EFFECTS OF TOOL WEIGHT ON FATIGUE AND PERFORMANCE DURING SHORT CYCLE OVERHEAD WORK OPERATIONS

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This study is a subset of a larger body of research that examined shoulder time to fatigue during overhead work in an attempt to reduce the prevalence and impact of work-related musculoskeletal problems in the shoulder associated with overhead work, particularly during automobile assembly. Existing evidence suggests that shoulder injuries are diverse in terms of tissues affected and symptoms presented. Furthermore, the cause of these injuries is multifactorial. The work presented here assumes that musculoskeletal injuries of the shoulder mechanism are at least related to, if not caused by, fatigue localized to the shoulder musculature. While the exact relationship between fatigue and injury has not been clearly established, there is consensus among researchers that fatigue plays and important role. Muscular fatigue, therefore, is viewed as a surrogate measure of risk, and task design to avoid fatigue is seen as a rational method to minimize this risk.

An experiment to determine the effects of tool weight on shoulder fatigue and performance during overhead work with work/rest cycles was performed. Times to fatigue were derived based on dependent measures including total task duration, controlled maximum muscle contractions, subjective ratings based on Borg's CR-10 RPE scale, electromyogram behavior (MdPF), and hand force performance measures. Experimental findings indicated that duty cycle (percentage of total task cycle time spent working) significantly affected task duration ($p<0.0001$), changes in maximum voluntary contraction values for the infraspinatus ($p<0.05$), and the minimum time for any shoulder muscle to fatigue as determined by changes in the EMG power spectrum ($p<0.05$). Time to fatigue for the mid deltoid as determined by changes in the median frequency of the EMG power spectrum was shown to change significantly ($p<0.05$) with change in tool weight. Large intersubject variation was observed for the dependent measures, which showed subjects experiencing different levels of fatigue while performing the same task. Limitations of the study and recommendations for future direction are also discussed.

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Chapter 1. INTRODUCTION

1.1 Motivation

The pervasive presence of work-related musculoskeletal disorders (MSDs), including disorders or injuries of the back, trunk, upper extremities, and lower extremities in industrial employees is commonly acknowledged. Although low back and neck pain rank highest in clinical frequency, the occurrence of occupational shoulder illness is on the rise (Sommerich et al., 1993). Specific soft tissue disorders of the shoulder region that have been associated with occupational risk factors through epidemiological research include: tendon-related disorders, such as rotator cuff and bicipital tendonitis; prolonged traumatic shoulder muscle pain; nerve-related disorders; neurovascular disorders, such as thoracic outlet syndrome; and syndrome disorders such as occupational cervicobrachial disorder (Sommerich et al., 1993). In the United States, the reported number of MSDs of the upper extremity in 1990 accounted for more than 60% of all occupational illnesses (NIOSH, 1995). In 1993, total compensable costs to the nation for MSDs was estimated to exceed $20 billion annually (NIOSH, 1995). MSDs are more prevalent in some industries than others. Based on data from 1989 OSHA 200 logs, motor vehicle manufacturers were among the top three industries with the highest reported rates of repetitive trauma disorders in the manufacturing sector (NIOSH, 1995).

The high frequencies and costs associated with musculoskeletal injuries have compelled many industries to implement control measures to reduce or eliminate these types of injuries from the workplace. When workstations are already in place, engineering controls that involve physically altering the task can be extremely expensive and time-consuming to implement. For this reason, organizations often resort to the use of administrative controls such as work/rest cycles and worker rotation to control worker exposure to tasks that are associated with a high injury rate. However, these controls can also be difficult to implement because there is a general lack of task-specific dose-response curves available for different types of MSDs. This is partly due to the fact that injuries caused from cumulative trauma have a multitude of contributing factors, such as the intensity or force exerted, number of repetitions required, posture, and the duration of exposure. These factors can interact in such a way that one factor causes one type of disorder for a particular person while it causes another in a different person (Sommerich et al., 1993). Such individual factors as sex, age, anthropometry, muscle strength, muscle endurance, and psychological factors including motivation can also affect exposure-effect relationships. Currently, there is no consensus on how different factors should be pooled and interpreted as a dose (Winkel et al., 1992). This lack of understanding causes additional problems for designers when attempting to implement a worksystem that will prevent injuries from occurring.

Certain shoulder injuries occurring in automobile manufacturing environments may be caused in part by repetitive overhead work; in fact, overhead work is frequently cited as an example of poor work design. A better understanding of the maximum human capabilities in overhead work situations is needed to reduce the number of occupational shoulder injuries by keeping the job demands below the worker’s capacity. Industries require practical data about human capabilities in specific work situations that can be used to evaluate current work operations and to design future workstations. For example, if it was known that the majority of operators were unable to perform work at a certain height for a given length of time, the designer could lower the work. The task or workflow could also be designed such that operators would only need to perform the job for short periods of time.

This study was specifically designed to simulate overhead assembly line work in the automotive industry. Data regarding the length of time that people can work in a variety of overhead situations without demonstrating signs of fatigue will be collected. It is important to realize that fatigue and injury are not the same thing. Fatigue, as defined for the purpose of this experiment, is a decrease in maximal ability. Work that causes fatigue appears to predispose operators to injury. In this experiment, fatigue is considered to be a surrogate or an indicator for potential injury. The risk factors that cause musculoskeletal injuries are known; what is not known is the specific relationship between the risk factors and fatigue (or potential for injury). Gaining understanding about this relationship and providing it to industry for design purposes are major motivating factors for this study. The main focus of the study is on tool weight because many overhead tasks require operators to hold objects such as tools or parts while completing the overhead task.

1.2 Biomechanics and Ergonomics.

The methods of ergonomics and biomechanics, two fields that overlap considerably, can contribute to the examination of the MSD problem. The main goal of ergonomics is to prohibit job demands (energy demands, forces, and moments acting on the body caused by loads, postures, and repetitive motion) from exceeding worker capacity (strength, tissue tolerance, endurance, flexibility, and coordination). Biomechanics uses laws of physics and engineering concepts to describe the physical interaction of workers with their tools, machines, and materials and to quantify the demands of a job in order to compare them to human capabilities.

Workplace interventions to reduce musculoskeletal injuries generally follow a proactive or reactive ergonomic approach. Reactive approaches include worker selection and worker rotation, and training. Worker selection involves the singling out of workers with specific physical or physiological attributes to perform certain jobs in an attempt to match the capacity of the worker to the task demands. Worker rotation requires workers to perform certain jobs only for restricted time periods. The goal of training is to modify or change the worker's behavior in an attempt to make the task less demanding on the worker. Although these approaches may be quick or relatively inexpensive to implement, they are administrative in nature and are often dependent on individual worker's motivation or willingness to accept the strategy. They usually occur after the work system has already been implemented in response to worker complaints or the occurrence of musculoskeletal disease symptoms. Kroemer et al. (1994) state that reactive approaches are "basically inappropriate" when compared with a proactive approach and should only be applied when no other solution exists.

Ergonomic job design, however, is used to actually alter the task itself as a means of "fitting the task to the person" rather than "fitting the person to the task". Ergonomic job design involves designing the entire work process to fit human capabilities. In contrast to the personnel selection strategy where only some workers are found qualified for the job, ergonomic job design allows the majority of workers to perform the task regardless of physical or physiological attributes. It is not necessary to train the workers to perform the task in a certain manner to diminish the effects of risk factors because the task has already been designed as to eliminate or reduce these factors. It is generally accepted that this type of proactive method is preferable to reactive approaches that are implemented after the work system is already in place.

1.3 Localized Muscle Fatigue and MSDs.

A variety of occupational biomechanics techniques are available to monitor and collect data relating to potentially injurious stresses placed on the human body during job performance. A commonly used technique involves the measurement of operator muscle fatigue. Fatigue is related to the amount and rate of change of some variable that in some way reflects muscle modifications during sustained contractions (Merletti et al., 1991). It can be brought about by a person's motivation level, a buildup of metabolites (e.g., lactic acid) in the muscle, a loss of energy supply, or a combination of the above. During heavy dynamic work or static exercise, blood circulation cannot keep up with the muscles' demands for oxygen supply and lactate removal, which leads to lactate accumulation, lowered pH, subjective perception of fatigue, and reduced endurance (Kilbom, 1990). Decrements in contractile capacity and motor precision can originate from muscle fatigue. Fitts (1996) defined muscle fatigue at the cellular level as a "decrease in the peak tension and power output resulting in a reduced work capacity, depending on a person's state of fitness, muscle fiber type and composition, and type of exercise being performed."

Many researchers, however, interpret the meaning of the word "fatigue" differently; therefore, the operational definition of muscle fatigue may change between studies. For example, Oberg et al. (1994) noted that scientists often use operational definitions dependent on measurement method to describe fatigue, such as impaired motor performance, increased EMG activity, shift of EMG power spectrum towards low frequencies, and impaired force generation. They also observed that the term "muscle fatigue" is often interpreted as a subjective sensation, manifested in an increased effort to maintain a force or discomfort and pain. Bills (1943) recommended that the concept of fatigue be divided into subjective, objective, and physiological subsets. Subjective fatigue is distinguished by a decline in alertness, mental concentration, and motivation, while objective fatigue is characterized by a decline in work output. Physiological fatigue is associated with external manifestations such as the inability to maintain a desired force output, muscular tremor, and pain localized to the specific group of muscles performing the contraction.

Hagberg (1981) stated that a muscle's endurance time was the duration a required force could be maintained, and when a muscle failed to do this, it was fatigued. DeLuca (1984), however, differentiated between muscle fatigue and a failure point. He described fatigue as a time-dependent process occurring as a muscle contraction is maintained for as long as possible, during which externally observable mechanical performance is unaltered. The failure point was defined as the point at which the desired force output of the muscle may no longer be maintained and contractile fatigue actually becomes observable. In 1988, Vollestad et al. distinguished between fatigue and exhaustion by defining fatigue as any exercise-induced reduction in the maximal capacity to generate force or power output and exhaustion as the point at which a required force or exercise intensity could no longer be maintained. According to this explanation, fatigue is a gradual, rather than abrupt, event that precedes exhaustion. For the purposes of this study, fatigue is simply defined as any decrease in maximal ability. Using this definition, fatigue can be quantified through the execution of maximum voluntary contractions at intervals over the duration of the task.

