The Correlation Between Biomechanical Loads and Psychophysical Ratings

by

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(ABSTRACT)

Psychophysics is defined as the scientific study of the relationship between stimuli and sensation. It has been used extensively over the last three decades for evaluation and design of manual materials handling tasks in many industries. Despite this, much is still not known about how subjective ratings, the core of the psychophysical methodology, relate to physical (biomechanical) loads. A fundamental assumption of this method is that humans are capable of estimating biomechanical and physiological loads that are placed on the body. Based on this assumption, estimates that are obtained through the methodology are used as an indicator of physical loads and stresses, and are assumed to be related to injury risk.

An experiment was performed to achieve two primary goals:1) determine the correspondence between biomechanical loads (moments at the elbow, shoulder and torso) and subjective ratings of joint loads, as well as subjectively determined maximal loads and 2) determine whether any particular joint (i.e. low back, shoulder, elbow) is the limiting factor when a subject determines a maximally acceptable load. Participants were instructed to pose in four different postures, one serving as a baseline (neutral, or 'familiar') posture, while the remaining three varied moments at the elbow, shoulder and torso. While in each of these postures, participants determined a maximum acceptable static load (MASL). Ratings of perceived exertions for specific joints were also reported, as well as whole body ratings while supporting various fractions of the MASL.

Experimental findings indicated that subject and posture effects neared significance as main effects on the magnitude of MASL. Strength was shown to be, at best, a weak predictor of MASL. Though no conclusive evidence was found to indicate that a specific joint is the limiting factor when determining maximum acceptability, trends in the data suggested that the low back and shoulder are possible candidates. Overall, the results of the study indicated that humans consider more than simple joint moments when forming perceptions of efforts and acceptability during static load handling.

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1. INTRODUCTION

1.1 Rationale

In order to minimize the risk of injuries resulting from manual lifting in the workplace, guidelines have been established to set limits regarding the amount of weight, frequency, and duration of exertion in lifting tasks. These guidelines, such as the NIOSH Work Practices Guide for Manual Lifting (WPG), are partially reliant on subjective data that has been gathered from various research findings (Waters, et al., 1993). This subjective data is obtained by using psychophysical methods to determine population lifting limits. Psychophysical methods are used to relate objective stimuli to subjective perceptions (e.g. pain or discomfort). One reason for the frequent use of the psychophysical approach in the last few decades is the relative ease of obtaining data through this method. Alternate methods for establishing limits or guidelines, such as the biomechanical and physiological approaches, can take much longer and be more costly to perform. For many researchers and practitioners, the psychophysical method has become the method of choice when a quick evaluation of workload is needed.

When employing the psychophysical methodology, two main approaches are typically used: 1) self-reporting of the effort levels exerted to resist an external force or torque: 2) the method of adjustment, in which a load is adjusted by a subject until it is perceived to be a comfortable weight. In order to use such subjective data, one must make the assumption that an individual can accurately identify the physical stresses to which his or her body is subjected during a given activity. In addition, it must be assumed that the use of such data when compiled as guidelines or lifting limits will lead to safer work. Given the subjective nature of this data, it is natural to question the degree of correspondence between psychophysical ratings and biomechanical loads. In other words, if only a weak relationship exists between subjectively determined stress and objective load magnitudes on various structures of the body, then the use of psychophysical data in developing lifting guidelines may warrant further investigation. To gain a better understanding of the relationship between physical loads and subjective assessments, subjective reports of physical stress, load acceptability and dependence on the loads placed on specific body joints were quantitatively examined.

There were two main goals in this study. The first was to determine the correspondence between biomechanical loads on several body joints and subjective ratings of joint loads, as well as subjectively determined maximal loads. Joint loads and moments were determined using standard kinetic analysis of multiple joints (specifically the shoulder, elbow and low back). Maximally acceptable loads were determined by using the psychophysical method of adjustment (Gescheider, 1997), whereby each subject adjusted the weight that was lifted, until the weight fit a comfort criterion set through verbal instructions. Subjective ratings of exertion were obtained by prompting the subject for a perceived level of exertion while a load was statically supported in a specific posture. These ratings reflected the subject’s perception of the exertion that was put forth for each task. The postures in which the subject posed were selected to isolate specific joints (elbow, shoulder and low back). Subjective ratings at each of these joints were later compared to a baseline posture so that any rating trends could be examined.

The second goal was to identify whether any particular joint (i.e. low back, shoulder, elbow) is the limiting factor when a subject determines a maximally liftable load. In other words, the goal was to find whether there is a 'weak link' of the body which determines the maximum load an individual is willing to lift. This 'weak link' is the area of the body, which in a lifting task, is perceived to withstand the least amount of relative physical stress. The term ‘relative’ is used here because, obviously, some joints are capable of withstanding more absolute stress than others. In this study, the focus was on perception of loads at a specific joint relative to the perceived maximum withstandable load at the joint. Past research has investigated whole body psychophysical ratings in depth, but has not concentrated on the isolation of specific joints. Though speculation has been made regarding the limiting joint, no research has identified a specific weak link of the body.

1.2 Applications

The psychophysical approach has been extensively used for over three decades to design and redesign manual materials handling tasks in many industries. Dempsey (1998) notes that although the psychophysical method does have shortcomings, it still provides important information that contributes to the determination of manual materials handling (MMH) lifting limits. Contributions of psychophysics to MMH guidelines need to be clarified in order to fully utilize its benefits while minimizing assumptions that may lead to the establishment of erroneous lifting limits.

The results of this study can be used to help ascertain the validity of the use of the psychophysical methodology to determine limits and guidelines for MMH. The relationship between joint loads and the subjective ratings of these loads can illustrate how accurately the loads are perceived. Once the strength of this relationship at specific joints has been identified, further work can be done to determine whether the standards need revision in light of this further understanding of objective loads and psychophysical ratings.

Applications of this research also include a further understanding of psychophysical methods related to manual lifting and the validity of its use in industrial situations. The results of this study should increase knowledge regarding the human perception of effort in lifting tasks, and may help in the long term to decrease lifting injuries by aiding in the development of more rigorous lifting guidelines.

2.0 LITERATURE REVIEW

2.1 Work-Related Injuries

Work related injuries associated with manual materials handling (MMH) are a significant problem in the workplace. Konz (1995) states that 27% of all industrial work related injuries are directly associated with MMH. This percentage accounts for 670,000 injuries per year, 60% of the $1 billion spent annually on workers compensation (Sanders and McCormick, 1993), and 93 million work days lost on MMH related injuries. Corporations realize that these statistics reflect a serious problem that needs to be remedied. In an attempt to address the problem, various programs ranging from lifting guidelines to stretching regimens are implemented to try to avoid workplace injuries. Although these attempts are made, workers still get injured. One reason that injuries still occur could be that the programs and guidelines that are implemented simply don't work.

2.1.1 Ergonomic Solutions

Several ergonomic approaches for controlling the extent of MMH injuries have been attempted, including biomechanical, physiological, and psychophysical methodologies. All three of these approaches use estimates of various physical phenomena to establish a solution. The biomechanical approach estimates forces and moments which act inside and out of the body. The physiological approach estimates the energy expenditure associated with dynamic tasks. Finally, the psychophysical approach estimates worker capacity to perform a given task based on perception of the difficulty of a task.

The use of the biomechanical approach involves calculating the forces and moments acting on the body while lifting a load. In order to develop guidelines regarding lifting tasks, these forces and moments are compared against limits based on maximal forces or torques. Konz (1995) suggests that the back is generally the weak link when considering lifting limits, though this statement is made without offering any supporting evidence. Reading this statement, the reader is not sure whether the low back is the physical weak link, or if it is the psychophysical weak link being most sensitive to changes in weight being lifted. The role that the low back and other joints play in the perception of effort in lifting tasks needs to be clarified.

The physiological approach is primarily effective for repetitive or prolonged lifting tasks, as it examines the energy requirements of a task over an extended period of time (Waters et al., 1993). For example, the specifications of a lifting procedure are can be used along with predictive equations to estimate the energy consumption required to perform a task (Sanders and McCormick, 1993). Many variables are used for this estimate of physiological demands (load position, frequency, load dimensions, etc.), making it, at times, a complex approach. Sanders and McCormick (1993, p.256) state that models based on the physiological approach indeed do “have limitations and care must be exercised when applying them”. More direct measures of energy expenditure also exist. These include measures of oxygen intake, maximum stress tests, submaximal stress tests, and measures of heart rate.

The psychophysical approach is the third major method used for determining MMH guidelines, and is the focus of this research. Waters et al. (1993, p.754) state that the approach “provides a method to estimate the combined efforts of biomechanical and physiological stressors of manual lifting". Therefore, if psychophysics is to be an effective measure for determining loads on the body, then one must assume that each person is able to accurately estimate the biomechanical and physiological demands to which they are being subjected. If one is not adept at perceiving simple physical loads that act on the body, then the guidelines that are based on these erroneous perceptions may not be accurate. No research to date has definitively proven that loads acting on the body can be accurately perceived.

2.2 Psychophysics

Psychophysics is defined by Gescheider (1997) as the scientific study of the relationship between stimuli and sensation - in other words, it is the study of how the body perceives outside influences that act upon it. Each individual may have differing perceptions of external stimuli that act on the body at any given time. For example, some may only be willing to comfortably lift a small fraction of their physical maximum. Others, however, may be willing to lift a significantly greater fraction of their physical maximum, while still fulfilling the self-defined criterion of 'comfort'. Individuals that do not accurately perceive a safe physical capacity may be at a higher risk of overestimating physical limits and consequently an increased risk of injury. Therefore, the meaning of the quantitative data gathered from psychophysical tests may not be clear. Some MMH-related guidelines are based on quantitative data that has been gathered from subjective studies, such as psychophysical studies of strength and acceptability. An example of this is the NIOSH Work Practices Guide (WPG), which is widely used in industry. The appropriateness of using limits such as the WPG, that rely on the assumption that individuals can perceive when an unsafe level of exertion is being reached, can therefore be questioned.

2.2.1 Psychophysics in Ergonomics

Snook (1978), in his classic article 'The Design of Manual Handling Tasks', suggested that the individual worker is the only one who can best sense various strains on the body which are associated with manual handling tasks. Also suggested is that only the worker can integrate these individual sensory inputs into one meaningful 'whole-body' response. This statement implies that workers can accurately perceive stimuli from each joint and muscle involved in the lifting task and mentally consolidate them as a 'whole body', or overall perception of the stimuli. It was also assumed that when choosing any lifting, pushing or carrying limits, that this limit would be a 'safe' limit. Snook et al. (1991) developed comprehensive tables that rely on this assumption. These tables give maximum values (forces and masses) of pushing, pulling, lifting, lowering, carrying and walking based on several task parameters. For example, when considering a lifting task, the parameters considered are the width of the load, the vertical distance of lift, the floor to knuckle height, and the frequency of the lift. Once these parameters are determined, one can check the table to find out what percentage of a working population would find the task acceptable. These tables, or a variation thereof, are still used to determine working standards.

Snook (1985) presents a list of advantages and disadvantages of the psychophysical methodology in regard to the determination of permissible loads. The advantages and disadvantages are as follows:

Advantages:

1. Psychophysics permits realistic simulation of industrial work
2. Psychophysics can be used to study intermittent tasks
3. Psychophysical concepts are consistent with the idea of a ‘fair day's pay for a fair day's work’.
4. Psychophysical results are very reproducible.
5. Psychophysical results appear related to low back pain

Disadvantages:

1. Psychophysics is based on subjective measures and will likely be replaced when a more objective measure is developed.
2. Psychophysical results from very fast frequency tasks are higher than recommended metabolic criteria.
3. Psychophysics is not sensitive to bending and twisting (of the torso)

The key disadvantage listed above is the first - an objective measure would be much more effective than the standard subjective one because less assumptions and approximations would be used to determine limits. This statement implies that although subjective measures are widely used in the determination of guidelines and standards, these measures are still not the most effective input to use. In other words, guidelines are being based on unverified and non-objective measures.

