then filtered through an 80 Hz high pass filter and a 1000 Hz low pass filter. The signal was then rectified and the mean was taken over a 20 ms moving window. This processed signal was digitized and stored in the computer. The sampling rate was 100 Hz, and a data acquisition system was used to convert the analog signals to a digital format. The acquisition system was driven by a portable personal computer.

PROCEDURE

Training

In order for the subjects to be acclimated to the lifting task, each subject was required to train for fifteen minutes per day for a total of five days. The training session consisted of lifting the box containing a weight of 11.3 kg to a height of 76 cm at a rate of 4 lifts per minute. This training period ensured that the subjects did not experience extreme muscle soreness during the first few experimental conditions, thus enabling a more accurate determination of the MAWL.

Determination of the MAWL

A classic psychophysical methodology was used to determine the MAWL for each subject. Each subject read and signed a consent form and then read the lifting task instructions, which were presented by Hamrick (1989). As explained in the lifting task instructions, the subjects adjusted the box weight to a weight that they felt they could lift over an eight hour work day without feeling overly tired. The MAWL was determined for each subject for the 4 lifts per minute condition on one day, and then each

subject returned three days later and his MAWL was determined for the 1 lift per minute condition.

EMG Measurements

Next, the subjects returned in order to participate in tests performed to measure muscle activity during the lifting task. Electrodes were attached to the subject over six muscle groups: the left and right rectus abdominis, the left and right erector spinae, and the left and right latissimus dorsi. The complete procedure is described by Hamrick (1989).

In order to correctly interpret the EMG signals, maximum and resting EMG values must be obtained. These values were determined by placing the subject in a reference frame that constrained the subject's hips and bent his back at an angle of 45 degrees from vertical. EMG data were collected during maximum voluntary flexion and extension exertions and also while the subject was at rest.

Finally, EMG data were collected while the subjects lifted a load. The subjects lifted the load at three levels and at two frequencies. The two separate frequency conditions were performed on different days. The three load levels were based on the MAWL determined during the psychophysical portion of the experiment. These three load levels were the MAWL minus twenty-five percent of the MAWL, the MAWL, and the MAWL plus twenty-five percent of the MAWL for the frequency at which the lift was performed. The order that each subject lifted the three weight levels was randomized for each subject at both frequencies. To minimize the effects of fatigue, a ten minute rest break was given to the subjects between testing under each condition.

During the lifting task, EMG data were collected at time 0 minutes, 4 minutes, 8 minutes, and 13 minutes. The data were collected for 5 seconds, during which a lift took place.

The beginning of the lift and the end of the lift were marked by an electronic switch that signaled 0 volts when the box was on the ground or on the table and signaled approximately 2.5 volts when the box was being lifted by the subject.

ANALYSIS

In order to determine the relative muscle activity for a particular task, the EMG data must be normalized by comparing the EMG activity during the task to the EMG activity during a maximum voluntary effort and to the EMG activity during rest. The normalization equation, as stated by Marras (1987), is as follows:

$$\text{Relative Activity} = \frac{\text{Task EMG} - \text{Rest EMG}}{\text{Maximum EMG} - \text{Rest EMG}} \quad (1)$$

For each subject, each muscle's EMG data were normalized under each condition relative to the muscle's own maximum value and minimum value. Once the EMG values were normalized, the mean and peak values were determined for each lifting condition. Furthermore, since the task was

symmetric about the sagittal plane, the mean activity level of the left and right muscles were averaged together in order to arrive at a single mean value for each muscle pair. Similarly, the peak activity level of the left and right muscles were averaged together so that a single peak value was obtained for each pair.

An analysis of variance (ANOVA) was performed to determine which of the factors, including interactions, affected muscle activity. Paired t-tests were performed on the data to check for differences in peak and average muscle pair activity between various weight levels. Also, a paired t-test was performed to see if the increase in peak and average muscle activity from the medium to high weight condition was greater than the increase in muscle activity from the low to medium weight condition.