The onset of localized muscle fatigue is detrimental to productivity as decreased strength and loss of precise motor control can have negative effects on performance in terms of speed and quality. In addition, this study is based on the assumption that fatigue in general can be used as an indicator of injury risk and that by minimizing fatigue the risk of injury will also be reduced. However, the exact pathophysiological relationship between fatigue and the probability of injury is not well defined. Kroemer et al. (1994) describe the relationship between health complaints and musculoskeletal injury as a mountain with a wide base of common occurrences of tiredness, fatigue, and discomfort. As the mountain rises, the complaints turn into the occasional aches, pains, and postural problems, followed by persistent pain and soreness. The peak of the mountain represents actual diagnosed disorders, injuries, and disease. Baidya et al. (1988) argued that "severe local muscle fatigue may be a precursor of repetitive strain injuries…in any event, it produces discomfort and limits production." Bystrom (1994) noted that "fatigue and lack of recovery have been proposed as crucial elements in the mechanisms for causation of long term effects on the musculoskeletal system" and Oberg (1994) cites studies in which accumulated muscle fatigue has been considered a causative factor in work-related chronic muscle pain.

A variety of exposure-effect models consisting of individuals externally exposed to certain task parameters and responding with varying degrees of acute and chronic effects also exist to support this assumption (Armstrong, 1993; Sejersted et al., 1993; and Winkel et al., 1992). The acute responses consist of physiological and psychological effects such as spectral EMG signal changes, changes in heart rate, and perceived fatigue. The chronic responses consist of injuries such as work-related upper extremity disorders and training effects. Armstrong (1993) summarizes these models, stating that "physical work requirements and individual factors determine muscle force and length characteristics as a function of time, which in turn determines muscle energy requirements. Muscle energy requirements can lead to fatigue, which can then lead to muscle disorders."

Sejersted et al. (1993) and Armstrong (1993) both examine muscle fatigue at the cellular level. They present the explanation that during repetitive, isometric contractions with low overall force, the recruitment pattern of the motoneurons can occur according to the size principle (i.e., the small units are activated at low forces). As a result, mechanical strain is placed on a few motor units because the same units can be recruited continuously during a given work task. Fatigue and incomplete recovery of these motor units could trigger biochemical damage. For example, prolonged elevation of cytosolic calcium in the muscle cells may be related to fatigue which, when combined with incomplete recovery, could harm the cell and result in injury.

Armstrong (1993) describes further mechanical and physiological changes that occur in muscles as they fatigue, such as the deformation and yielding of connective tissues within the muscle and increases in intramuscular pressure. Ion shifts, electrical excitation, activation of contractile proteins, and shifting concentrations of substrates and metabolites also occur. These changes are conveyed to the central nervous system, causing sensations of effort and discomfort (perceived fatigue). A message is also sent that increased blood flow to the muscle is needed to prevent the accumulation of metabolites. If intramuscular pressure is maintained at a high level for extended periods of time, the blood flow to the muscle can be insufficient and the force generating capability decreases. The fatigue process in muscles develops along with acute pain, which can be measured subjectively and considered to be a warning sign that chronic injury is possible.

The time to develop an injury and the extent of the injury depend on the amount of recovery time between periods of fatigue. If the activities causing fatigue are such that the muscle tissue is unable to adapt to the exertion and are repeated over extended periods of time, joint and tissue degeneration and inflammation and chronic pain can develop (Chaffin et al., 1991). The muscles' rate of recovery from fatigue can depend on several factors, including the duration of exercise, the intensity of exercise, and the physical fitness of the individual. Changes in muscles due to fatigue are usually reversible if the muscle is given sufficient time to rest and recover (Armstrong, 1993). The repair of damaged fibers and tissues is often greater than the original damage, which allows the muscle to adapt to high stress levels. However, if the damage occurs too often, the muscle may not be able to repair itself fast enough, and muscle disorders may result.

1.4 Shoulder Fatigue.

Chaffin (1973) first used the term *localized muscle fatigue* to describe a type of fatigue associated with such external manifestations such as the inability to maintain a desired force output, muscular tremor, and localized pain. The effects of this fatigue are localized to the muscle or group of synergistic muscles performing the contraction (DeLuca, 1994). One area of the body in which localized muscle fatigue often occurs in industry is the shoulder. There are three main groups of muscles in the shoulder that help control arm movement (Winkel et al., 1992). The trapezius, levator scapula, rhomboid, and serratus anterior arise from the main skeleton and insert on the scapula, helping to move and stabilize the structure. The rotator cuff muscles, including the teres minor, infraspinatus, supraspinatus, and subscapularis arise from the scapula and insert on the tuberculum, stabilizing the glenohumeral joint. The third group of muscles includes the primary movers of the upper arm: the biceps, deltoid, and triceps, which arise from the clavicle and scapula and insert onto the humerus. Shoulder fatigue results from the sustained exertion of one or more of these muscles or muscle groups.

The mechanization of industrial work processes has resulted in simplified work movements; however, the use of the arms and the number of movements required per unit time have increased (Jonsson, 1982; Hagberg, 1981). Work tasks demand less energy, but the velocity and monotony involved represent a local stress on skeletal muscles, primarily in the back, neck, shoulders, and upper arms. Specific risk factors that contribute to shoulder MSDs have been identified (Sommerich et al., 1993). They include awkward postures (shoulder abduction, neck flexion, arm extension), static postures (sustained positions for prolonged periods of time), and lack of sufficient rest. Heavy work or direct weightbearing imposes a high level of strain on rotator cuff tendons by requiring substantial contraction levels in the muscles. Wiker et al. (1989) found that hand held weights as light as 0.95 kg could induce fatigue in a task requiring repetitive arm movement. Repetitive arm movement (particularly for fine or detailed work) requires continuous activation of the first two groups of muscles described above, so work tasks that require continuous arm movements generate load patterns with a static load component (Winkel et al., 1992).

In an analysis of occupational health clinic patients receiving a diagnosis of non-traumatic MSDs, 68.8% of patients with shoulder pain stated that they worked with their hands primarily at or above shoulder level (Bjelle et al., 1979). Herberts et al. (1984) found that the infraspinatus muscle in particular was very sensitive to small increases in hand held weight when the arm was in an elevated position. In addition, the deviation of the upper arm from the vertical position increases the load on the upper trapezius and rotator cuff muscles. Hagberg (1984) proposed that working with elevated arms may accelerate the degree of rotator cuff tendon generation through impairment of circulation due to static tension in tendons and humeral compression against the coracoacromial arch.

1.5 Fatigue Measurement.

Fatigue can be measured subjectively through the use of scales or questionnaires or objectively through physiological methods such as electromyography (EMG). Less commonly used objective measures of fatigue include changes in performance accuracy, altered muscle and body segment coordination, and changes in posture. A research issue of interest and obvious value involves the question of which of these measures are the most valid indicators of fatigue and how they are related to one another. Although a definitive answer to this question does not exist, it has become apparent that the most valid measurements of fatigue depend on how fatigue is defined and on the reliability of the measurements. For example, if fatigue is defined as a decrease in maximal ability, as in this study, fatigue can be directly measured by taking maximum voluntary contraction (MVC) measurements over the course of a task. Perhaps the most common measure used in the evaluation of fatigue is the value of the subject's maximum voluntary contraction (MVC), which Vollestad (1997) calls the "gold standard" for identification of fatigue occurrence. MVCs can be defined as the force generated by a subject when the subject is encouraged to perform to their highest ability and the subject believes their maximal effort has been exerted. They are performed by instructing subjects to generate the highest possible force in a setting where muscle length changes are restricted to the initial tightening of the muscle-tendon unit (Vollestad, 1997). However, MVC values can be limited by lack of motivation and inhibitory effects at various levels in the central nervous system and at the muscle level (Vollestad, 1997). Reliable and reproducible test conditions are key to accurate MVC measurements.

The use of EMG would be an indirect measure because EMG does not directly measure maximum ability. However, it cannot be said with certainty that the direct measurement (MVCs) is more valid than the EMG measurements because MVCs can be affected by individual factors such as motivation that do not affect EMGs. However, in order to obtain reliable EMG measurements the experimental environment must be tightly controlled. DeLuca (1984) elaborates on this situation, noting that "many methods for evaluating fatigue are, by their very nature, 'doubly subjective'…they rely on the cooperation of the individual performing a prescribed task and on the disposition of the observer when assessing the performed task. (It is usually possible for the observer to induce the subject to make an exertion beyond the initial presumption of his capability and/or interest)" (DeLuca, 1984, p. 251).

The following sections provide a review of methods of fatigue measurement to be used in this study. Table 3 provides a summary of the advantages and disadvantages of the various methods.

1.5.1 Electromyography (EMG). Physiologic data within muscles shows time-dependent changes that indicate processes leading to the mechanical failure point of the muscle (Merletti et al., 1991). Electromyography is an objective measurement technique used in biomechanics research to estimate muscle fatigue by monitoring changes within muscles before deterioration of mechanical performance can be observed (Merletti et al., 1991; DeLuca, 1997). EMG signals are obtained as recordings of the sum of several motor unit potentials, or the myoelectric signal, emitted from contracting muscles (Chaffin et al., 1991). The reading reflects the number of motor units recruited and the rate at which they fire for a particular movement (Sommerich et al., 1993).

The myoelectric signal can be measured using either indwelling or bipolar surface electrodes over the bulk of the muscle (where most of the active fibers lie) under examination. Surface electrodes are more commonly used, most likely because they are less invasive. The EMG signal is low when compared to other ambient signals on the skin's surface, so the EMG signal must be detected with a differential configuration (DeLuca, 1997). The two detected signals are subtracted and then amplified.