Karwowski et al. (1992) studied the human ability to discriminate between different levels of load heaviness in manual lifting. After conducting an experiment which had subjects rank order boxes by weight, assign linguistic descriptors of perceived load heaviness, and indicate confidence levels regarding correctness of perceived box order, they concluded that load discriminability is severely impaired if there are differences less than 4 lbs. between different boxes. They also stated that the number of "sequential ordering errors, assignment of linguistic variables, and estimated confidence levels were highly dependent on the load differential and weight range" (Karwowski et al., 1992, p.729). Due to this range of weight and load differential, the researchers felt that the lifting limits set by studies using the psychophysical response need to be reevaluated because of reliance on the assumption that individuals can effectively discriminate between different loads of any magnitude.

In another study which investigated how the human perceives loads on the body, Thompson and Chaffin (1993) found that back stress which results from occasional lifting exertions is generally not well-perceived. The subjects in this study were asked to lift a self-determined maximal load from floor to knuckle height. Subjects then used Borg's CR-10 rating scale to rate perceived exertion at the low back. The results showed that there was no correlation (R^2=0) between estimated L5/S1 compression forces and the subjective ratings given at the low back. The authors used this lack of correlation to offer an explanation as to why there are so many low back injuries in the workplace: if back stress is not accurately perceived, then workers cannot effectively perceive 'safe' load magnitudes when lifting. This misperception, then, may be an important contributor to back injury risk. This study also shows that, with respect to the low back, psychophysical responses may be a poor way to predict human exertion limits.

Hadler (1997) suggested that it is far more important to consider worker comfort when determining workload than to be concerned with how or when one performs a lifting task. He states that “people, all people, get backaches” (Hadler, 1997, p.939). But, whether that backache is reported as an ‘injury’ in the workplace depends on how the workers is allowed to cope with the back pain. While suffering discomfort, if the worker is forced to perform tasks that irritate the low back, he or she is more likely to report the discomfort as an injury. However, if the worker is allowed to let the discomfort abate at his or her own pace, it would likely not be reported as an injury, mainly because it was given time to heal. In other words, if workers are allowed to regulate the exertions that are performed, injuries are less likely to occur. The workers may suffer discomfort from time to time, but this discomfort would be given time to heal, and an injury would not be reported. Hadler (1992) concludes that instead of being concerned with exact lifting frequencies, or precise lifting limits, a greater concern should be the overall comfort of the worker who is performing the job. This implies that overall comfort is more important than perceived comfort at specific joints.

2.3 Use of Psychophysics in Task Design and Evaluation

The two primary psychophysical methodologies which are used in manual lifting are the concept of a ‘Maximum Acceptable Weight of Lift’ (MAWL) and the use of ‘Ratings of Perceived Exertion’ (RPE). Both of these methods rely on the assumption that individuals can detect and integrate stimuli that are caused by biomechanical and physiological loads to subjectively evaluate stress on the body (Sanders and McCormick, 1993). Furthermore, both are attempts to measure perception, which cannot otherwise be directly obtained, and allow for quantitative task analysis and guidelines.

2.3.1 MAWL

Sanders and McCormick (1993, p.257) state that when using psychophysics to assess a lifting task, subjects are instructed to “adjust the weight of a load . . . to the maximum amount they can sustain without strain or discomfort and without becoming unusually tired, weakened, overheated, or out of breath”. The load that is chosen by this method is deemed the MAWL. The premise behind the determination of a MAWL is that an individual can accurately extrapolate to the amount of weight that can be comfortably lifted over the course of an eight-hour work shift. ‘Comfort’ can only be defined on an individual basis, but as cited above, the instructions also state that the lifter should not become unusually tired, weakened, overheated or out of breath.

The method used to determine a MAWL is the psychophysical method of adjustment. When employing this method, the subject is instructed to perform a lifting task with an initial load determined by the experimenter. This load will be either very light or very heavy. The subject is then instructed to add or subtract weight from the load and repeat the lifting task. This process of adding or subtracting weight continues until the subject has reached a load that is perceived to fit the given criteria (maximum amount that can be sustained without discomfort, etc.) (Snook and Irvine, 1967).

Mital (1987) reported that inexperienced students tended to underestimate MAWL less than experienced industrial workers. In this experiment, data were obtained from 74 inexperienced students and was compared to the data of 74 experienced industrial material handlers. The groups did not differ significantly in physique or isometric strength exertion capabilities. Each subject group was given the same instructions, which were based closely on the classic MAWL method (Snook and Irvine, 1967). The results of the study showed that there was a significant difference in the weights that the two groups were willing to lift for an 8 hour shift. Because of the anthropometric, as well as strength similarities between the two groups, the implication is that there is a learning effect that takes place when one is experienced in manual handling. The results of this study seem to support the idea that mental cues, and/or experience and learning, can override physical cues resulting from a manual-materials handling task.

Ciriello et al. (1993) investigated the effect of lifting boxes with and without handles. Six male industrial workers were asked to lift handle-equipped and non-handle-equipped boxes through three different vertical ranges. The results of this study showed that boxes without handles yielded an average 16% decrease in MAWL when compared to lifts with handled boxes. This illustrates the critical role that the hand plays in the lifting motion. It also shows how the use of different muscle groups when lifting can cause the MAWL to change. The primary point that can be gathered from this study is that MAWL is very sensitive to the orientation of the hand and wrist and the physical loads on these structures. It also suggests the relative insensitivity of other body parts.

Davis et al. (1997) showed that the MAWL does not change significantly when subjects are deprived of visual feedback during the lifting trials. In this experiment, which determined the MAWL for 12 male students, a curtain was placed between the subject and the box to eliminate visual feedback. The results showed no significant differences in MAWL when comparing shielded and unobstructed subjects, implying that subjects do not use visual cues to determine the amount of weight they are willing to lift. The results of the study also showed that as the distance from the box to the spine increased, the MAWL that was chosen decreased. Because the load at the spine is a function of the distance between the load and the low back, the implication of this result is that MAWL values are sensitive to the loads at the spine.

To highlight the role of safety in lifting tasks, Karwowski (1996) slightly modified the instructions given for the determination of the maximum acceptable loads. In his study, he instructed subjects to "Adjust your own workload...with respect to your own perception of how safe it is for you" (p. 618). He named the load that was determined using these instructions the maximum safe weight of lift (MSWL). Other than the instructions, this study was conducted in the same manner as the standard MAWL method. The results showed a decrease in the magnitude of the load compared to standard MAWL determination. Karwowski notes that the results of his study show that subjects perceive a difference between 'acceptable' weights and 'safe' weights. He states that when subjects are judging weight based on acceptability (as in MAWL trials), performance and efficiency are the primary focus. However, if a maximal load is judged based on safety (as in MSWL trials), the safety of the subjects themselves is the primarily consideration. The results of this study illustrate the importance of the wording of instructions and subjects' perceived objective when determining maximum loads.

2.3.2 RPE

The basis behind using psychophysical scaling to rate exertions is that "sensory organs and conscious perceptions reveal important disturbances in the environment" (Borg, 1990, p.55). In other words, individuals perceive forces or 'disturbances' that are acting on the body, and rating scales allow the individual to assign verbal or numerical anchors to these perceived disturbances. Therefore, these disturbances, that cannot be easily measured by any physical means, can be classified by using these rating scales.

Borg (1970) has shown that a categorical rating scale could be used to rate exertion. He conducted an experiment that prompted subjects to rate perceived exertion from 6-20 while performing a task. The results of this study showed a correlation of r=0.80 between heart rate and 10*RPE value. Borg later developed a similar scale which ranged from 0 - 10 and used verbal expressions to describe the level of exertion, where 0 is no noticeable stimuli and 10 is an extremely strong (almost maximum) level of exertion. He called this the category-ratio (CR-10) scale (Borg, 1990). Borg (1982) reports that this scale is correlated with percent maximum voluntary contraction (%MVC). A rating on this latter scale, when multiplied by 10, is roughly equal to the %MVC that is required to perform the exertion.

Pandolf et al. (1984) conducted an experiment in which nine subjects performed prolonged upper and lower body exercise. This prolonged exercise was in the form of leg cycling and arm cranking. While the oxygen uptake for both exercises was not significantly different, the results showed that the mean RPE for the arms was significantly less than the RPE for the legs, and that central RPE was generally lower than local RPE. The authors concluded that RPE values may be more readily monitored from smaller muscle masses, as opposed to larger muscle masses. In the case of their study, these muscle masses were the upper body (arms) and the lower body (legs), respectively.

In a previously noted editorial, Hadler (1997) found, by a review of past research, that RPEs are limited by large inter-individual variation in perceived exertion. More importantly, in regard to manual lifting, he found a significant impact of cognitive factors on RPE values. This illustrates the fact that RPE values can be affected by more factors than merely the perception of the external stimulus itself. Environmental and possible intrinsic, or motivational stimuli may also play a large part in the determination of RPE values. Due to these other factors, the correlation between physical loads and RPE ratings within one subject may differ with small changes in environment and attitude. By this, the consistency of RPE rating is called into question.

Resnick (1995) conducted a study investigating the generalizability of psychophysical ratings, looking specifically at inter- and intra-subject variability as well as inter-task variability. He had subjects perform static lifting tasks with a variety of loads, and then rate perceived exertions using the Borg CR-10 scale. Considering intra-subject variability, he found that two-thirds of the conditions tested showed a standard deviation in CR-10 ratings less than 10% of the mean rating. This suggested that CR-10 ratings were repeatable regarding an individual subject. When the CR-10 ratings were compared to maximum elbow flexion strength, high correlations were found, suggesting that ratings were consistent across subjects, based on maximum strength. Resnick also showed work that suggested that CR-10 ratings were consistent for different tasks.

Boussenna et al. (1982) investigated the relationship between torque at a specific joint versus whole body and specific joint discomfort. In their study, subjects posed in four different postures each designed to change the torque at the ankle, knee and hip. In these postures, the subjects were instructed to maintain a posture in which the arms were held out perpendicularly in relation to the torso, while holding a light pen with both hands. The light pen was then pointed at a target that was oriented at four different heights (100, 75, 50 and 25% of shoulder height). The smaller the percentage, the more the subject was required to bend over, hence changing the torques at the joints of the low body. The amount of time that the subject could maintain this posture was also recorded, and was shown to decrease as the subjects were further bent over. The results of the study showed that changes in overall discomfort were significant between postures and subjects. Boussenna et al. (1982) also reported that body part discomfort did show a relationship to the torque at the joint distal to the site of discomfort, suggesting that the subjects could perceive exertions fairly well at specific areas in the body. It was noted, though, that it is more difficult to perceive muscle forces at joints with many acting muscles than it is to perceive muscle forces at joints with fewer acting muscles. For example, the relationship between discomfort and torque at the ankle is stronger than the same relationship at the hip. Boussenna et al. (1982) infer that this result was likely due to the perception of discomfort being more ‘diffused’ at the hip because of the presence of more muscles.

Corlett and Bishop (1976) conducted a study to record the distribution of discomfort in the body during an extended period of work on a spot welding device. The ultimate goal of the study was to compare levels of discomfort between the standard device and the level of discomfort on a new, ergonomically designed device. The basis of the experiment was the thought that a comfortable worker would be less distracted, and therefore, more productive. The method of defining a level of overall discomfort involved summing individual sensations of 12 different regions of the body. As workers performed a 3 hour spot-welding task, they were first asked to indicate an overall level of discomfort using a seven-point scale. Subsequently, the workers were asked to assess which of the 12 regions of the body were giving them the greatest sense of discomfort. The number of regions that were identified as being ‘uncomfortable’ was directly proportional to the overall level of pain experienced during the task. The results of the study showed that while discomfort was reported in various parts of the body, these parts were functionally related. The results also showed a significant decrease in discomfort when using the ergonomically redesigned welding device.

2.4 Summary

Three main methodologies have been used to establish control strategies for MMH injuries: biomechanical, physiological, and psychophysical. Overall, the psychophysical approach is the easiest and least expensive to use, but it relies on many assumptions. One main assumption is that humans can accurately perceive the biomechanical and physiological demands that act on the body. Another assumption is that work design that is based on psychophysical limits will help establish safe procedures. Many guidelines, such as the NIOSH WPG, are based on data gathered from psychophysical studies, although no research has yet been performed which demonstrates that humans can accurately perceive and report loads acting on the body. The two main psychophysical methods involved in determining psychophysical lifting limits are MAWL and RPE. Previous investigations have shown that the process of judging objective loads subjectively relies on many variables, such as environment and worker attitude, as well as physical loads. In terms of perception of exertion at specific joints, only the low back has been studied in depth, with conflicting results.