RESULTS

The MAWL that was obtained for each subject using the psychophysical method at each frequency is given in Table 2.

Table 2. Maximum Acceptable Weights of Lift (kg).

Subject	1 lift/minute	4 lifts/minute
1	30.8	22.0
2	18.1	14.5
3	29.0	21.8
4	19.1	17.7
5	18.1	14.1
ave.	23.0	18.0
s.d.	5.7	3.4

A paired t-test showed that there is a significant difference in the MAWL between the two lifting frequencies ($t_4=3.77$, $p=0.0196$).

The ANOVA revealed that the weight lifted had a significant effect on average latissimus dorsi activity ($F_{2,8}=12.41$, $p=0.004$), peak latissimus dorsi activity ($F_{2,8}=36.09$, $p<0.001$), average erector spinae activity ($F_{2,8}=51.96$, $p<0.001$), and peak erector spinae activity ($F_{2,8}=21.08$, $p=0.001$). No other factors, including interactions, were found to influence the activity in these muscles and no factor was found to influence either peak or average rectus abdominis activity.

An analysis was performed for each muscle pair to see if the increase in muscle activity from the medium to high weight condition was greater than the increase from the low to medium weight condition. The results of this analysis show that there was a significant difference for peak latissimus dorsi activity ($t_{38}=2.357$, $p=0.012$), average latissimus dorsi activity ($t_{38}=2.054$, $p=0.024$), and average erector spinae activity ($t_{38}=1.683$, $p=0.050$).

The muscle activities at the different weight levels are given in Table 3 and are shown graphically in Figure 1 (only for muscles where the increase

in activity from the medium to high weight condition was significantly greater than the increase from the low to medium weight condition).

Table 3. Muscle pair activity (% max) at the three weight levels.

	MAWL-0.25 (MAWL)	MAWL	MAWL+0.25 (MAWL)
ave ld	0.1087	0.1385	0.1937
peak ld	0.3267	0.3809	0.5352
ave es	0.4091	0.4638	0.5400
peak es	0.7066	0.7766	0.8794
ave ra	0.1608	0.1976	0.2174
peak ra	0.4062	0.5201	0.5884

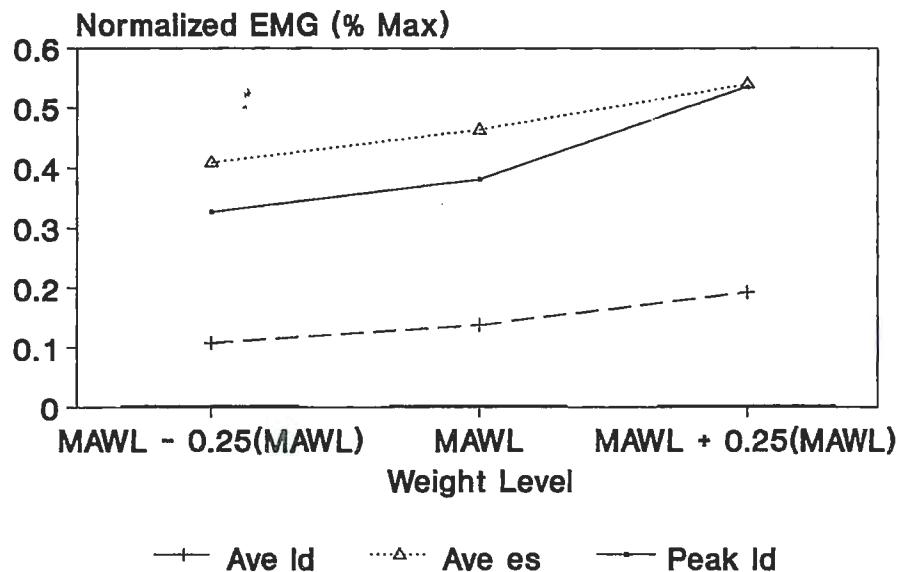


Figure 1. Muscle Activity vs. Weight

DISCUSSION

The results of the psychophysical study imply that a significant difference does exist in the MAWL between lifting at 1 lift per minute and 4 lifts per minute. As the frequency of lift increases from 1 to 4 lifts per minute, a person's MAWL decreases. This finding is consistent with the findings reported by Snook (1978).