Muscle fatigue can be evaluated using EMG by observing changes in the spectral characteristics of the myoelectric signal. Typically, the amplitude increases in the low frequency range and the mean or median frequency decreases with fatigue as evidenced in a variety of studies (Christensen, 1986; Merletti et al., 1990, Sundelin et al., 1992; Sundelin, 1993; Oberg, 1994). These changes are thought to be the result of increased motor unit recruitment or increased motoneuronal stimulation in response to reduced muscle contractility, slowing of muscle membrane potential conduction rates, or from increased synchronization of recruited motor unit activation (Wiker et al., 1989, DeLuca, 1984). DeLuca (1979) explained the relationship between the two signal changes (amplitude increase and mean frequency decrease) by noting that during a sustained contraction, the low frequency components of the myoelectric signal increase; therefore, more myoelectric signal energy will be transmitted through the low-pass filtering effect of the body tissue.

However, the myoelectric signal is sensitive to many other parameters besides fatigue. DeLuca (1997) presents a thorough analysis of these factors, dividing them into causative, intermediate, and deterministic categories. Causative factors, which are said to have an elemental effect on the EMG signal, include both extrinsic factors that are associated with electrode structure and its placement on the surface of the skin and intrinsic factors that are associated with the physiological, anatomical, and biochemical characteristics of the muscle. Extrinsic causative factors can be controlled by the researcher whereas intrinsic causative factors cannot. Intermediate factors represent physical and physiological phenomena that are influenced by one or more of the causative factors. They influence the deterministic factors, which directly affect the information in the EMG signal. See Table 1 for a summary of these factors.

The EMG signal can also be affected by electrode impedance, the length of time that the muscle has been contracted, the contraction level of the muscle, the percentage of cycle time filled by the task under examination, ambient temperature, and posture (Chaffin et al., 1991, Sommerich et al., 1993). There are other disadvantages to the use of EMG to assess fatigue besides the fact that such a large number of factors can affect the measurement. For example, large individual differences between subjects under equivalent working conditions have been found as well as EMG signs of fatigue in some muscles but not others bearing equal or greater burdens. In some studies, greater EMG indices of fatigue were found in initial work periods rather than later when more severe levels of fatigue would be expected (Wiker et al., 1989).

Causative	Intermediate	Deterministic
Extrinsic: • Area and shape of electrode detection surfaces • Distance between electrode detection surfaces • Location of electrode with respect to the motor points in the muscle • Location of the electrode on the muscle surface with respect to the lateral edge of the muscle • Orientation of the detection surfaces with respect to the muscle fibers Intrinsic: • Number of active motor units • Fiber type composition • Blood flow • Fiber diameter • Depth and location of active fibers • Amount of tissue between surface of the muscle and the electrode	• Band-pass filtering aspects of the electrode • Detection volume of the electrode • Superposition of action potentials in the detected EMG signal • Crosstalk from nearby muscles • Conduction velocity of the action potentials that propagate along the muscle fiber membrane • Spatial filtering effect due to relative position of the electrode and active muscle fibers	• The number of active motor units • Motor unit force-twitch • Mechanical interaction between muscle fibers • Motor unit firing rate • The number of detected motor units • Amplitude, duration, and shape of the motor unit action potentials • Recruitment stability of motor units

Table 1. Factors affecting the EMG signal (Adapted from DeLuca, 1997).

Sommerich et al. (1993) cite several studies in which EMG readings have been found to relate to shoulder pain. However, it has not been shown whether elevated EMG levels are a precursor or a result of shoulder pain. The following table shows a variety of studies relating to shoulder fatigue that have used EMG as a dependent measure and their findings.

Author(s)	Population, Sample Size	Task Type	Dependent Measures	Results/Conclusions
Christensen, 1986	Male day patients at a rehabilitation and revalidation institute Age range: 26-53 years N = 7	Pillar drill, repetitive work	EMG (trapezius, anterior deltoid, infraspinatus), heart rate; RPE; MVC; efficiency	Changes in amplitude indicated high static levels of activity. No change in amplitude observed for any muscles over course of task. MPF decreased in trapezius only.
Hagberg, 1981	Female volunteers Age range: 18-29 years N = 6	Repetitive arm elevations (concentric or eccentric shoulder flexion); weights from 0-3.1 kg.	EMG (trapezius, anterior deltoid, biceps brachii); heart rate; RPE; torque in shoulder joint; serum creatin kinase	Exertion of descending part of trapezius during tasks involving repetitive shoulder flexion may promote discomfort and complaints referred to the neck. Time constants ofEMG amplitude increased, correlated with workload, endurance time, slope coefficient of RPE-HR linear regression. RPEs increased faster than HR increased.
Hagg et al., 1991	Female assembly worker volunteers, some with occupation-related myalgia in shoulder-neck region. Age range: 25-62 N = 43	Monotonous, repetitive assembly work (monitored over 2 years)	EMG (trapezius, infraspinatus)	Workers who had already contracted shoulder myalgia showed significantly greater electromyographic signs of fatigue (ESF) during work than healthy workers performing the same task. ESF during work may not be used as a predictor of muscle injury, but as a diagnostic tool.
Hammarskjold et al., 1992	Male carpenter volunteers Age range: 23-49 years N = 10	Standardized nailing, sawing, screwing tasks and arm-cranking fatigue trial	EMG (forearm, midpoint of the two radial extensor carpi, brachial biceps, anterior deltoid, trapezius, infraspinatus); performance measures (number of movements, time taken for each task, quality of work); RPE	Upper trapezius and anterior deltoid RMS amplitude increased the most for all tasks. After fatigue trial, quality of work became inferior; number of movements and pace not significantly affected.

Author(s)	Population, Sample Size	Task Type	Dependent Measures	Results/Conclusions
Malmquist et al., 1981	Male building workers Age range: 17-62 years N = 56	Five building tasks	EMG (mid deltoid, anterior deltoid, trapezius, supraspinatus)	Significant localized fatigue found in trapezius and supraspinatus during static tasks even when force exerted was small, indicating that stereotyped tasks have a greater tendency to cause localized muscle fatigue than varied tasks, even when the latter is heavier. Used new proposed fatigue index method.
Oberg et al., 1994	Ten male and ten female volunteers Age range: 23-58 N = 20	Arm abduction task with varying hand loads and durations (0 kg for 5 min and 2 kg for 2.5 min)	EMG (trapezius); RPE	Significant correlation of EMG and RPE at high load levels. No correlation at low load levels. MPF and RPE seem to provide different fatigue information. MPF did not seem to be a valid estimator of muscle fatigue at low load levels.
Sundelin, 1992	Female student volunteers Mean age: 26.3 N = 6	Repetitive arm work, standardized simulation task	EMG (trapezius, infraspinatus); RPE	MPF decreased and RMS amplitude increased in all muscles of most subjects suggesting that dynamic work movements do not protect the shoulder and neck muscles from fatiguing processes in highly repetitive work with short cycle times.
Sundelin, 1993	Female student volunteers Mean age: 25.5 N = 12	Repetitive arm work with and without pauses	EMG (trapezius, infraspinatus); RPE	RMS amplitude increased and MPF decreased in both types of tasks. Changes were less pronounced when pauses were introduced. RPEs were similar for both types of tasks.
Suurkula et al., 1987	Female assembly workers Age range: 23-61	Assembly tasks	EMG (trapezius, infraspinatus)	Workers who experienced symptoms characteristic of occupational shoulder and neck disorders had a lower mean level of zero crossings (similar in interpretation to median power frequency shifts) when compared to pain free workers during brief test contractions.

Table 2. Studies relating to shoulder fatigue using EMG as a dependent measure.

In summary, it appears as though EMG signals relate to fatigue in some cases but not in others. The amount of variation control and differences in tasks and in methods used to analyze EMG data may account for many of the inconsistencies in conclusions drawn by different researchers. However, mean or median power frequency shifts and amplitude increases with the onset of fatigue are well documented. It is therefore advantageous to use EMG as an objective measure as long as the experimental environment can be carefully controlled, as EMG readings cannot be affected by variables such as subject motivation or understanding of the procedure.

1.5.2 Subjective Measures. Subjective measures are often used to supplement physiological measurements. It is important to understand the relationship between objective and subjective measures of physical stress because humans react to the environment as they perceives it and not as it "really is" (Borg, 1970). Perceived exertion is believed to be influenced both by central factors such as strain on the cardiorespiratory and central nervous systems and local factors such as strain of the working muscles or joints (Hagberg, 1981b, Grant, 1994). These signals combine to form the subjective response to workload. The decrease in physical working capacity as perceived by a human subject does not seem to grow linearly with the decrease as measured by physical lab test. In addition, when physical workload increases, perceived exertion does not grow linearly with physical load. (Borg, 1970). Instead, a well known, curvilinear relationship exists between the intensity of a range of physical stimuli and human perception to intensity (Grant et al., 1994; Kilbom, 1990). Grant et al. (1994) present a partial list of studies that show results of a linear or curvilinear relationship of perceived exertion with actual static force exertion. In their own study, they found that EMG and ratings of perceived exertion were both strongly and positively correlated with normalized grip force in short duration, repetitive tasks requiring the application of a grip force to a cylindrical handle. Neither measure was found to be a consistently better predictor of grip force.

The Borg Rating of Perceived Exertion (RPE) Scale (Borg, 1985) is a formal technique that can be used to subjectively assess fatigue in human subjects. The scale provides a simple rating method to measure perceived exertion in which the values grow fairly linear with respect to work load (Borg, 1970). The Borg General Scale (see Figure 1), a modification of the RPE Scale, is a category scale with ratio properties that can yield ratios and levels and allow comparisons. The scale ranges from 0 to 10 where 0 represents no fatigue and 10 represents maximum fatigue. It has a correlation of about 0.88 with heart rate, particularly if large muscles are involved in the effort (Kroemer et al., 1994). The scale is explained to the subject before the exercise or exertion is performed. Verbal explanations or anchors are used to support the numerical ratings. After the subject performs an exertion they are asked to give a rating based on the scale.

The advantage of using subjective measurements such as rating scales is that they are easy to administer and no instrumentation or calibration is required. The process is generally noninvasive (although it may interrupt the task) and the data easy to interpret. In some cases, psychophysical rating methods may provide a suitable alternative to EMG for estimating force in manual work (Grant et al., 1994). Ratings of exertion are also helpful in determining when to interrupt or stop a work test (Borg, 1970). However, subjective ratings may not reflect only the variable being measured (e.g., fatigue). For example, highly motivated subjects tend to underestimate their exertion level (Kilbom, 1990).