Clearly, the validity of using psychophysical methods to determine lifting limits needs to be investigated further. Since work has been done investigating the effect that loads have on whole body perception of loads with mixed results, it is of interest to investigate human perception of exertion at the local level, at specific joints, which is the focus of the present research.

3.0 EXPERIMENTAL METHOD

3.1 Overview

It should first be noted that in this experiment, though the concept of a MAWL was used, the load that was determined by each subject was not a 'true' MAWL. Each subject did not go through the full motion of a lifting task, but only statically supported a load in a certain posture. Each subject, however, used the method of adjustment to determine an acceptable load. This method of determining a maximal load, and the load itself, are defined here as a Maximum Acceptable Static Load (MASL).

The goal of this experiment was to investigate the relationship between physical loads and subjective ratings of these loads. In order to carry out this investigation, four different sets of data were collected for each subject: strength capability, MASL, RPE, and joint moments. To begin the experiment, the subject performed a strength test of the elbow, shoulder and torso. This data yielded strength curves as a function of joint angle that were used to normalize later data, facilitating comparisons among subjects. MASLs were obtained in four different postures. After having supported a load for 10 seconds, each subject was prompted to give RPE ratings of specific joints. Joint moments at the shoulder, elbow, and low back were calculated for each posture and used in subsequent comparisons to the subjective data (RPE and MASL).

3.2 Subjects

Ten college students participated in this study and were compensated at a rate of $5.00 an hour. Each subject earned approximately $20 by the end of the four hours required for the experiment. The group of subjects consisted of five males and five females. An equal number of males and females were chosen for generalizability.

Before inclusion in the study, each potential subject was questioned to ensure that he or she was qualified and able to participate in the study. A subject screening process was conducted to eliminate any potential participants who had prior manual lifting experience or undergone training, had previous musculoskeletal problems, or were involved in any weight lifting programs. No potential subjects were eliminated as a result of this screening process. Once each subject completed the screening process, an informed consent form was completed (Appendix A).

3.3 Experimental Design

The design of this experiment was within-subjects. Two independent variables were presented, and five dependent variables were recorded. All independent variables were presented in a completely random manner, and are discussed below.

3.3.1 Independent Variables

The independent variables in this experiment were posture and Percent MASL (%MASL). Each subject posed in four postures, each posture designed to isolate a specific joint. Posture 1 was designed as the baseline posture to which the following three postures were compared. Posture 2 maintained the same moment arm (MA) from the load to the shoulder and torso, but reduced the MA, and hence the moment, to the elbow. The MA from the shoulder to the elbow remained the same, while the MA to the low back increased in Posture 3. Posture 4 reduced the MA to the shoulder, while maintaining the MA to the elbow and low back. These postures can be seen in Figure 3.3-1. The second independent variable was Percent MASL (%MASL). Each subject was instructed to support each of five fractions (10, 30, 50, 70, and 90%) of the MASL, which had been determined by the subject in an earlier part of the experiment.

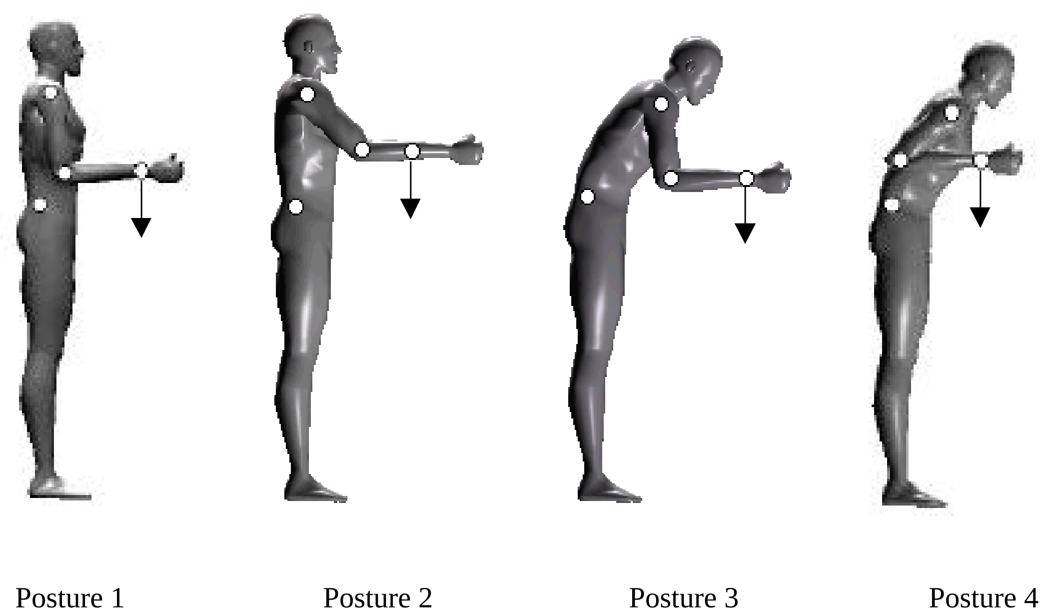

Figure 3.3-1. Four postures used in the psychophysical portion of the experiment. (Arrows indicate the location of load attachment.)

3.3.2 Dependent Variables

The dependent variables were MASL, whole body RPE, elbow RPE, shoulder RPE and low back RPE. MASL (kg) was determined in each of the four postures for each subject. The RPE values were reported by the subject using the Borg CR-10 rating scale (Figure 3.3-2) to rate exertion.

♦	Maximal	
10	Extremely strong	(almost max)
9		
8		
7	Very strong	
6		
5	Strong	(heavy)
4	Somewhat strong	
3	Moderate	
2	Weak	(light)
1	Very weak	
0.5	Extremely weak	(just noticeable)
0	Nothing at all	

Figure 3.3-2. Borg CR-10 Rating Scale (Borg, 1990)

3.3.3 Procedure

This experiment was conducted in two separate sessions for each subject. The first session involved testing the strength of the subject. The second was the psychophysical testing that determined the MASLs, RPEs, and joint moments of each subject. The methods used to obtain each type of data are described below. Each session lasted one to two hours, and took place on separate days.

3.3.3.1 Strength Testing

Strength testing was done in order to normalize joint moments. The moments needed to be normalized so that comparisons between the different postures of a single subject and comparisons between subjects could be made. The strength of the elbow, shoulder, and torso of each subject was evaluated.

To test the strength of each subject, a variety of equipment was used. For the elbow and shoulder tests, this equipment included a wooden chair affixed with upper arm guides, 2” nylon straps, and wooden handles. A strain-gauge force transducer was used for the elbow and shoulder strength evaluation. This transducer interfaced with a LabView™ Virtual Instrument (VI) to record voltages, which would later be converted to forces. The torso test included a 2” nylon strap and a Bertec™ force plate, which also interfaced with a LabView™ VI. The VIs for both configurations were calibrated for each subject. The calibration was done by recording the output that a series of known weights produces, and generating a calibration curve to fit the data. The output for each known weight was recorded three times, with the average of these values used to generate the calibration curve.

To obtain strength data for the elbow, each subject was seated in the wooden chair, and instructed to place the upper arm in the upper arm guide which was adjusted for them, as seen in Figure 3.3-3.

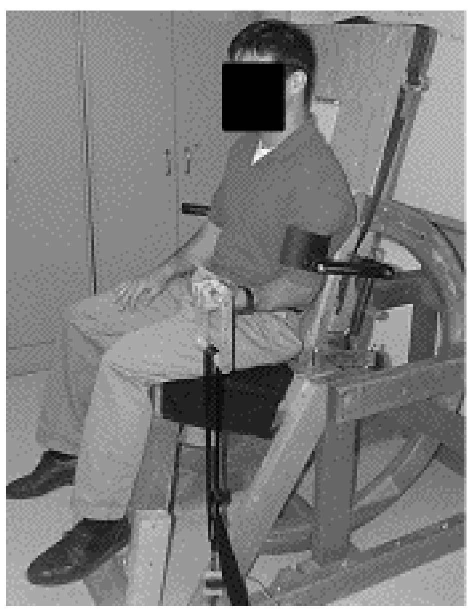

Figure 3.3-3. Elbow strength test configuration.

A wooden handle connected to a 2" nylon strap was grasped by the subject, and the strap was pulled taut. This strap was connected to a force transducer that was attached to the wooden chair. This test was performed for both the right and left arms. The included angle between the upper arm and lower arm, as well as the perpendicular distance between the line of action of the strap and the center of rotation of the elbow, were measured with a goniometer and a tape measure, respectively. Once these measurements were recorded, the subject was instructed to pull up on the strap, exerting a maximal force with the biceps. The subject was also instructed not to 'jerk' the strap, but to gradually increase the exertion, reach a maximum, and then gradually ease the exertion. Once the exertion was completed, voltages were obtained at a sampling rate of 500 Hz for a duration of 6 seconds. The subject was then instructed to exert another maximum force in the same manner as the first exertion. This process was repeated for six different included angles of the elbow (45, 65, 85, 100, 120, 135^{o}), alternating between both arms in order to obtain sufficient data points to construct a strength curve for both the left and right elbows. The order in which the exertion at each angle was tested was randomized between subjects. Each subject was given two minutes of rest between each exertion to minimize fatigue.

The test of shoulder strength was very similar to the elbow strength test. Each subject was secured in the same apparatus as in the elbow test, but the arm guides were moved out of the way of the subject's range of motion, as seen in Figure 3.3-4. A 90^{o} included angle between the subject's upper and lower arm was maintained for each exertion of the shoulder. The strap was situated co-linearly with the forearm, and the location of the force transducer was adjusted accordingly. Each subject grasped the same type of handle and nylon strap as in the elbow test. The perpendicular distance between the strap, which is connected to the force transducer, and the rotational center of the shoulder was measured to determine the moment arm. Maximum exertions for five angles (-20, 10, 25, 45, 70 and 90°) were performed by the subject. Each exertion was repeated once, for a total of two at each specific angle. The angle that was measured was the included angle between the upper arm and the torso. Once a set was completed on one arm, the other arm was tested at the same angle. The order of exertions at each angle tested was randomized between subjects, and two minutes of rest between each exertion was given.

Figure 3.3-4. Shoulder strength test configuration.

Finally, the voltages recorded for the shoulder and elbow tests were converted to moments. This conversion was done by using the calibration curves (kg), multiplying by 9.81 m/sec^2, and multiplying by the length of the moment arm to the center of rotation for the specific angle being measured. Moments due to body segment masses were also incorporated into the calculations, with subject-specific center of mass parameters obtained from commercial software.

To test torso strength, each subject was secured in a lower-body restraint apparatus in a standing position, as seen in Figure 3.3-5. A Bertec^{TM} Force Plate (#K80102) was anchored beneath the apparatus. The apparatus prevented any motion between the torso and the feet, which allowed the legs to act as a rigid body. Forces and moments that were recorded at the feet by the force plate were used in a kinetic analysis to calculate the moment at the low back. A strap attached to an adjustable rail that was anchored to the wall was placed around the subject. The strap passed around the upper torso just under the arms, and the moment arm was measured between the strap and the subject's low back.

Figure 3.3-5. Torso strength test configuration.

In several orientations of the torso, the subject was instructed to perform a maximum torso exertion force against the 2” nylon strap for four seconds, gradually increasing to the maximum effort, and then gradually easing the extension. The resulting maximum forces and moments at the feet were measured by the force plate and recorded. Before the subject exerted a maximum effort in a given posture, the force plate was zeroed, and a baseline ‘resting’ moment was established for each angle to be tested. The recording of the resting moment involved the subject assuming the desired angle of the torso, while not exerting any force on the strap. A maximum extension force was exerted for a total of six times at included angles (between upper leg and torso) ranging from 135^{o} - 185^{o} in increments of 10. This test yielded the maximum torso exertion moments in Newton-meters.

3.3.3.2 Psychophysical Tests

For the psychophysical portion of this experiment, the subjected first determined a MASL while positioned in each of the four postures (Figure 3.3-1). After these were determined, the subject gave whole body, elbow, shoulder, and low back RPE ratings while supporting five different fractions of the MASL. Both the MASL and RPE trials were conducted with the subject in a configuration shown in Figure 3.3-6.