The finding that peak and average muscle activity in both the erector spinae muscle pair and the latissimus dorsi muscle pair increases as the weight level increases is not surprising; the muscles must increase their activity to provide force to counteract the moments generated by the extra weight in the box. However, the increase in peak and average muscle activity for the latissimus dorsi muscle pairs, and in average muscle activity

for the erector spinae muscle pairs, is greater from the medium weight condition to the high weight condition than from the low weight condition to the medium weight condition. This phenomenon appeared to be consistent between subjects and between conditions. Thus, people appear to be sensitive to the rate of change in muscle activity when the load weight is increased. It can be seen from Figure 1 that the latissimus dorsi activity seems to increase more non-linearly with increasing weight than the other muscles. The reason for this effect, however, is not clear.

People may have a maximum threshold of effort. Above this threshold, the person feels that s/he can not lift the weight at the given frequency without feeling overly tired, so the person subtracts weight from the box. Below this threshold, the person feels that s/he can lift more weight at the given frequency, so s/he adds more weight to the box.

Since the increase in EMG's is higher from the medium to high weight condition than from the low to medium condition, it appears as if more effort per unit weight increase is required at weight levels above the MAWL than at weight levels below the MAWL. However, further research should be conducted to determine more precisely the weight level at which this increase in effort is required by looking at muscle activity at weight levels closer to the MAWL. Snook (1978) reports that an acceptable range of test/retest values is that the retest should be within 15% of the original test, so observing the electrical activity in the muscles during lifting at the MAWL minus 15%, the MAWL, and the MAWL plus 15% should provide a sufficiently narrow range.

The increase in required effort could be due to muscle co-contraction. When co-contraction occurs, the antagonist muscles become active, thus creating a moment which opposes the movement in the desired direction. In order to continue the movement in dynamic situations, the activity in the agonist muscle must increase. However, based on the measured activity of the rectus abdominis group, minimal co-contraction was observed in this study. Co-contraction could have been present in other trunk muscles; this phenomenon has been observed by previous researchers. Flanders and Cordo (1987) observed significant co-contraction in the muscles about the elbow joint during isometric contractions. Zetterberg, et al. (1987) found that there was significant antagonist activity during heavy, isometric trunk loading.

Co-contraction may be minimal in the low weight conditions and significant in the high weight conditions. During the psychophysical determination of the MAWL, the subject may experience a significant decrease in effort by removing weight from the box when the load level is above the MAWL. Conversely, when the load level is below the MAWL, the subject may experience only a slight increase in muscular effort when weight is added to the box. So, the payoff in the form of reduced muscular effort may be relatively large when weight is decreased at weight above the MAWL, and the cost in the form of increased effort may be relatively small when weight is increased at levels below the MAWL. Thus, motivated subjects could arrive at the MAWL when they feel that adding weight to the box results in an increase in effort which is more than they can comfortably tolerate.

The findings indicate that the increase in muscle activity relative to the external load increase is non-linear, and there are critical thresholds at which the muscles become stressed. At this point, the worker judges the task to be unacceptable, based upon biomechanical factors.

SUMMARY

This investigation combined two fields of study: biomechanics and psychophysics. By providing a biomechanical interpretation of the psychophysical methodology to determine lifting capacity, the two fields were linked. Consequently, this study may help to interpret literature in both areas of knowledge. In addition, the information gained may help to develop a biomechanical model of work capacity evaluation, which may prove to rely less upon the motivation of the subjects and be less expensive and less time consuming than the psychophysical method.

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