The Borg General Scale	
0 --	nothing at all
0.5 --	extremely weak (just noticeable)
1 --	very weak
2 --	weak
3 --	moderate
4 --	somewhat strong
5 --	strong
6 --	
7 --	very strong
8 --	
9 --	
10 --	extremely strong (almost maximal)

Figure 1. The Borg General Scale.

1.5.3 Performance measures. Performance measures to evaluate fatigue are found more rarely than physiological and subjective ratings of fatigue in the literature. Hammerskjold et al. (1992) used a variety of performance measures in their study on the effect of arm-shoulder fatigue on performance in experienced carpenters. Carpenters performed three standardized tasks (nailing, sawing, and screwing) and their performance was measured in terms of quality, number of work movements, and time taken to complete the task. Subjects then performed a fatiguing arm-cranking task and repeated the three standardized tasks. Performance was measured again. One of the main findings of the study was that the quality of the nailing and sawing jobs after the fatigue trial were inferior to the quality during the first trial. An increased number of misses during nailing and more deviations from premarkings during sawing were observed. Hammerskjold et al. concluded that precise manipulations can be affected by previous muscle loading. There is not a great deal of additional information in the literature dealing with how work loads below the exhaustion level (at the fatigue level) affect immediate precise manipulations required by ordinary tasks. However, given the importance of quality in today's manufacturing industry, it is clear that performance measures provide a necessary and significant contribution.

	Advantages	**Disadvantages**
EMG	• Documented MPF shifts and amplitude increases with fatigue • Subjects have no control over the EMG reading	• May be invasive or hinder task • Large intersubject variations • May require expensive or complex instrumentation • Can be affected by many factors other than fatigue • Not useful for highly dynamic tasks or exertions involving combinations of several different muscles • Data collected requires interpretation • Often impractical for field use
RPE	• Information from CNS and cardiorespiratory systems and working muscles appear to be integrated into a single indicator of physical strain • Easy to administer and no instrumentation or calibration is required • Process is generally noninvasive • Data relatively easy to interpret • Helpful in determining when to interrupt or stop a work test	• Different subjects interpret scale differently; ratings may not reflect only the variable being measured (e.g., fatigue).
MVC/Performance	• Is considered a direct measure of fatigue • Low intrasubject variability of unfatigued MVCs with practice and encouragement	• Can be affected by individual factors such as motivation

Table 3. Advantages and disadvantages of fatigue evaluation measures.

1.6 Gaps in the Current Literature.

In terms of fatigue, much has been discovered about the human physical capacity for static (prolonged, isometric) exertions. The Rohmert curve (Rohmert, 1960), which shows the endurance time of a muscle (time to fatigue) as a function of the static exertion level of the muscle (% maximum muscle force), is one example of this type of research. In other words, the curve shows how long a person can sustain a contraction as a percent of their maximum contraction capability. However, very little work has been done regarding human physical capacity during intermittent work that includes work/rest cycles. Also, relatively few studies have been carried out to determine force generating capacity at intervals during dynamic exercise, one reason being the practical difficulty that force generating capacity recovers rapidly, requiring measurements immediately following the completion of the exercise (Vollestad et al., 1988). It is also useful to establish relationships between objective measures of fatigue and perceived ratings of exertion. In addition, ergonomics literature lacks, in general, specific, practical design guidelines that can be used to assist engineers in the design of workstations and tasks to help eliminate or reduce the onset of musculoskeletal diseases.

Chapter 2. RESEARCH OBJECTIVES

2.1 Rationale for the Study

This study specifically addressed the issue of handheld weight over a range of common part and tool weights as overhead work is performed in order to determine the impact of weight on fatigue. The study was based on the fact that repetitive arm movement and working conditions in which the arm is elevated above shoulder height have been found to contribute to the development of MSDs in the shoulder. However, quantitative design guidelines to help eliminate or reduce the impact of MSD development have not been developed. In this study, localized muscle fatigue was used as an indicator of future musculoskeletal injury accompanied by chronic pain. Although many subjective and objective measures of fatigue currently exist, it has not yet been demonstrated how to use these measures to design worksystems or jobs in the field. Therefore it is important to provide industry with usable data, perhaps in the form of charts or tables, that can be used in a proactive ergonomic design strategy to ensure that future worksystems developed do not adversely affect the health and well-being of workers. This data could also be used to modify existing worksystems that may increase the probability of worker injury.

The primary objective of this research was to generate initial data towards the development of a practical design tool that can be used by practitioners both to evaluate current overhead work operations and as a predictive tool to evaluate overhead work at the design phase. The end product is a preliminary set of empirical data that specify the maximum duration a task with certain parameters can be performed without significant local muscle fatigue. This data may be used to design further overhead work-related studies. The results of these studies could be compiled to form a comprehensive data set in the form of tables encompassing a large population. Ideally, ergonomists or designers would be able to use these tables during the work design process to estimate expected times from the commencement of an overhead work operation until the appearance of objective and quantifiable local shoulder muscle fatigue. To use these tables, the practitioner would find the appropriate combination of task variables, which could include tool weight, work height, within-cycle work duration, and hand position. Using these parameters, the practitioner would be able to estimate the amount of time that an overhead operation could be performed without risking local muscle fatigue. Existing worksystems would be able to be evaluated in a similar manner if the appropriate parameters of the worksystem were described in the dataset. When a sufficient experimental database has been compiled it will be possible to describe population distributions, similar to the Snook psychophysical database for manual lifting (Snook et al., 1991). Industry will then have the ability to formulate policies or make decisions regarding, for example, what target percentage of the population is to be accommodated for specific overhead tasks and whether the decision should be based on physiological, subjective, or performance measures.

When considering the significance of this sort of data presented in a clear and easy-to-use format, it is important to remember that although the occurrence of occupational shoulder illness is on the rise, controls for MSDs are difficult to implement because of the lack of task-specific dose-response curves available. It is also critical to gain an understanding of the relationship between the risk factors involved in the onset of MSDs and fatigue, a variable that can be readily measured using a variety of methods. This study was based on the assumption that fatigue during a task is an indicator that the task could cause injury if performed over long periods of time. On a large scale, the data compiled from this experiment may eventually provide the basis for a tool that can be used to design cyclic work tasks and workstations.

2.2 Experimental Goals

This study was performed with two main goals in mind. The first goal was to determine when operators experience muscle fatigue during overhead work using subjective and objective measures. In particular, achieving this goal involves quantifying the effect of increased tool weight on time-to-fatigue within specific task parameters. The second goal was to provide industry with this data in a form that could be used to design new worksystems or modify existing systems for the purpose of reducing the probability of shoulder injuries during overhead work tasks. Because shoulder and neck MSDs are highly prevalent in the automotive manufacturing industry, a major objective of this study was to make the resulting data practical for use in industry. Efforts were taken to make the experimental environment as similar as possible to one experienced in a manufacturing environment. For example, the work task cycle time used was typical of those found in automobile assembly facilities. Study participants, like assembly line operators, did not work the full length of the cycle. Short recovery periods were provided. Also, the participants were required to work at different heights that were percentages of their maximum overhead reach and to use different forearm positions when holding the tool.

The following hypotheses related to data obtained during the simulated overhead work tasks were tested:

Hypothesis #1: The effect of increased hand tool weight on time to fatigue will be nonlinear.

Hypothesis #2: The effect of increased hand tool weight on time to fatigue will differ depending on task parameters. For example, it would be expected that time-to-fatigue will decrease at a faster rate as the percentage of cycle time worked increases.

Hypothesis #3: The effect of increased hand tool weight will differ depending on how fatigue is measured. For example, the change in EMG spectrum may not be as noticeable as the change in RPE and/or MVC.

These hypotheses resulted from observations during pilot testing. For example, during pilot testing, adding even small amounts of weight to the tool affected time-to-fatigue to a significant degree. The proportion of work to rest during each cycle was also observed to have a significant effect on fatigue.

Chapter 3. EXPERIMENTAL METHODOLOGY

In order to achieve the research objectives, an industrial overhead task was simulated in a laboratory environment under a variety of different conditions. The main experimental task consisted of the performance of a point-to-point tapping motion between two overhead targets with a wand-like tool. This task was chosen because it could be performed overhead and discontinuously (with fixed work/rest cycles). In addition, the task was highly stereotyped and not highly dynamic. Tapping targets also provided a means to measure performance. The pacing of the task was held constant using auditory tones, with a cycle time of sixty seconds. Participants' performance levels and global and localized muscle fatigue were measured and recorded during breaks in performance of the tapping task. The following information specifies the particular details of the experiment.

3.1 Participant Screening

The experiment was conducted with two male and two female participants. Subjects were recruited through the use of an advertisement displayed on the Virginia Tech campus. They were paid $10/hour to participate in the experiment and received an additional $20 as a bonus upon completion due to the relatively large time commitment required. The subjects were between the ages of 18 and 22 to match the age range of the target working population. Only right-handed subjects were accepted because some of the apparatus used were only built to accommodate right-handed people, for practical reasons such as design simplicity, cost, and ease of building. In addition, the use of right-handed subjects only ensured that differences in time-to-fatigue were not due to an extraneous variable such as arm used. Subjects were of a moderate activity level and physical fitness and had not experienced severe shoulder or back injuries. After subjects volunteered to participate in the experiment by contacting the researcher, they were asked the following questions to ascertain their suitability for participation:

- Do you have any medical conditions that may be adversely affected by physical exertion?
- Are you right-handed?
- How old are you?
- Have you injured your right shoulder or lower back within the past two years?
- Do you exercise extensively, moderately, or not at all? (Subject activity and fitness level were also determined by observation).