Figure 3.3-6. Subject in apparatus for psychophysical tests

The part of the experiment concerning MASL had each subject determine a maximal, yet comfortable weight using the method of adjustment. The subject was instructed to briefly support the weight (for 1 – 2 seconds), and subsequently adjust it until a weight was reached that could be comfortably supported for ten seconds. The detailed method is explained below. The determination of the MASL also investigated the relationship between the loads selected and postures in which the loads were selected, which provided information regarding joint sensitivity.

To begin, each subject was secured to the same apparatus that was used in the torso strength test, so the legs acted as a rigid body. Reflective markers were affixed at the point of contact of the load, elbow, shoulder and approximate L5/S1 location. The spatial location of these markers was recorded by a Qualisys MacReflex^{TM} motion capture system. This system used two cameras to capture the 3D location of the reflective markers on the body using a sample rate of 12 Hz for a period of 6 seconds. A video feed from the MacReflex^{TM} cameras was sent to a television so that the subject could clearly see the marker positions. For each posture, a transparency was taped to the screen, and the placement of the reflective markers was marked with a colored pen. The subject was instructed to line up the reflective markers with the original locations that were marked with colored pen on the screen. This procedure ensured that the postures remained consistent across trials (Figure 3.3-7).

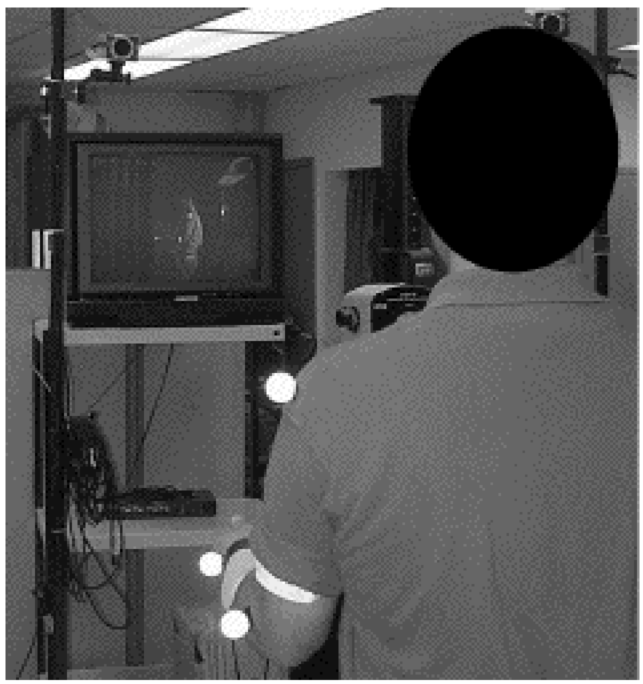

Figure 3.3-7. Subject shown lining up markers.

Plastic braces were fitted on the forearm of each subject and secured with an elastic bandage. These braces were worn by the subject to minimize any pressure points that would result from the straps resting on bare skin, and eliminated any loading of the hands and wrists. The loading of the wrist was specifically eliminated (unloaded) for this study so that only the effects of loads on the larger, stronger joints can be studied. It was assumed that the wrists of most subjects are relatively and significantly weaker than the elbow, shoulder or low back. While there is interest in investigating the role of the wrist in the lifting motion, the focus of the present study is on other body parts, given the expected sensitivity of the hand and wrist to handle size, shape, placement and orientation.

Straps supporting the load were placed on the forearm, over the plastic braces. The load, which consisted of plastic-bagged lead shot, was contained by a steel box with dimensions of 30.48 x 20.32 x 10.16 (units in centimeters), as seen in Figure 3.3-8. The steel box was attached to the 5.08 cm straps, and rested on an adjustable table in front of the subject until all parties were ready to begin the trials. This table was placed in front of the subject at a height at which it was possible to lift the load and assume a posture with minimal vertical travel distance. The subject also rested the load on the table between trials.

Figure 3.3-8. Steel box that held load of lead shot (seen in the plastic bags)

For each trial, the subject began with a random amount of weight in the box (ranging from very light to very heavy, with respect the MASL chosen by each subject). Once positioned in one of the four postures, and the location of the markers recorded both on the transparency and saved in a MacReflex^{TM} file, the subject was instructed to adjust the weight in the box while remaining in the set posture. These instructions can be found in Appendix B. The subject continued to adjust the weight until they felt that a maximum weight had been determined that could be comfortably supported statically for ten seconds. The definition of comfort was left entirely to the subject. The subject was allowed as much time as necessary to adjust the weight of the load, though most subjects did not take more than 2-3 minutes to adjust the load. If any fatigue was apparent after a load was chosen, a short break was given until the subject was sufficiently rested. The load was weighed and recorded once the subject determined a maximal, comfortable weight. The subject was given as long a rest period as needed before beginning the next trial. Once the subject had rested, three more trials were conducted in the same manner, one for each of the remaining postures.

The part of the experiment concerning RPEs investigated the relationship between subjective ratings and actual biomechanical loads that acted on the body. The MacReflex system again was used to record the posture of the subject. Reflective markers remained at the point of contact of the load, shoulder, elbow, and approximate L5/S1 location. The plastic braces from the first trials also remained in place.

While situated in each posture, the subject supported five different loads. Each of these loads was a certain percentage of the MASL determined for each posture in the first part of this experiment. The percentages that were used were 10, 30, 50, 70 and 90%, and were presented to the subject in random order. To begin the experiment, the experimenter prepared the load, and then helped the subject place the straps on the forearm in the appropriate position. The subject was then instructed to resume the predetermined posture by lining up the reflective markers with the colored marks on the television screen (Figure 3.3-7).

Once the posture was achieved, the subject was instructed to support the load for ten seconds. While the load was supported, the experimenter recorded the posture using the MacReflex™ system. After ten seconds elapsed, the subject was instructed to place the load back on the table. The experimenter then prompted the subject for subjective ratings of exertion (RPE) of overall body, elbow, shoulder and low back. The instructions given to each subject can be found in Appendix C. Once this data was collected, and the subject had sufficiently rested, the next load was presented. This cycle was repeated until all weights were presented in each of the four postures.

3.3.4 Analysis

3.3.4.1 Strength data

Strength data for the torso was collected and plotted, and a first-order polynomial was fit to the points. This line yielded a mean strength value for the torso of each subject. A sample torso strength curve can be seen in Figure 3.3-9.

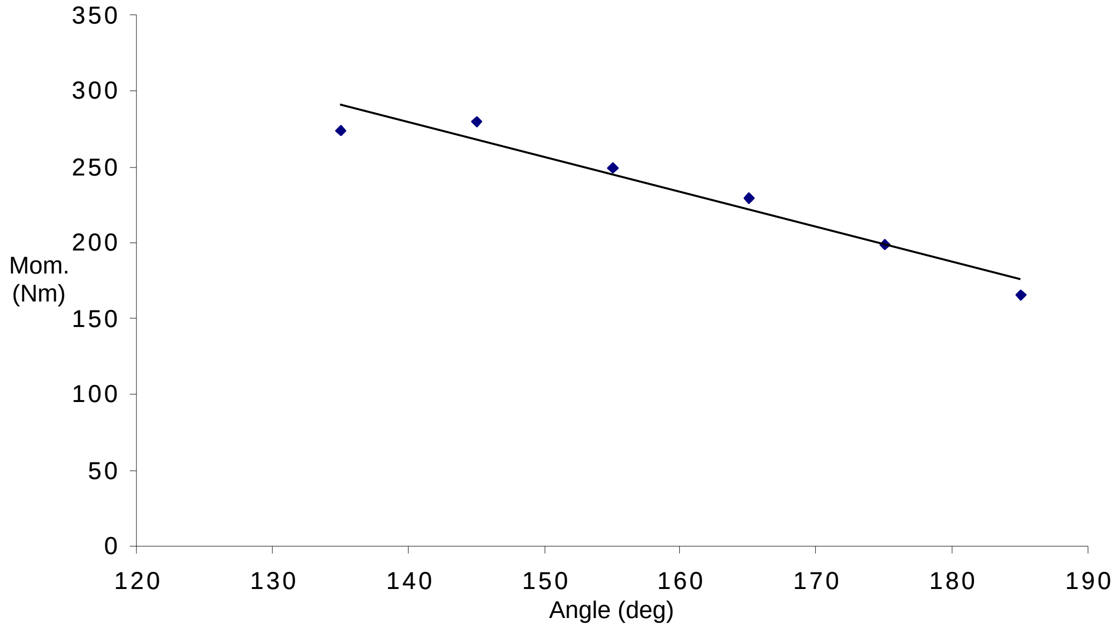

Figure 3.3-9. Sample torso strength curve

Strength data for the shoulder and elbow was collected and plotted in the same manner as the torso, but for the left and right arms separately. Both the elbow and shoulder strength data were fitted with second-order polynomials. Because MASL and RPE trials involved the use of both arms, the data points for both the left and right elbow were plotted and a curve was fitted to the group of points as a whole. This fitted curve yielded a mean strength value for the arms of each subject. A sample elbow strength curve can be seen in Figure 3.3.10. The same procedure was followed for the shoulder strength values, and a sample shoulder strength curve can be seen in Figure 3.3.11.

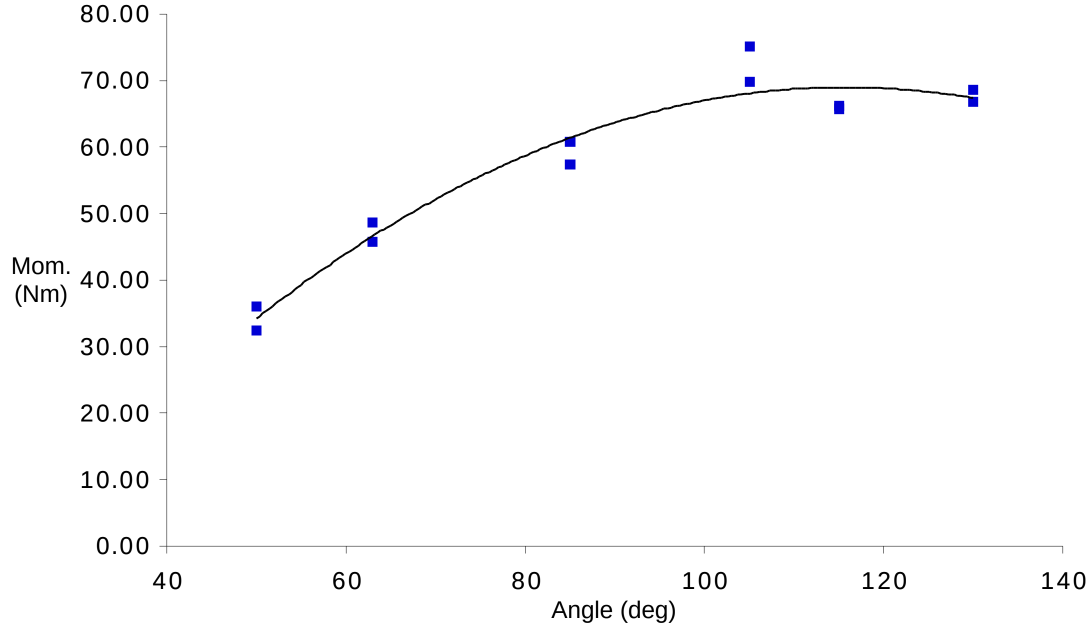

Figure 3.3-10. Sample elbow strength curve

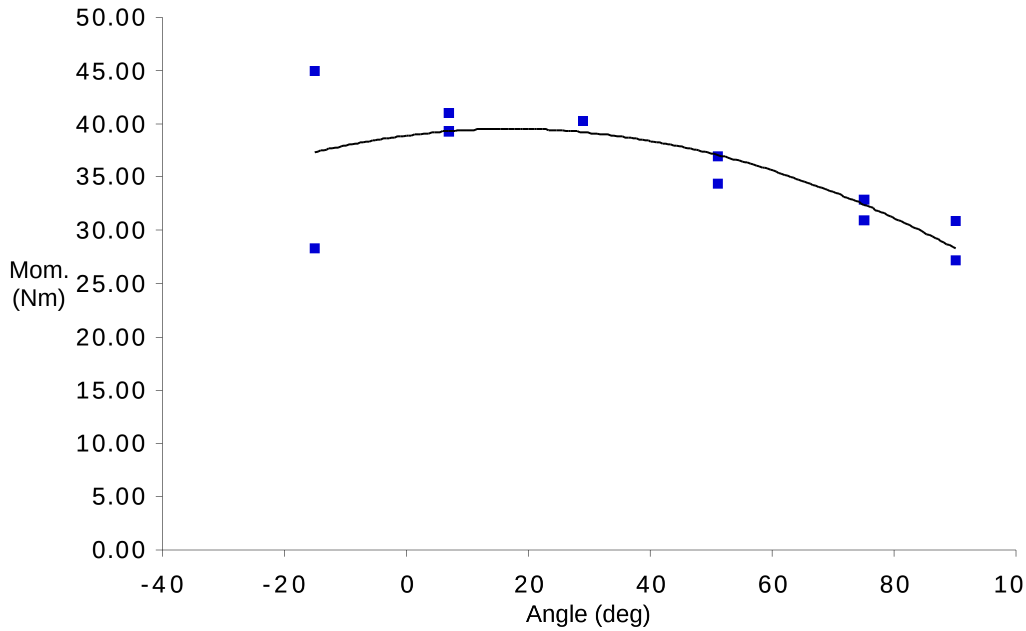

Figure 3.3-11. Sample shoulder strength curve

The R^2 values for the elbow, shoulder and torso trendline fits for each subject are shown in Table 3.3-1. Root Mean Squared (RMS) and standard error are also shown for the elbow and shoulder, and torso, respectively. It should be noted that the trendlines fit the shoulder data well, but the small R2 values resulted from the 'flat' (nearing horizontal) relationships between strength and posture.