Subjects accepted for participation had no medical conditions that could be adversely affected by physical exercise, were right-handed, had not had a shoulder or back injury, and were of a moderate activity level. For example, subjects were eliminated if they stated that they never exercised or if they were exceptionally active athletes. The purpose of these questions was to determine if the potential subject fit the required experimental profile and to ensure their safety in performing the task. Subjects were also given a brief description of the experimental tasks, the time commitment involved, and the compensation provided. Subjects were informed that they may be asked not to continue participating in the experiment if at some point it was determined that they did not match the defined participant profile and that they could also choose to terminate the experiment themselves at any point.

3.2 Experimental Tasks and Procedures

The experimental tasks were performed in the Industrial Ergonomics laboratory on the Virginia Tech campus. This lab is environmentally controlled and sheltered from outside disturbances. Two researchers were present during each session. Each participant was required to attend one training session approximately two hours in length and six experimental sessions, each at a maximum of approximately four hours in length, in order to complete the experiment.

Subjects were required to schedule sessions with a minimum of 48 hours between sessions to control for confounding effects of residual muscle fatigue.

3.2.1 General Procedures. Subjects performed three basic tasks over the course of the experiment: (1) MVCs, (2) tapping overhead targets, and (3) holding a test weight in a consistent posture while an EMG reading was taken.

MVCs were performed for the lumbar region and for the four shoulder muscles targeted, the mid deltoid, trapezius, anterior deltoid, and infraspinatus. These four muscles were specifically targeted because pilot studies showed that these were the main muscles used in overhead work. In addition, they are prominent and easily accessible for surface EMG placement. A variety of studies found in the literature target the same muscles in shoulder fatigue and overhead work research (see Table 2). Subjects performed the MVCs in the postures shown in Figure 2. The most important factors to control during the MVC task were the position of the straps that restrained the subject's movements and the subject's posture to ensure that sources of postural variation, which are associated with changes in muscle length, were minimized. The general procedure for completing MVCs was as follows.

(1) Subjects placed themselves in a fixture designed particularly for this experiment (see Figures 3 and 4). When necessary, they were secured with velcro straps.

(2) The posture required to perform the exertion was explained by the experimenter.

(3) Experimenters asked the subject to smoothly ramp up to their maximum, peak, and ramp down over a time period of approximately five seconds (no jerky motions), emphasizing that accurate readings of the subject's true maximum are critical to data integrity.

(4) The subject was asked if they were ready to perform the exertion.

(5) When the subject answered affirmatively, a researcher said "go" and the subject performed the exertion. The researchers encouraged the subjects to reach their maximum.

(6) If the force value of the exertion or the shape of the curve appeared to be unsatisfactory, the subject may have been asked to perform the exertion again, after a rest break if necessary.

The general procedure for the tapping task was as follows.

(1) Subjects were given a wand-like tool.

(2) Subjects were required to tap back and forth between two targets placed on the wall, in sync with a series of auditory tones played by the experimenters. Subjects were shown the pronated position of the forearm that must be maintained during the task.

(3) Subjects were asked to tap as close as possible to the center of the targets.

(4) Subjects started tapping as soon as the auditory tones started and stopped as soon as the auditory tones stopped.

(5) It was assumed that subjects attended to the task; that is, paid attention to the beeps and watched the center of the target. If it became obvious that this was not the case the subjects were reinstructed.

(6) With the exception of forearm position, subjects were able to maintain any posture they liked during the task (except for bracing themselves against the wall).

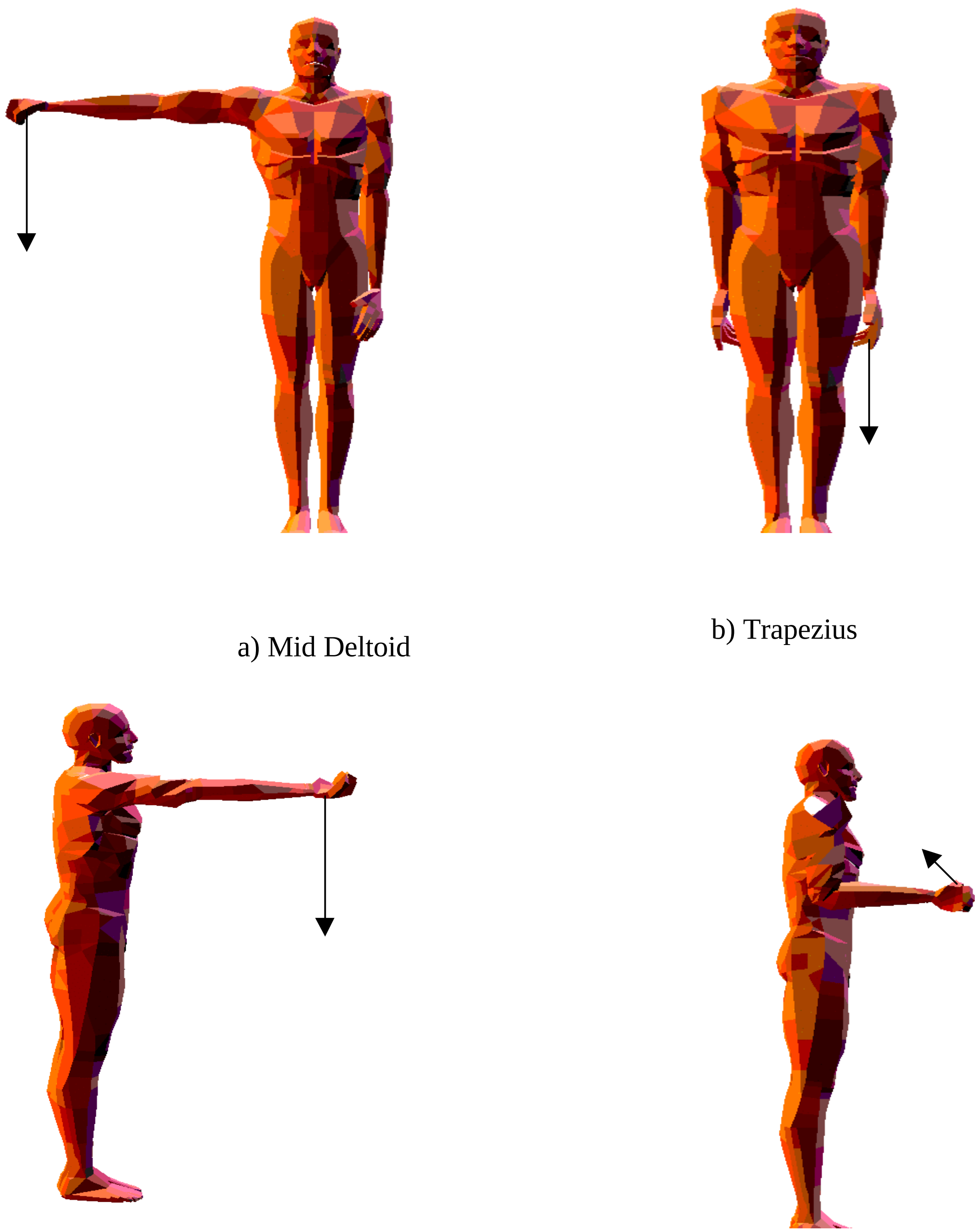
The general procedure for obtaining EMG readings from test contractions was as follows.

(1) Subjects were asked to perform one of four postures that isolated one of the muscles being tested. These postures were the same as used for performing MVCs (see Figure 2). Consistent postures under controlled conditions are necessary for obtaining valid EMG power spectra.

(2) The subject accepted a weight handed to them by a researcher and held it while an EMG reading was taken.

(3) The researcher took the weight from the subject.

3.2.2. Lab Preparation. Prior to a subject's arrival at the lab, the researchers completed certain tasks. All data sheets and forms to be completed over the course of the session were prepared along with the subject's payment. The strain gauges were calibrated and the Labview data collection programs were configured using the slopes and intercepts resulting from the calibration procedure. The appropriate weights were prepared for the subject's test contractions and the targets were set to the appropriate heights. In addition, the fixtures were adjusted according to the particular subject's anthropometric dimensions.



a) Mid Deltoid b) Trapezius c) Anterior Deltoid d) Infraspinatus

Figure 2. Postures for MVCs and EMG readings.

Figure 3. Fixture for lumbar MVC performance.

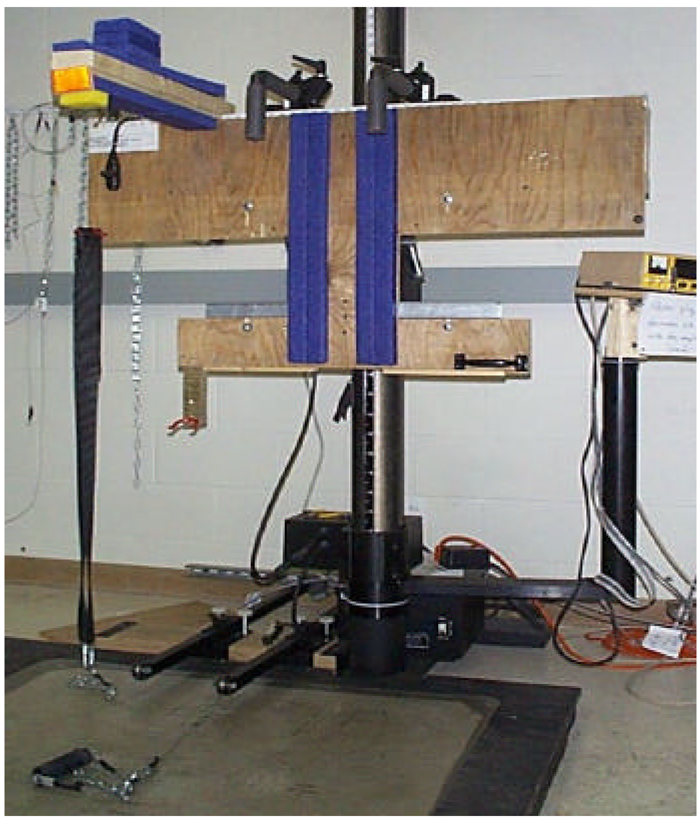


Figure 4. Fixture for shoulder MVC performance.

3.2.3. Training Sessions. Upon arrival at the lab, subjects completed an informed consent form approved by the Virginia Tech Institutional Review Board (#99-016) and a short pre-test survey (see Appendices 1 and 2). At this time, all participants were made aware of their freedom to withdraw from the research program at any time, for any reason, without penalty. Experimenters did not try to persuade participants to continue if they were not willing. Participants were paid for the amount of time that they did participate. Subjects were also assured that all data collected for the experiment would be treated with confidentiality, and that their anonymity would be protected at all times.

Subjects were then required to change into the appropriate clothing for the experiment (athletic clothing, i.e., shorts and a tank top) provided by the lab that allowed access to the shoulder and back muscles for EMG placement. A variety of anthropometric data was recorded for each subject (see Appendix 3), some of which was used to calculate test weights and target heights. The experimental apparatus was adjusted to the subject's particular height and link lengths and this data was recorded for use on subsequent testing days.

Six pairs of EMG electrodes and two grounds were affixed to the subject. All electrode pairs were separated by approximately ¼" or 1-2 cm in the postures assumed during the testing trials. The required skin resistance was verified to ensure that the noise included in the signal was decreased. The electrode leads were connected to preamplifiers and taped to the subject's back and the gains set. Subjects were given approximately 2-5 minutes to rest and stretch. Three MVCs for each muscle (lumbar, middeltoid, trapezius, anterior deltoid, and infraspinatus) were measured using the ramping procedure described earlier. The load moment arms (distance from the load application to joint center of rotation) were recorded. Joint centers of rotation were found through palpation of the joint. This information was used to determine the test weights that were used on testing days for measuring EMG and also as a baseline against which MVC values were compared on testing days. The subjects were then shown how to perform the tapping task and to rate their fatigue using Borg's CR-10 RPE Scale (see Appendix 4). Once the subject felt comfortable performing the task, the EMGs were removed and the subjects paid for their time. The researchers calculated the test weights and target heights using data collected and joint moment data obtained from 3D Static Strength Prediction Program (3DSSPP), a biomechanics software package.

Training day procedures (see Appendix 5 for protocols) were necessary for both the subject and the experimenters to determine if the subject was a suitable candidate for the study. Requirements for suitability included the willingness of the subject to commit the necessary time to finish the study, the appearance that the subject was motivated to perform to the best of their ability, the lack of any previous or current illnesses or injuries that would inhibit performance or increase the probability of injury due to the experimental procedures, the ability to obtain reliable EMG readings from the subject, and the subject's comfort with the experimental procedures.

<u>Testing Sessions.</u> On testing days, subjects performed three basic tasks: (1) tapping overhead targets, (2) MVCs, and (3) holding a test weight while maintaining a particular posture while an EMG reading was taken. Participants were not required to memorize postures or task sequence, as researchers cued them. Before testing sessions begin, it was ensured that the subjects had performed no abnormal activities that would cause them to feel any residual soreness or discomfort that could affect task performance. EMG electrodes were affixed and gains were set. After a 2-5 minute resting and stretching period, baseline global (whole body) and local (shoulder and low back) RPE values were recorded. If these values were not zero the reason was determined. Baseline MdPF values were recorded using test weights and the procedure described earlier. Three graphs (raw, RMS, and frequency spectrum) were displayed on the computer monitor when test contractions were recorded (see Figure 5). Raw values were not allowed to exceed ten. RMS values were relatively constant and flat. The spectrum diagram graphed frequencies between 30 and 200 Hz. Upon observation of the spectrum diagram, a note was made of any obvious spikes at 60 Hz as they were notch filtered if it was determined that they were due to external noise. This can occur, as the use of AC power sources exposed the testing environment with 60 Hz frequencies.

Subjects performed one baseline MVC for the lumbar (used to normalize data collected during dynamic testing), and one for each of the shoulder muscles (used to determine if the shoulder fatigued over time). The subject then began the task configuration shown in Figure 6. The task consisted of blocks of ten duty (work/rest) cycles. Subjects repeated the 10-cycle experimental task until one of the following stopping criteria occured: (1) the subject's MVC values dropped below 75% of the baseline MVC value for that day, (2) the subject's RPE for the shoulder increased above 6, (3) the subject stated that they felt that they could no longer continue the exercise, or (4) the subject completed 18 ten-cycle blocks (180 duty cycles, or three hours of tapping). Protocols for testing day tasks are found in Appendix 6.

3.2.5. Safety Measures. The following procedures were safety measures taken to minimize the risks of participation in this experiment. Before beginning the experiment, the researchers ensured that the subjects had no prior injuries or medical conditions that could be aggravated by task performance. When subjects performed lumbar MVCs, they were secured in the fixture by three straps. When shoulder MVCs were performed, subjects stood on a plastic mat to prevent slipping. During task performance, researchers continuously monitored subjects' conditions for signs of strain. Tasks were discontinued if the subjects' MVCs fell below 75% of their baseline values or if the subjects' subjective ratings of fatigue rose to six or higher for the shoulder. The subjects themselves could also choose to discontinue the task at any time if they felt extreme discomfort, fatigue, or pain.

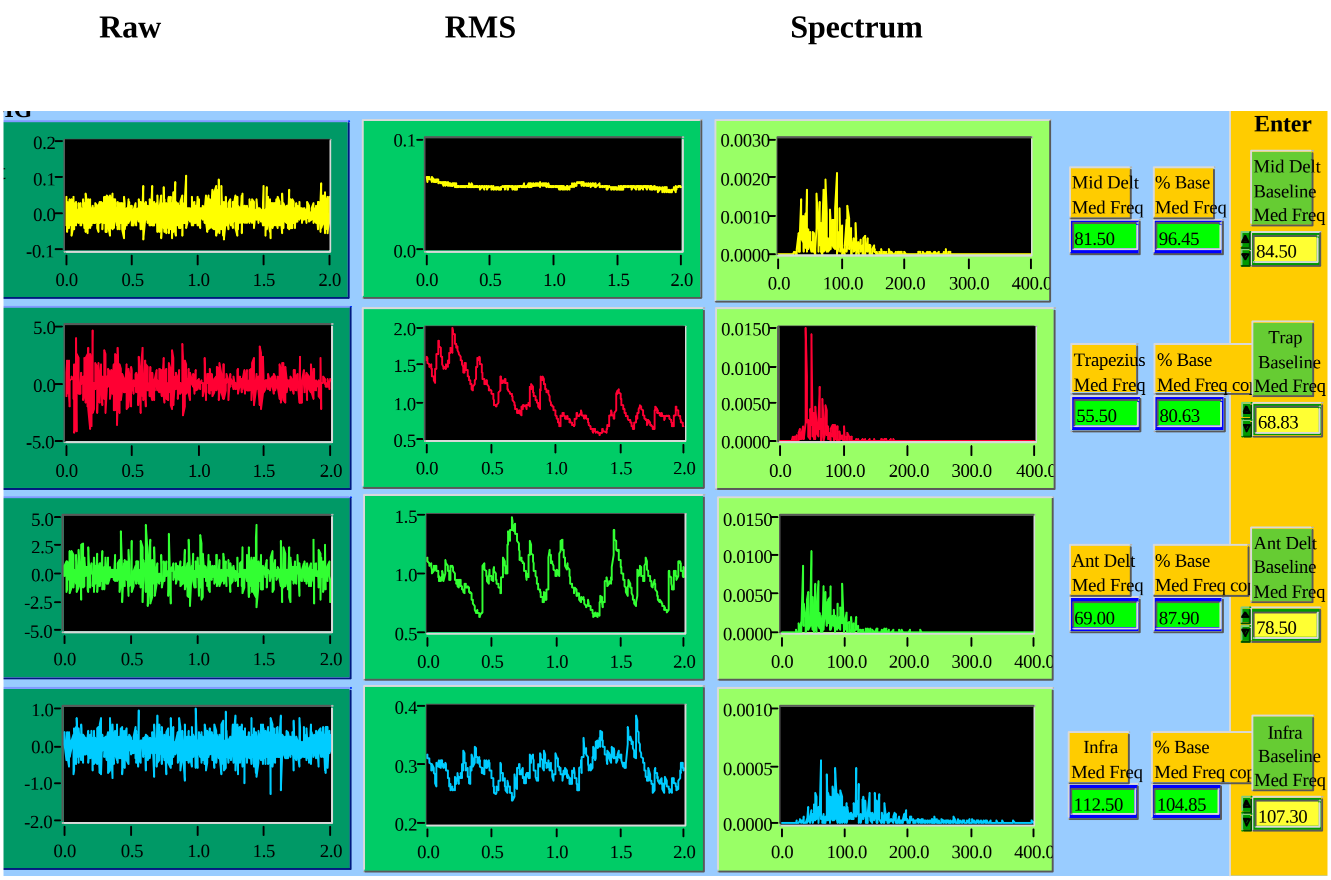


Figure 5. Display of EMG readings.