Table 3.3-1. R^2 Values and Errors for Strength Data Trendlines

Subject	Elbow (second order)	RMS Error (Nm)	Shoulder (second order)	RMS Error (Nm)	Torso (first order)	Std Error (Nm)
1	0.803	2.79	0.389	5.49	0.937	12.42
2	0.758	3.64	0.237	2.85	0.753	21.34
3	0.664	3.65	0.032	2.50	0.791	28.75
4	0.548	4.20	0.455	3.00	0.879	12.88
5	0.952	3.21	0.318	5.48	0.972	19.70
6	0.907	1.86	0.458	3.70	0.940	20.65
7	0.903	2.51	0.541	4.02	0.906	22.95
8	0.797	2.94	0.027	3.57	0.805	14.30
9	0.566	4.07	0.045	4.22	0.905	15.66
10	0.917	1.89	0.041	2.58	0.643	16.35
MEAN	0.782	3.08	0.254	3.74	0.853	18.5
STDEV	0.146	0.83	0.204	1.09	0.102	5.14

3.3.4.2 Biomechanics

Once postural data was collected from the MacReflex™ system, the 3-D data was exported to a Microsoft Excel™ file. Since both cameras used to record the postures were oriented nearly perpendicular to the subject's sagittal plane, the depth coordinate was discarded to simplify calculation. Disregarding the depth coordinate left only data in the sagittal (defined as X-Y in MacReflex™) plane. The center of mass (COM) of each subject's torso, upper arm, and lower arm was also taken into consideration when calculating joint moments. The COM locations and masses of the subject's upper arm, lower arm, and torso were estimated using the University of Michigan's 3DSSPP software package. In order to produce these specifications, each subject's height, weight and gender was entered into the software. Once an estimation of the mass and COM location was determined by the software, the body segment weight was factored into the moments around the elbow, shoulder and low back.

To find the moment around each joint due to the mass of the box and the body segment, the horizontal perpendicular distance from the location of the load and COM was calculated using simple trigonometry and an Excel spreadsheet. These values were then multiplied by the mass of the load and the segment mass, respectively, with each reported in Newtons (N). The sum of the resulting values (load and body segment moments) was reported as the joint moment in Newton*meters (Nm).

4.0 RESULTS

4.1 Relationship Between Subject, Posture and MASL

A summary of MASL values obtained in each posture is shown in Figure 4.1-1. Postures 2 and 3 showed a decrease in MASL when compared to the baseline (Posture 1), while Posture 4 showed an increase in MASL.

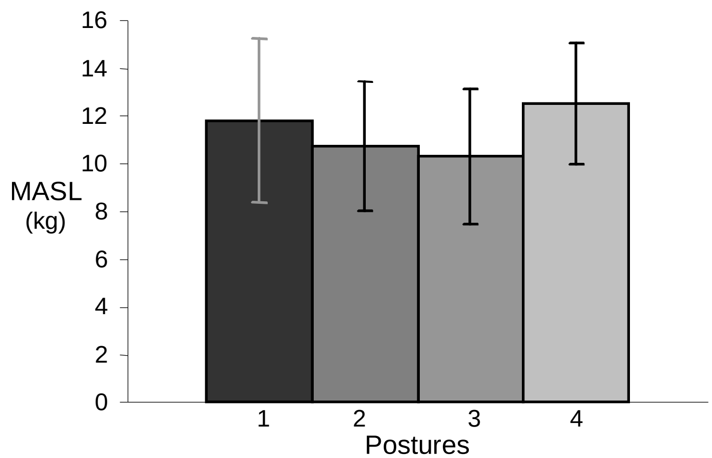

Figure 4.1-1. MASL values obtained in each posture

Once the data was collected and compiled, it was apparent that it did not follow a normal distribution. Therefore, results from parametric tests could not be used. However, an ANOVA was performed merely to check for trends in the data, and also to provide the experimenters with some insight regarding what to expect from non-parametric tests.

Upon conducting an ANOVA, merely to check for trends, subject and posture were both significant main effects on the magnitude of MASL ($p<0.0001$ and $p=0.0066$, respectively). The ANOVA summary table for this test can be seen in Table 4.1-1. When an analysis was done to investigate the effect of subject and posture on the difference in MASL between the baseline posture and Postures 2, 3, and 4, ANOVA again revealed significant effects ($p<0.0001$ and $p=0.0013$ respectively), as summarized in Table 4.1-2. Significant subject and posture effects ($p=0.0004$ and $p=0.0012$) were also shown by ANOVA in the analysis of percent difference in MASL (($MASL_i$ – $MASL_1$) / $MASL_1$) as seen in Table 4.1-3. Recall that the results of these ANOVAs can not be used as definitive tests for the non-normally-distributed data. The significant ANOVA results did indicate, however, that favorable results may come from non-parametric tests on the same data.

Table 4.1-1. ANOVA Summary Table of the effect of Subject and Posture on MASL

Effect	df	Sum of Squares	F-value	P-value
Subject	9	246.96	13.77	< 0.0001
Posture	3	30.21	5.05	0.0066

Table 4.1-2. ANOVA Summary Table of the effect of Subject and Posture on Difference in MASL

Effect	df	Sum of Squares	F-value	P-value
Subject	9	115.19	9.22	< 0.0001
Posture	2	27.27	9.82	0.0013

Table 4.1-3. ANOVA Summary Table of the effect of Subject and Posture on Percent Difference in MASL

Effect	df	Sum of Squares	F-value	P-value
Subject	9	6228.20	6.44	0.0004
Posture	2	2158.95	10.04	0.0012

As previously mentioned, it was found that the distributions of differences in mean MASL as well as the percent differences in MASL were not normally distributed. Because of this non-normal distribution, Wilcoxon Signed-Rank non-parametric tests were necessary to test for significant differences in the mean MASLs between postures. The summaries for these tests can be seen in Tables 4.1-4 and 4.1-5, respectively. Both tests failed to show that there were significant differences between mean MASLs. The difference between postures 1 and 3 approached significance at p=0.105 for both tests. When the difference between Posture 1 and 2, and 1 and 4 were compared, each test also showed consistent trends at p=0.160 and p=0.193, respectively. The difference between Postures 1 and 2, and 1 and 4 both displayed consistent trends at p=0.160 for the comparison of percent difference.

Table 4.1-4. Signed-Rank Results for Differences Between Mean MASL Values

	P2 – P1	P3 – P1	P4 – P1
Hypothesized Value	0	0	0
Actual Estimate	-1.074	-1.504	0.669
Test Statistic	-14.50	-16.50	13.50
Prob > | t |	0.160	0.105	0.193

Table 4.1-5. Signed-Rank Results for Percent Differences Between Mean MASL Values

	P2 – P1	**P3 – P1**	**P4 – P1**
Hypothesized Value	0	0	0
Actual Estimate	-7.47	-11.15	8.40
Test Statistic	-14.50	-16.50	14.5
Prob > | t |	0.160	0.105	0.160

4.2 Relationship between strength and MASL

The relationship between MASL and strength was investigated using multiple linear regression. The MASL values across all subjects were grouped by posture (1 - 4) and were modeled as a function of elbow, shoulder and torso strength. For a fifth model, MASL values across all subjects and postures were modeled as a function of strength across all subjects and postures. A summary of these regression results including the constants and coefficients for the equations of each posture can be seen in Table 4.2-1. The regression models revealed greater coefficients for shoulder strength for each posture, most notably in Posture 2 (0.618) and Posture 3 (0.479). The model also shows that some of the coefficients for the elbow and all of the coefficients for the torso strength values are negative, implying a model that is not very robust.

Table 4.2-1. Results of regression analysis modeling MASL as a function of strength in each individual posture (1 – 4) and over all postures and subjects (overall).

MASLi	Constant	Elbow Strength Coeff.	Shoulder Strength Coeff.	Torso Strength Coeff.
$MASL_1$	3.16	0.050	0.321	-0.0345
$MASL_2$	4.36	-0.139	0.618	-0.696
$MASL_3$	2.94	0.052	0.479	-0.0605
$MASL_4$	4.13	0.0914	0.324	-0.0363
$MASL_{overall}$	4.14	-0.0272	0.310	-0.0214

Upon inspection of the R^2 values associated with the regression equations seen in Table 4.2-2, only the models for Postures 2 and 4 showed that strength was a good predictor of MASL (R^2=0.571 and R^2=0.768). All others failed to produce R^2 values greater than 0.50.

Table 4.2-2. Linear Regression Results Relating Strength and MASL

Posture	Mean MASL (kg)	RMS error	R^2
1	11.80	3.079	0.461
2	10.73	2.165	0.571
3	10.30	2.811	0.336
4	12.50	1.500	0.768
Overall	11.33	2.407	0.369

4.3 Relationship between RPE ratings and Percent Strength

The relationship between RPE and percent maximum strength was examined by plotting RPE ratings versus percent maximum strength, and comparing the slopes and intercepts between each posture and the baseline posture. Sample illustrations of these relationships can be seen in Figures 4.3-1, 4.3-2 and 4.3-3. These figures are from a single subject whose trends were representative of the overall trend of the subject pool.

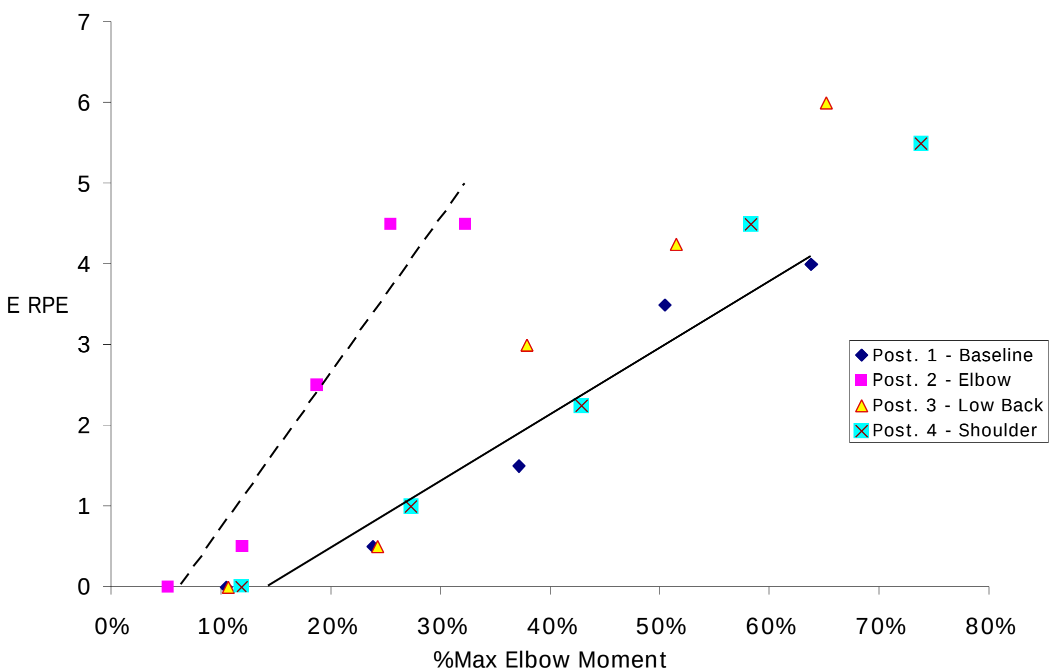

Figure 4.3-1. Sample graph of Elbow RPE vs. %Max Elbow Moment (Lines are fit to Posture 1 and Posture 2)

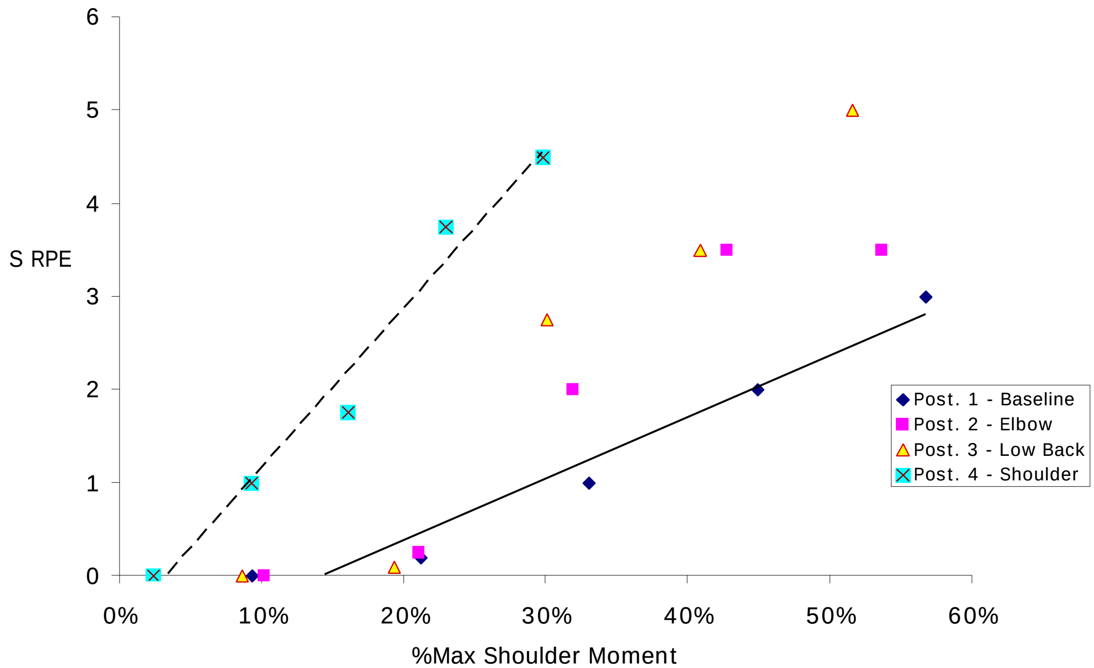

Figure 4.3-2. Sample graph of Shoulder RPE vs. %Max Shoulder Moment (Lines are fit to Posture 1 and Posture 4)

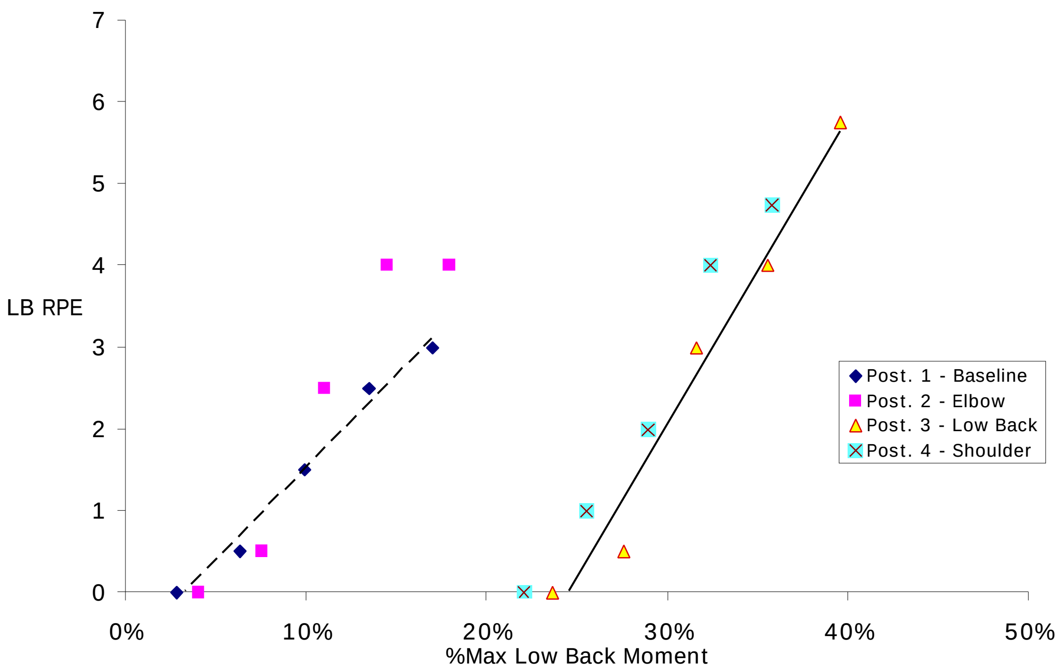

Figure 4.3-3. Sample graph of Low Back RPE vs. %Max Low Back Moment (Lines are fit to Posture 1 and Posture 3)

Upon inspection of Figure 4.3-1, a noticeable difference between the slope of Posture 1 (baseline) and Posture 2 (elbow) is apparent. The same trend can be seen in Figure 4.3-2, between Posture 1 and Posture 4 (shoulder). Though, in both Figure 4.3-1 and 4.3-2, the intercept of the lines is similar. In Figure 4.4-3, a difference between the intercepts of the lines for Posture 1 and Posture 3 (low back) is apparent, while the slope appears to be similar. These trends were consistently observed across subjects, as detailed in Table 4.3-1. In the table, the shaded columns illustrate the similar intercepts for the elbow and shoulder graphs for each subject as well as the similar slopes of the low back graphs. The non-shaded columns illustrate the differing slopes of the elbow and shoulder graphs, and the differing intercepts of the low back graphs.

Table 4.3-1. Slopes and Intercepts of Fitted Lines for RPE vs. Percent Strength Data

	Elbow (Fig 4.3-1)				Shoulder (Fig 4.3-2)				Low Back (Fig 4.3-3)			
	INTERCEPT		SLOPE		INTERCEPT		SLOPE		SLOPE		INTERCEPT	
Subj.	Base	E	Base	E	Base	S	Base	S	Base	LB	Base	LB
1	-1.16	-1.20	8.26	19.24	-0.93	-0.55	6.58	17.16	22.54	37.64	-0.72	-9.24
2	-0.79	-1.42	5.69	18.89	-0.64	-0.26	4.87	9.32	7.50	6.67	-0.20	-1.29
3	-2.07	-2.55	14.12	30.33	-1.52	-1.13	9.67	17.85	26.68	46.71	-1.16	-12.73
4	-0.54	1.05	5.09	8.39	0.23	-0.37	4.30	4.82	11.36	18.40	0.11	-3.56
5	-0.63	-0.08	11.14	13.51	-1.04	0.17	11.64	10.51	44.31	31.38	0.79	-3.88
6	-1.42	-2.29	24.13	39.14	-2.02	-1.38	15.99	18.19	55.86	66.46	-1.47	-11.79
7	-0.39	-0.38	2.65	7.10	-0.63	-0.46	4.29	16.36	2.06	24.98	-0.04	-4.30
8	-2.89	-1.46	13.45	17.98	-2.30	0.09	10.95	19.53	54.41	42.68	-2.98	-13.66
9	-1.30	0.00	11.31	6.44	-0.57	-0.01	4.72	4.69	11.59	5.91	-0.44	-0.82
10	-1.46	-0.68	18.15	24.76	-1.39	-0.26	12.48	14.31	53.30	21.42	-1.58	-4.76

Because of these trends, an analysis was done that compared the slopes from Figures 4.3-1 and Figures 4.3-2, while intercepts were compared from Figure 4.3-3. It should also be noted that though none of the graphs were exactly linear, a general linear trend was apparent. Therefore, linear regressions were deemed sufficient to use for analysis. The use of linear regressions also allowed ease of analysis.

A Wilcoxon Signed-Rank test was conducted to test for significant differences in the slopes and intercepts. Each comparison yielded significant differences as seen in Table 4.3-2.

Table 4.3-2. Signed-Rank Results for Differences Between Slopes and Intercepts of Lines Representing Joint RPE vs. %Max Strength

	Elbow	***Shoulder***	***Low Back***
	%Difference P2 – P1 slope	**%Difference P4 – P1 (slope)**	**P3 – P1 (intercept)**
Hypothesized Value	0	0	0
Actual Estimate	77.13	51.64	-5.885
Test Statistic	51.0	52.0	0.0
Prob > | t |	0.019	0.014	0.006

5.0 DISCUSSION

5.1 Summary of the Study

The psychophysical approach has become an increasingly popular methodology for evaluating workload. It has become so, in part, due to its relative ease of implementation and economy. Although it has been used extensively, much is still not known about how subjective ratings, the core of the psychophysical methodology, relate to physical (biomechanical) loads. The primary assumption of this method is that humans are capable of estimating biomechanical and physiological loads that are placed on the body. Therefore, individuals are thought to know the physical limits of the body, and would not consciously exert a force that could injure the body. By this assumption, the estimates that are obtained through the methodology are used as an indicator of physical loads and stresses, and are assumed to be related to injury risk.

The assumption that a relationship exists between subjective ratings and biomechanical loads is essential to justify the use of the psychophysical methodology for the evaluation of workload and for the establishment of standards. Past research has investigated this relationship in part, but the body of research as a whole has not been conclusive. For example, Resnick (1995) conducted a study that investigated inter- and intra-subject variability in psychophysical applications. He found that CR-10 ratings showed repeatability for individual subjects. He also showed that the ratings were consistent across subjects and tasks. Contrarily, in a review of many studies regarding low-back pain, Hadler (1997) found that RPE ratings were dependent on cognitive, not just physiological factors. Thompson and Chaffin (1993) also found that subjects could not consistently perceive exertions of the low back. They concluded in their study of lifting that during occasional lifting tasks, people are not aware of, and do not perceive levels of stress equally. The inability to effectively perceive loads could lead to choosing loads that have the potential to injure the body (Thompson and Chaffin, 1993). These examples of conflicting results imply that more needs to be learned about psychophysics so that the role that it plays workload evaluation and the establishment of standards can be clarified. In order to gain a better understanding of the relationship between subjective ratings and physical loads, this study investigated subjective reports of physical stress and load acceptability and the dependence on the loads placed on specific body joints.

The two main goals of this study were to: 1) determine the correspondence between mechanical loads on several body joints and subjective ratings of joint loads, as well as subjectively determined maximal loads and 2) to identify whether any particular joint (i.e. low back, shoulder, elbow) is the limiting factor when a subject determines a maximally liftable load. This second goal, in other words, was to find whether there is a 'weak link' of the body that determines the maximum load an individual is willing to lift. These goals were established to investigate how the relationship between joint loads and the subjective ratings of these loads can illustrate the accuracy of load perception. Further understanding of this relationship can help determine the validity of the standards that are determined using the psychophysical methodology. Better understanding of human perception of effort in lifting tasks may also help in the long term to decrease lifting injuries by aiding in the development of more rigorous lifting guidelines.