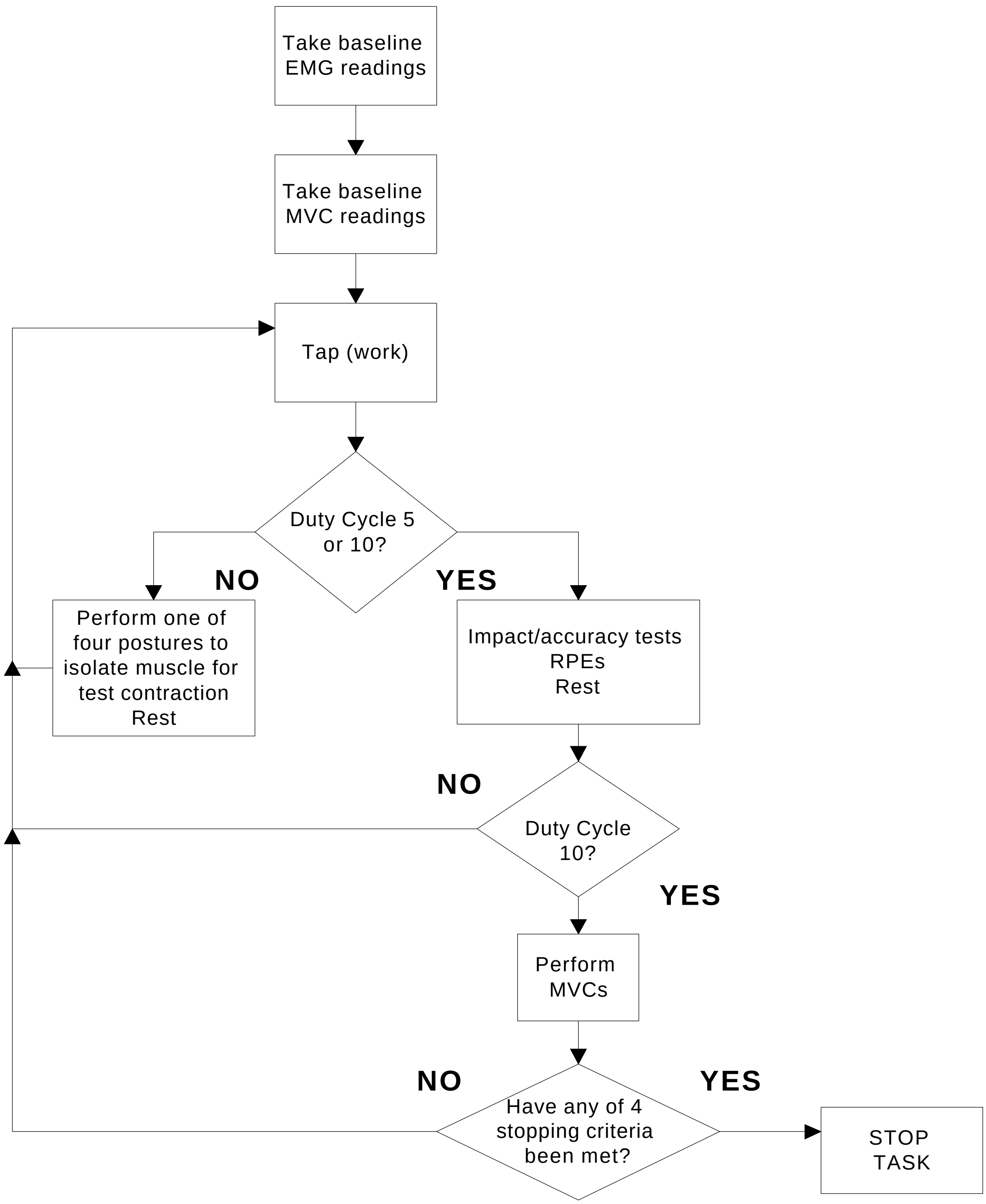


Figure 6. Task configuration.

3.3 Apparatus and Materials

The primary apparatus that were used to measure performance were EMG surface electrodes, weights for isolation of specific shoulder muscles, the task workstation (including targets and tool), and fixtures used to perform MVCs. All EMG and MVC force data was collected using Labview software.

3.3.1 EMGs. The use of surface electromyography to measure muscle activity requires electrodes covered with a salty gel (providing a path for electrical conductance) to be adhered to the skin over the bulk of the muscle being measured. The general procedure used for EMG placement was as follows. Before placing the electrodes on the skin, the skin was abraded using a fine grain sandpaper, and if necessary, hair was removed using a disposable razor. The skin was cleaned of excess oils using cotton and rubbing alcohol. Table 4 and Figure 7 indicate the muscles used and their location. All electrodes were oriented perpendicular to the length of the muscle fibers and placed over the bulk (belly) of the muscle (DeLuca, 1997). The skin resistance was determined using a resistance meter approximately twenty minutes after the electrodes were placed on the skin to ensure that the gel had reached chemical equilibrium. The required skin resistance was less than 10 k Ω for shoulder muscles and 20 k Ω for lumbar muscles. The higher the skin resistance, the more noise included in the signal. The skin determines the impedance of the electrodes, and the meter reads the voltage drop across the electrodes.

Muscle Targeted	EMG Placement
Mid Deltoid	Midway between origin (acromium) and deltoid insertion point
Anterior Deltoid	Midway between lateral third of the clavicle and deltoid insertion point
Trapezius	2 cm lateral to midpoint of C7 and acromium
Infraspinatus	3.5 cm to medial border of scapula and 3 cm below spine of scapula
Right Erector Spinae	Slightly higher than the top of the iliac crest on the right side of the spine
Left Erector Spinae	Slightly higher than the top of the iliac crest on the left side of the spine
Ground 1	C7 spinous process
Ground 2	Sacrum (S1) vertebrae

Table 4. EMG placement.

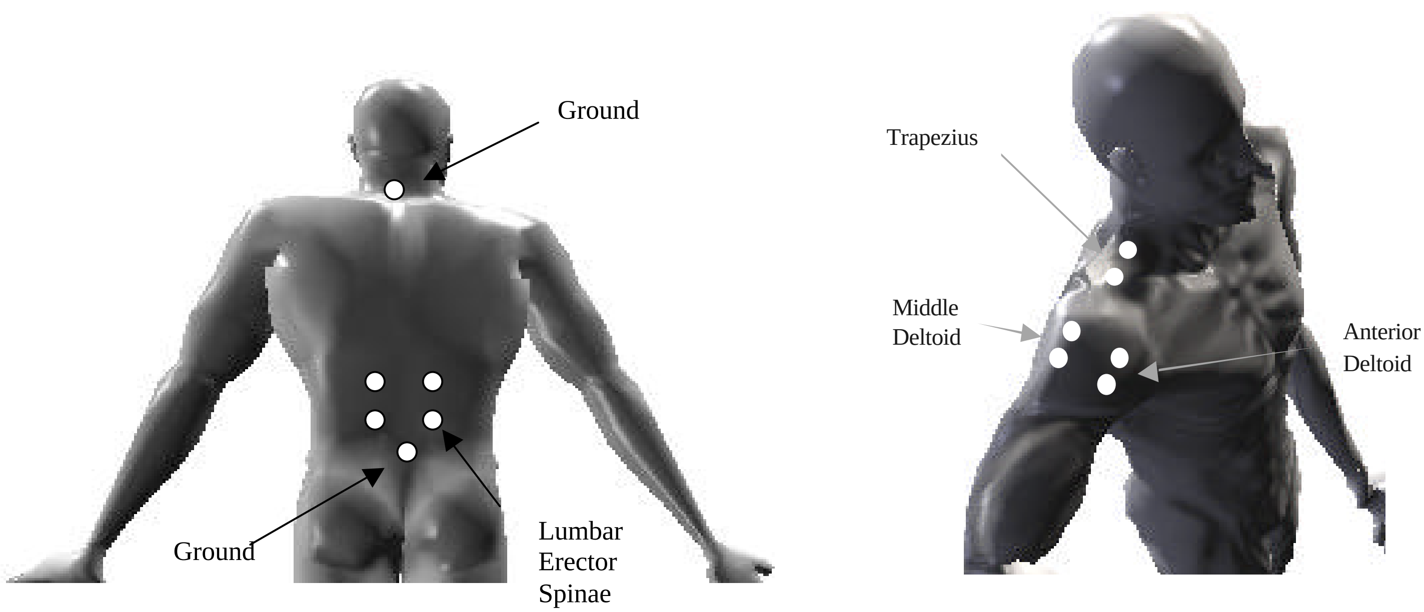


Figure 7. Illustration of surface electrode placement

Because the myoelectric signal is so small in magnitude compared to other ambient signals on the skin surface, the electrode leads were connected to preamplifiers and an amplifier to magnify the signal. Raw myoelectric signals obtained during the test contractions were preamplified (x100), then hardware amplified to a range of ~±5V and filtered (30-500 Hz). EMG gains were set so that the signal did not come in above or below ±10 volts because the data collection system only recognized signals in that range. When setting gains, the subject's maximum (or close to maximum) muscle output must be known. Therefore, an MVC targeting the muscle under examination was performed while the voltage output was observed on the amplifier. The gain was considered adequate when the voltage reading on the amplifier was between one and three volts. A time constant of 110 msec was used. The time constant tells the amplifier how wide of an area to integrate over when it is smoothing the rectified (RMS) data to represent the activity in the muscle under examination. A value of 110 msec was selected because if the value is too large, critical data may be lost and if the value is too small, the data will be difficult to interpret. The amplified and filtered signals were A/D converted and sampled at 1024 Hz.

3.3.2 Workstation. The workstation consisted of two targets placed on strain gauges and attached to the wall on tracks (see Figure 8, which shows a subject tapping). The targets could be moved in either vertical direction. A tape measure placed alongside of the track provided a reference for target location. The tool used was a small plastic wand with a handle and pointer. Buckets with handles and filled with sand or lead shot served as weights used for EMG readings. The weights of the buckets could easily be varied for different subjects. Bucket weights were based on the subject's maximum strength for the muscle under examination and the moment arm for the exertion.

3.3.3 MVC fixtures. A lumbar MVC fixture (see Figure 3) and a shoulder MVC fixture (see Figure 4) were used to help provide consistency of posture each time a subject performed an MVC. Subjects stood on wooden platforms with their backs against a wooden panel and adjustable, foam covered fixtures resting against their chests. The height of the backboard and attached fixtures could be adjusted up and down. Strain gauges were attached to tracks on the wall behind the fixture. Wires connected the strain gauges to fabric straps that the subjects used to exert their maximum forces.

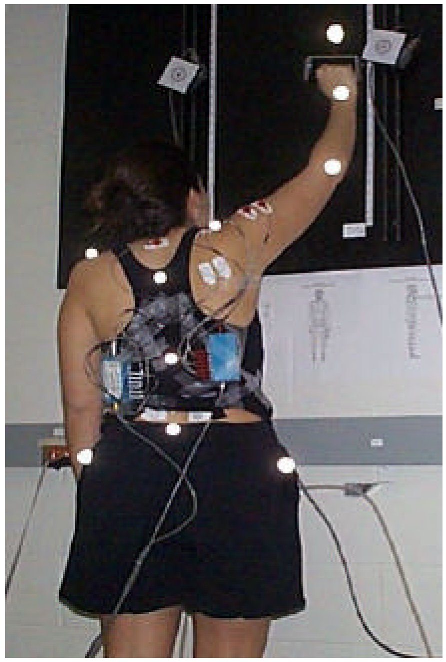


Figure 8. Subject tapping targets.