To achieve the two goals stated above, a study was conducted in which subjects posed in four different static postures. These postures were designed to investigate only the effects on the upper body. Therefore, each subject was secured to a stable apparatus from the waist down. While in each of these postures, the subject was instructed to use the psychophysical method of adjustment to choose a weight that felt as if it was maximal, yet still 'comfortable'. Various fractions of the maximum load were then supported in each of the four postures. The subject then reported on the overall exertion that was perceived, as well as the exertion felt in specific joints. The ratings of exertion and the maximum supportable loads that the subject determined were then compared with the strength demands imposed on several major body joints.

5.2 Effects of Posture on MASL

The dependence of load perception on posture was investigated by instructing the subject to determine a MASL in each of four different postures. One of the postures (Posture 1) was designed to be the comparison posture, while each of the other three postures kept all load moment arms constant except one around a single joint: elbow (Posture 2), shoulder (Posture 4) or low back (Posture 3). If any of the non-baseline postures (refer to Figure 3.3-1) led to significantly higher or lower acceptable loads than the baseline, the implication would be that the joint loads that changed in the corresponding posture was influencing perception and that joint was potentially limiting. When compared to the baseline, the load moment arms around the low back increased while the moment arms for the shoulder and elbow decreased. This change in load moment arms around the joints between postures led to a change in the moments around the joints. Changes in joint moments consequently led to a change in the task demands related to supporting the load (expressed in this experiment as percentage of strength required). Comparison between certain postures allowed for isolation of the elbow, shoulder or low back, so that perception of different loads on the same joint could be investigated. Due to the design of the experiment, and by simple mechanics, the results of the study should have shown an inverse relationship between the moments and the MASLs.

Certain results were expected and were related to the changes in loads and task demands associated with the specified postures. In Posture 2 the moment arm to the elbow decreased while the moment arms to the low back and shoulder stayed roughly the same as in Posture 1, the baseline. Therefore, the subject was expected to choose a heavier MASL in Posture 2 because the decreased moment arm would allow them to support a heavier load with a resulting moment that was the same as in the baseline posture. In Posture 3, the moment arm to the low back increased while the moment arms to the elbow and shoulder stayed roughly the same. In this posture, the subject was expected to choose a lighter MASL, because the increase in moment arm would necessitate a lighter load to maintain the same moment as the baseline. In Posture 4, the moment arm to the shoulder decreased while the low back and elbow remained similar to the baseline. Just as in Posture 2, the subject was expected to choose a heavier MASL in Posture 4, because the decreased moment arm would allow them to support a heavier load with a resulting moment that was the same as in the baseline posture. These expectations were established with the assumption that individuals choose loads that maintain the safety of the joints, and hence maintain a relatively constant maximum moment around the joints.

Trends regarding the differences in MASL did appear for all three joints. The results show that Posture 3 (increased low back moment arm) and Posture 4 (decreased shoulder moment arm) yielded lighter and heavier loads, respectively, which was expected. However, Posture 2 (decreased elbow moment arm) yielded a lighter MASL than that of the baseline posture, which was not expected because of the substantial decrease of the moment arm around the elbow. In this posture, the subject had to support the load with the arms slightly outstretched with the shoulder positioned in a posture that deviated from a neutral, or familiar position, as seen in Figure 3.2. It is known that with a change in posture, there will be an associated change in strength (Chaffin and Andersson, 1991; Kroemer, Kroemer, Kroemer-Elbert, 1990). When positioned with the muscle at its resting length, strength capability is generally at its greatest. As the muscle deviates from the resting length, strength capability decreases. (The exception to this decrease in strength capacity is when the muscle is extremely extended. When extreme extension occurs, the connective tissue in and around the muscle acts passively to increase the tension associated with the muscle. The conditions in this experiment, though, are not consistent with positions extreme enough to yield substantial effects of passive tension.)

This change in strength is explained by the length-tension relationship (Chaffin and Andersson, 1991; Kroemer et al., 1990). The length-tension relationship of muscles relates changes in posture with changes in strength. This relationship, in turn, is explained by the physical structure of the muscle itself. Muscles are made up of protein filaments that interact by cross bridges that slide and grip each other to cause muscle contractions, or tension. At a muscle's 'resting length', the number of cross bridges between the filaments is at a maximum, facilitating a maximum contraction. If a muscle is extremely stretched or contracted, the number of cross bridges between the filaments is either too few or too numerous, respectively, to generate a maximum tension.

From the description of the length-tension relationship, one can see that the muscle is able to generate maximum strength at its resting length. Similarly, postures that tend to lengthen or shorten a muscle away from its resting length generally yield a decrease in strength capabilities when compared to postures that are more neutral or in the middle of the joint range (Chaffin and Andersson, 1991, Kroemer, 1990). In Posture 2, the arm of the subject was extended, resulting in the length of the biceps exceeding its resting length. The result of this change in length likely caused a change in the strength of the biceps. Although differences in strength were considered in this experiment (by using the strength curves to normalize strength demand data as Percent Max Strength), the change in strength could have had an influence on the perception of the exertion being made to support the load.

The results associated with Posture 2 suggest that even with a substantial decrease in moment arm around the elbow, the non-neutral posture of the shoulder was enough to influence the perception of the load. As already noted, this change in perception could be partly due to a change in strength. It is also possible that the change to an awkward posture triggered other perceptual sensors of the body and contributed to a change in perception. This change in perception could be rooted in the orientation of the muscles and tendons. The body is equipped with sensory nerve fibers called stretch receptors and Golgi tendon organs (Chaffin and Andersson, 1991). These fibers, in part, are used as protection mechanisms against overextension of muscles and tendons. When a muscle reaches its extension threshold, the stretch receptors trigger a reflex that contracts the muscle to prevent damage to the muscle. Conversely, Golgi tendon organs inhibit muscle contraction when they sense that the tendon is reaching its threshold of tension. As well as reflex actions, these sensory fibers also convey a feeling of pain when the threshold of the tendon or muscle is reached (Chaffin and Andersson, 1991).

Some of the postures used in this experiment placed the subject in a position that caused various muscles to deviate from a resting position (non-neutral posture). This non-neutral posture, and associated displacements or loading of tissues (e.g. ligaments, joint capsule, etc.), may have caused the sensory nerve fibers to convey a sense of slight pain or discomfort that might have affected perception of the load. Another aspect of the experiment that could have had an effect on load perception is the placement of the straps on the forearms. The muscles and tendons of the forearms could have been affected by the pressure caused by the straps. Since these muscles and tendons contribute to perception of forces acting on the body, overall perception could have been effected.

As discussed above, trends in the MASL difference between postures were apparent, but the quantitative differences were not as significant as expected. Non-parametric tests failed to show significant differences between the MASLs of different postures, though the results did exhibit a consistent trend. MASLs in Postures 3 and 4 were chosen that were noticeably lighter and heavier, respectively, than the MASL chosen for the baseline posture. This result suggests that sensitivity was shown to changes in task demands at the shoulder and low back. Though generally for Posture 2, a load that was lighter than the baseline was chosen, which is the opposite of what was expected. This trend indicates that the elbow was not sensitive to changes in strength demands during these static lifting tasks. The effects of strap placement, as discussed above, could have interfered with load perception at the elbow. Additionally, Posture 2 involved the subject posing with arms outstretched (Figure 3.3-2). In real-world situations, humans intrinsically expect, from experience, that holding a load with the arms are stretched away from the body (as in Posture 2) will be more difficult than holding a load close to the body. Although the point of the load was closer to the elbow for Posture 2, the expectation of the subject might have been that they would have more difficulty supporting the load due to the outstretched orientation of the arms. In this case, stimuli other that physical moments, such as experience or expectation, could have overridden pure physical stimuli. An indication that can be taken from these results is that when perceiving the effects of these loads, humans may consider more than just simple moments around the joints.

5.3 Relationship between strength and MASL

To investigate whether strength was a predictor of the MASLs that were chosen, a regression analysis was conducted. Each of the three maximum strengths (elbow, shoulder, low back) that were recorded served as the regressors used to predict the MASL. The ability to predict MASL using the peak strength of each subject could clarify the correspondence between mechanical capacity of joints and self-determined maximal loads. Indications regarding a weak link of the body were also investigated. The presence of a weak link would be suggested by a coefficient in the regression equation that was large relative to the coefficients of the remaining two joint variables.

The results of the regression analysis relating strength and MASL showed that shoulder strength had a greater coefficient than the elbow and torso across all individual postures, as well as over all postures predicting overall MASL. This could indicate that the shoulder exhibits characteristics of being a weak link, or limiting joint. Though, this result should be tempered with the fact that of the remaining coefficients for the elbow and the torso, over half were negative values. Additionally, only two of the R^2 values for the regressions were greater than 0.50 (Posture 2 (elbow): $R^2 = 0.571$ and Posture 4 (shoulder): $R^2=0.768$). But, these results regarding the R^2 values seem to support earlier discussion stating that humans may be more sensitive to postures that place them in a position which deviates from a neutral, 'resting' position. Posture 2 and Posture 4 were the two postures that required the arms to be in an especially extended and flexed position, respectively. If the subjects showed higher sensitivity to these extreme postures, the strength at the joint that was most affected by the posture would exhibit the greatest influence over the MASL values. In the case of Postures 2 and 4, the non-neural position of the arm seems to increase the sensitivity of the shoulder, and therefore makes shoulder strength a more influential predictor of MASL than elbow or torso strength.

In respect to strength over all postures, a weak relationship was found between peak strength and MASL, with only 36.9% of the variability in MASL explained by the overall posture-specific joint strength demands. The lack of a strong relationship suggests that strength in this study, strength was not a strong predictor of subjectively-chosen maximum loads. The result showing that shoulder strength has a greater influence over MASL than elbow or torso strength may warrant further investigation.

The result showing a weak relationship between peak strength and MASL does not agree with Resnick's (1995) study that found a very strong relationship between peak strength and Borg CR-10 ratings. In this study, only the strength and subjective ratings at a single joint (the elbow) were studied. In contrast, the present work dealt with the whole upper body, focusing on the shoulder, elbow, and low back. The use of all the segments and links of the upper body for a lifting task requires the lifter to integrate many stimuli from various areas of the body to formulate a subjective assessment of the lift. This integration of multiple stimuli to form an overall assessment of the activity is more complex than assessing the exertion of a single muscle group or joint. This complexity may lead to difficulty in subjectively assessing loads that are placed on the body.

The results of Mital's (1987) study that showed the underestimate of MAWL by inexperienced lifters (of the same strength as experienced lifters) suggest that factors other than strength are responsible for the determination of psychophysical lifting limits. Similarly, the results of the present study seem to suggest that strength capability and joint loads are not the only influence in the determination of lifting limits. Mital's results imply that factors of a non-physical nature (experience of the lifter) was an important factor in determining lifting limits. In the present study, strength was not a good predictor of lifting limits, which implies that some other factor superseded it. As discussed earlier, the non-neutral postures in which the each subject was posed could have influenced the perception of the stresses on the body. Though none of the subjects were trained in manual lifting tasks, intrinsic knowledge of how to lift could have been enough of an experience factor to affect perception of the stresses.

5.4 Relationship between RPE and Percent Strength Demands

RPE data was collected in this study to determine the correspondence between mechanical loads on several body joints and subjective ratings of joint loads. For comparison between subjects, the RPE ratings at each anchor (10, 30, 50, 70 or 90%) were summarized by plotting them versus the percent strength demand at that anchor. The relationship between RPE and percent strength demand was examined by fitting a line to these points. The objective for the comparison of these lines is as follows: Posture 2 - compare elbow and baseline RPEs, Posture 3 – compare low back and baseline RPEs, Posture 4 – compare shoulder and baseline RPEs. Sample graphs can be seen in Figures 4.3-1, 4.3-2, and 4.3-3 in the Results section.

It was expected that the graphs of the RPE vs. Percent Strength Demands for each posture would follow the same trend (i.e. the fitted lines for the joint-RPE data for each posture should have shown similar slope and intercepts). Significant differences in the slopes of the fitted line for elbow and shoulder RPEs were found when compared to each respective baseline. Significant differences were also found in the intercepts of the fitted line for low back RPE compared to the baseline.

If joint moments comprise the primary inputs when a sensation of exertion is formed, then one would expect RPE ratings at each level of percent strength demand to be equal. Since differences were found, this suggests that more than just simple moments around a joint are being considered when exertion is perceived. This change in perception could be due to a change in posture. With changes in posture, as discussed previously, changes in length and tension of muscles and tendons affect certain reflexes and also stimuli that are sent from the muscle as a result of exertions. This implication is supported by Bousenna, et al. (1982), who studied the relation between discomfort and postural loading at the joints. He found that perceived levels of discomfort in joints in the lower body were significantly affected by changes in posture. As the postures became increasingly extreme, perceived discomfort for each subsequent posture increased in the areas of the body that were directly involved with the change in posture.

5.5 Limitations of this study

The purpose of this study was to perform an initial investigation of the relationship between biomechanical loads at specific joints and the perception of these loads. Due to the introductory nature of the study, a few limitations should be addressed. This study was conducted using static postures, which do not represent dynamic lifting tasks. Dynamic lifting tasks better represent real world lifting applications. Human response to dynamic tasks is also different and more complex than the response to static tasks. The static postures used were intended to capture a brief moment of a full lifting motion, so a static analysis could be used to calculate the loads on the body. This static analysis was relatively easy to conduct experimentally, and easy to compare between subjects and postures. However, because of its static nature, some aspects of a realistic dynamic lifting task such as dynamic muscle contraction and the effects of moments of inertia (of the body and the load) are lost. In an ideal case, a dynamic evaluation should be done to fully capture the whole lifting motion from start to finish. But the preparations and analysis of a dynamic evaluation such as this far exceed the scope and purpose of this study, which is the reason a static evaluation was deemed sufficient.

In this study, influences of any external or internal forces on the lower were excluded. This was achieved by securing the subject to an anchored apparatus from the waist down during the static support trials. In a more comprehensive study, the lower body should be included in the analysis of the lifting motion in order to capture the entire 'system' of linkages that contribute to lifting an object. A similar limitation, addressed earlier, is that the effects of the wrist and hand on the task were eliminated by placing a plastic brace on the forearm of each subject. The effects of the hands and wrists were eliminated from this study so that only the effects of loads on the larger, stronger joints can be studied. Though there is interest in investigating the role of the wrist in the lifting motion, given the expected sensitivity of the hand and wrist to handle size, shape, placement and orientation. These linkages should be included in a more complete study so that the effect on the lifting motion is understood. Both lower body, and hand and wrist limitations would require much more elaborate procedures and analysis, but would better represent a realistic lifting task.

The number of subjects chosen for this study was only ten. As is the case in any experiment, a larger sample size would make the data gathered from the study more statistically powerful and generalizable. Generally, with a larger sample size, several of the trends observed might have reached statistical significance. Also, by inspection of the data in this experiment, it seemed that some inter-subject variability was present. A larger sample size might compensate for this inherent variability between subjects, and thus might clarify any trends in the data. Also, it should be noted that intra-subject variability was not considered in this study because only one trial was run per condition.

5.6 Conclusions

This study was conducted to investigate the relationship between subjective ratings and biomechanical loads. Two goals were set for this investigation: 1) determine the correspondence between mechanical loads on several body joints and subjective ratings of joint loads, as well as subjectively determined maximal loads and 2) identify whether any particular joint (i.e. low back, shoulder, elbow) is the limiting factor when a subject determines a maximally liftable load.

The results showed that subjective ratings of joint loads varied significantly between postures when taken as a function of Percent of Strength Demands. This difference in the perception of equal strength demands suggests that more is involved in the perception of loads than simple joint moments. The results of the study also showed that strength is a weak predictor of subjectively determined maximum loads. No conclusive evidence was found that indicated a joint or area of the body that acts as the limiting factor in the determination of subjective loads. As indicated by trends in the data, the low back and shoulder are possible candidates for the ‘weak link’ of the body, though the trends were not significant.

An apparent implication of this research is that stimuli resulting from joint moments may not be only input to the perception of loads. Other physiological stimuli such as those related to proprioception may cause a more sensitive perception to forces acting on the body. Factors related to basic lifting experience may also play a role. The influence of other mental and physiological factors besides strength imply that psychophysically determined lifting limits may need to be investigated further to verify whether lifters are able to limit themselves to choosing safe maximal loads. In summary, the results imply that perception of biomechanical loads is a very complex issue that warrants further investigation to clarify certain trends that were discovered in this study.

5.7 Future Research

There are many ways to continue the investigation of the relationship between biomechanical loads and the perception of these loads. One method would involve taking the hands and wrists into consideration when performing the static support tasks. This would provide a more realistic representation of a lifting task, and could potentially give more insight into whether a single joint or area of the body exists that limits the loads humans are willing to lift. A test of this type would require the inclusion of more variables such as the moments and forces acting on the wrist joint and the type, size, and orientation of the handle. All of these variables would greatly increase the complexity of the experiment and consequently, the analysis. However, the clues provided by the current experiment may assist in identifying trends to look for in any subsequent experiments regarding biomechanical loads and psychophysical lifting limits.

Another natural progression of this study would involve allowing the subject to stand freely while choosing a load to support. This would make the task more realistic and possibly affect how the effects of the loads on the body are perceived. Factors such as the balance of the subject, weight distribution at the feet, and the moments and forces acting on the lower body would have to be taken into account for this experiment.

Once all static variations of this experiment are considered, the next step would be to conduct a dynamic investigation. An investigation such as this would require many more variables, such as moments of inertia, three-dimensional posture analysis, muscle activation/force and balance. Each of these variables requires significantly more equipment and instrumentation such as electromyograms (EMGs), dynamic force plate data, and possibly a 3D dynamic simulation of the task to predict internal muscle and joint forces. A study of this scope would take much planning and effort, but would likely be more representative than a static experiment. But, by using the results of static studies such as this one as reference, a dynamic study would likely provide useful information regarding human perception during dynamic lifting tasks.

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APPENDIX A

Informed Consent Forms

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)

Informed Consent for Participants of Investigative Projects

Title of Project: The Correlation between Psychophysical Ratings and Biomechanical Loads

Principal Investigators: Dr M. A. Nussbaum, Assistant Professor, ISE
Andrew W. Lang, Graduate Student, ISE

I. Purpose of this research

You are invited to Participate in a study investigating the perception of physical stress under different conditions in which certain weights are supported by the hands. You will be asked to perform a strength test of your torso, elbow and shoulder in order to determine your maximal exertion in each of those areas of you body. You will then be asked to support a predetermined weight with you hands and report your perceived level of effort in certain areas of the body while supporting the load. The results will be used to help understand the factors that are important in the perception of physical stress. We hope to use the results of the study to develop more rigorous guidelines for application in industrial manual material handling.

II. Procedures

The procedures to be used in this study are as follows:

1. You will be tested for maximal strength of your elbow, shoulder and torso. In order to do this, you will be secured in an apparatus and asked to exert a maximal force in various postures. Select body measurements will also be taken (e.g. weight, height).
2. Reflective markers will be affixed on various joints. These markers will be tracked by am infra-red camera system. This system records the position of the markers only, and does not record images of you.
3. You will be fitted with braces on your forearms that you will wear during the lifting procedures. These braces are made from plastic, and will be secured with ace bandages.
4. You will be asked to adjust the weight of a box by adding and subtracting weight until you reach a weight that is comfortable to you. This will be done in various postures. The experimenter will give you specific instructions regarding this procedure once the experiment begins.
5. You will be asked to support a load while in various postures and report your level of exertion.

6. You will be given several rest periods throughout the experiment. You may take as much additional time as you require.

The total estimated time of the experiment is four hours (including rest periods)

III. Risks and Benefits of this Research

Your participation in this study will provide information that will help in understanding how physical stress is perceived during the lifting and handling of heavy loads.
The potential risks involved in the experiment are muscle fatigue or soreness related to exertion of the shoulder, elbow, and torso. Any fatigue that occurs will be similar to that which occurs after lifting objects over an extended period of time or working out at the gym.

IV. Extent of Anonymity and Confidentiality

It is the intent of the investigators of the project to report the findings of this study. The information that you provide will have your name removed and only a subject number will identify you during analysis and any written reports of the evaluation. None of the collected data will contain any information which can identify you visually.

V. Compensation

If you decide to participate in this study, you will be paid $5.00 an hour for the time that you participate. The evaluation is expected to last approximately 4 hours total. You will be paid at the conclusion of your testing session.

VI. Freedom to withdraw

You are free to withdraw from this study at any time and for any reason without penalty. If you choose to withdraw during the study, you will be compensated for the portion of the testing which has been completed.

VII. Approval of Research

This research has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and the Department of Industrial and Systems Engineering.

VIII. Participant's Responsibilities

I know of no reason why I cannot participate in this study. I have the following responsibilities:

1. To notify the investigator at any time about a desire to discontinue participation.
2. To notify the investigator at any time about any physical discomfort during the course of the experiment, such as sharp pains or numbness.
3. To notify the investigator of any medical conditions which may be negatively influenced by extended muscular exertion. This included primarily any history of back problems or musculoskeletal disorders. This may include heart disease, conditions influenced by blood sugar levels, or any other medical problems which may interfere with results or increase the risk of injury or illness.

IX. Participant's Permission

Before you sign the signature page on this form, please make sure that you understand, to your complete satisfaction, the nature of this study and your rights as a participant. If you have any questions, please ask the investigator at this time. Then, if you decide to participate, please sign your name below, and on the following page.

____

Signature of the participant

Signature Page

I have read a description of this study and understand the nature of the research and my right as a participant. I hearby consent to participate, with the understanding that I may discontinue participation at any time if I choose to do so.

Signature ____________________________

Printed Name ____________________________

Date ____________________________

The researchers for this experiment are Dr. Maury A. Nussbaum, Assistant Professor, and Andrew Lang, Graduate Student. These researchers can be contacted at the following address and phone number:

Industrial Engineering Department
250 New Engineering Building
Virginia Tech
Blacksburg, VA 24061
540.231.6053

In addition, if you have detailed questions regarding your rights as a participant in University research, you may contact the following individual:

Mr. Tom Hurd
Director of Sponsored Programs
301 Burruss Hall
Virginia Tech
Blacksburg, VA 24061
540.231.9359

APPENDIX B

Instructions to determine MASL

You are going to be asked to determine a maximally comfortable load in four different postures. The experimenter will position you in these postures, and you will monitor your position by checking the location of the markers on the television monitor.

Once the experimenter helps you get positioned in a posture, you will adjust the weight of the box that you are supporting by adding or removing sealed bags of lead shot that are provided for you. To test the weight that you have determined, lift the box and assume the posture that is on the television display. Support this weight for a few seconds (1-3).

The load that you want to determine by this adjustment process is the maximum load that you feel that you could support comfortably for ten (10) seconds. (Since you will only be supporting the load for 1-2 seconds during the adjustment period, you will have to estimate the weight you feel would be comfortable to support for 10 seconds.)

Once you are satisfied that you have determined a weight that you feel could be comfortably supported for ten (10) seconds, please tell the experimenter.

If you need clarification regarding these instructions, please ask the experimenter.

APPENDIX C

Instructions to Determine RPE

You will be asked to support a load for ten seconds in the posture that is illustrated for you on the television display.

The experimenter will present you with a load. Once he instructs you to begin, please lift the load and assume the posture that is noted on the television display. Support this load while remaining in the posture until the experimenter instructs you to place the load back on the table.

Immediately after you have rested the load on the table, the experimenter will ask you to rate the exertion that you felt was necessary to support the load. You will rate your whole-body exertions, as well as your elbow, shoulder and low back/torso. Please use the 1-10 scale that is provided for you to rate your exertion.

If you need any clarification about this rating process, please ask the experimenter.

VITA

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Andrew Lang was born in Butler, Pennsylvania on March 8, 1975. He attended Virginia Tech as an undergraduate in Industrial and Systems Engineering, and received a B.S. in May of 1997. He then continued his studies at Virginia Tech, entering the human factors graduate program in the fall of 1997. During this time, he served as a teaching assistant in classes such as 'Introduction to Human Factors', and 'Work Design'. He completed all coursework by the spring of 1999. He accepted a position as a Human Factors Engineer at Westinghouse Electric Company in Pittsburgh, Pennsylvania and began this job in August of 1999, while continuing work on his thesis. Andrew successfully defended his thesis for a M.S. degree in I.S.E. on May 12, 2000.

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