3.4 Independent Variables

The independent variables in this experiment were (1) duty cycle time, which could be 20 seconds of work and 40 seconds of rest or vice versa, and (2) tool weight. The portion of the one minute duty cycle spent working had two levels, either 1/3 (20 seconds) or 2/3 (40 seconds). The mass of the tool had three levels, the first of which was 0.34 kg (0.75 lbs) for conditions A and B. The second and third tool weights were 0.68 kg (1.5 lbs) and 1.02 kg (2.25 lbs). These values are slightly less than those seen in previous studies in the literature regarding fatigue in repetitive arm elevations (Hagberg, 1981) as the task under examination is dynamic rather than static. The weights were chosen to be evenly spaced and were intended to cover the range of typical hand tool weights.

Certain variables such as age and previous injury were controlled in the experiment. Subjects were required to tap in sync with a series of auditory beeps in order to control the pace of the task. The postures used to obtain EMG measurements were standardized and the weights used were based on the individual's maximum voluntary contraction value for the specific muscle being tested. All subjects used a common fixture for the MVC testing that was adjusted to their anthropometric dimensions. Some variables, such as technique and force of tapping, were not controlled. Neither could the experimenters control for potentially strenuous activities performed by the subjects outside of the experimental environment, although the subjects were asked if they had performed any abnormal activities before beginning each experimental condition. The personality, pain tolerance, and tolerance for monotonous tasks also differed between subjects. However, these same variables differ between actual workers in the field and are therefore considered acceptable and even necessary to increase the generalizability of the results.

3.5 Dependent Variables

The dependent measures obtained throughout the experiment were both objective and subjective in nature. Both types provided an indication of the subject's level of fatigue.

3.5.1. Objective Measures. Because time-to-fatigue is operationally defined as a loss in performance capability for the purposes of this experiment, the truly direct measure of performance is that of strength in the shoulder muscles. Therefore, MVCs were measured and recorded for the mid deltoid, anterior deltoid, trapezius, and infraspinatus every ten trials. It was expected that the maximum forces in at least one of the shoulder muscles tested would decrease with time during the tapping task.

The EMG signal detected during sustained contractions has well-known spectral modification properties with fatigue over time; for example, the shape skews due to reductions in mean and median power frequencies (DeLuca, 1997). For this reason, the myoelectric signal for shoulder muscles was measured during static low-force test exertions performed during the resting segments of each tapping cycle. The readings were taken at this time because signal stability can only be approached if a muscle contraction remains isometric (DeLuca, 1997). From power spectrum analyses, time-to-fatigue can be operationally defined as a fixed percentage of frequency change in median power frequency (MdPF) and this time tabulated as a dependent measure. Changes in muscle MdPF were assumed to represent changes in underlying physiological processes and, further, to indicate increased risk of potential musculoskeletal injury.

3.5.2. Subjective Measures. Subjective assessments were obtained using Borg's General Scale. These measures were used to determine when to stop the experimental task. It was important to carefully and consistently explain the meaning of the measures to each subject before each condition in order to get reliable and uniform ratings. For example, each time the subject participated in the experiment it was explained that the use of decimal places was acceptable and that the value of ratings did not depend on the value of previous ratings. The subjects also needed to understand that the global rating should not reflect the feeling in one particular part of the body, but rather the body as a whole.

3.5.3. Performance Measures. Tapping force was also monitored and used as a performance measure. Very few experiments have used such measures of signs of fatigue or attempted to correlate them with more traditional objective and subjective measures. It was expected that the peak impact forces and the variability in impact forces would increase with time during the tapping task.

3.6 Experimental Design

The data collected for this study incorporated a subset of a much larger collection of data for a broader overhead work study with sixteen subjects. The larger study used target height, percentage of cycle time working and resting, and arm orientation as independent variables. From within this large study, the most difficult and easiest conditions were identified and used in the present investigation, which included an additional variable, tool weight. The design for the experimental portion of the study is shown in Table 5. Note that conditions A and B were previously run as part of the larger study. The design for the current study was a 2x3 full factorial with two independent variables: (1) duty cycle or percentage of cycle time spent working and resting (2 levels), and (2) weight of the tool (3 levels). All variables were between-subject. Subjects numbers one and three were female and subjects numbers two and four were males (see Table 5). The six task conditions, which were randomized in a balanced Latin Square design, are defined in Table 6.

1	**2**	**3**	**4**
A	A	A	A
B	B	B	B
1	**2**	**3**	**4**
2	**3**	**4**	**1**
4	**1**	**2**	**3**
3	**4**	**1**	**2**

Table 5. Experimental design.

Condition Number	**Number of Seconds Spent Working Over 60 Seconds**	**Tool Weight (kg)**
A	20	1
B	40	1
1	**20**	**2**
2	**40**	**2**
3	**20**	**3**
4	**40**	**3**

Table 6. Experimental conditions.

Chapter 4. DATA ANALYSIS

With the exception of the subjective (RPE) measures all other dependent measures were compiled and analyzed in order to obtain *changes* (percentage of initial values) with respect to time. The use of a change in level, as opposed to the use of the magnitudes themselves, was necessary in order to facilitate comparisons across conditions and subjects. However, subjective measures could not be evaluated in this manner because of individual differences between subjects. Sample data obtained for each of the classes of measures is given below.

The analysis proceeded by quantifying linear trends in percentage changes versus time. There is not an accepted standard for deciding when fatigue has occurred or when fatigue has become significant for any of the objective measures. This was approached by quantifying the variability in the data using the mean squared error ($\sigma =$ MSE) for simple regression (the residual error, or error about the regression line). It was assumed that when the dependent measure exceeded the MSE level, this indicated the time in the task when the fatigue measure had changed to a significant degree (Figure 9). The times when the measure exhibited a significant change were tabulated as the 'time-to-fatigue'. This method was based on the definition of fatigue as a continuously occurring process rather than a discrete point in time.

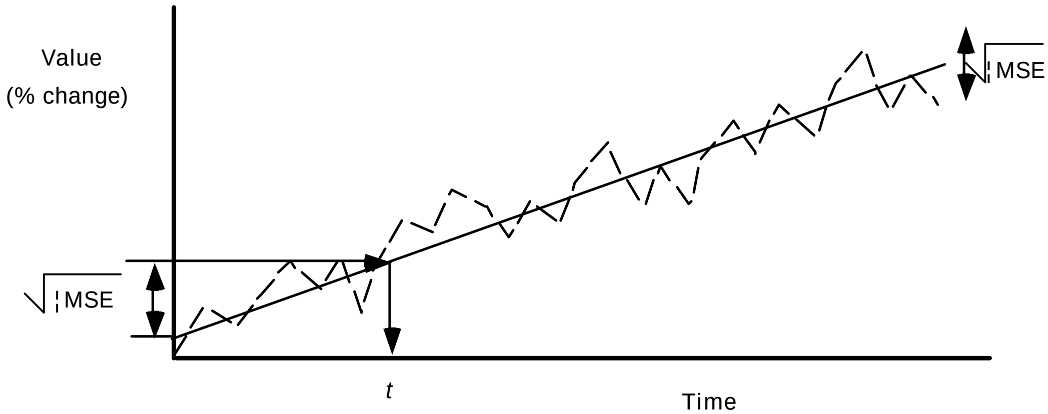


Figure 9. Illustration of analysis used to determine 'time-to-fatigue' (t) based on significant changes in a dependent measure. The percentage change in the value (versus the baseline level) is shown as a function of time. The MSE (residual error from linear regression) characterizes variability in the data.

4.1 Maximum Voluntary Contractions (MVCs)

Subjects performed maximal exertions for each of the four shoulder muscles at 10 minute intervals throughout each condition. The changes in peak forces are shown as function of time for a particular subject and condition (Figure 10).

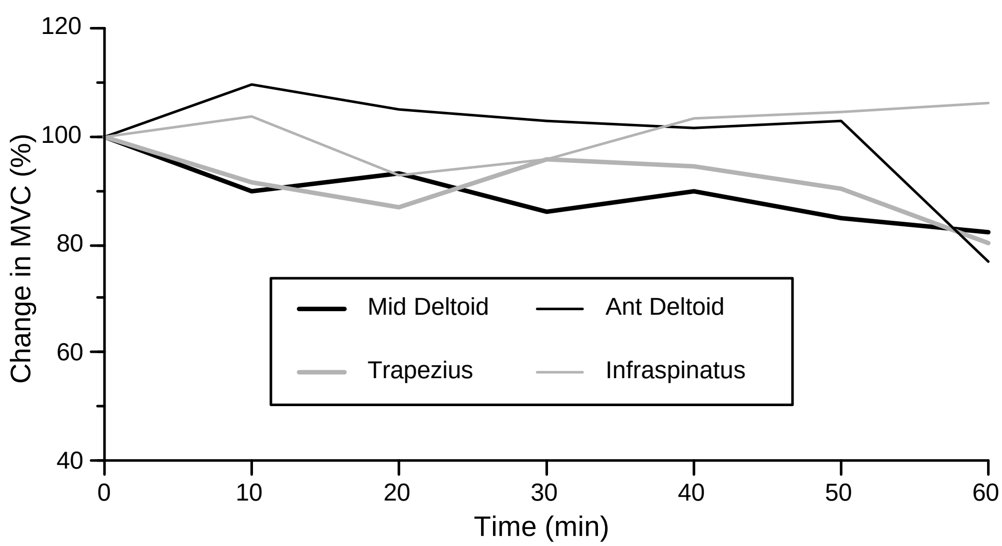


Figure 10. Changes in maximum exerted forces of the four shoulder muscles. The mid deltoid and trapezius muscles show evidence of gradually decreasing force capability.

4.2 EMG Median Power Frequency (MdPF)

Two second samples of the raw EMG data, obtained during test contractions performed every fifth minute for each muscle, will be processed (Hanning window and FFT) to obtain the spectral content of the signal and the median power frequency (MdPF) associated with the signal (Figure 11). The change in MdPF values for the four muscles are shown as function of time (Figure 12).

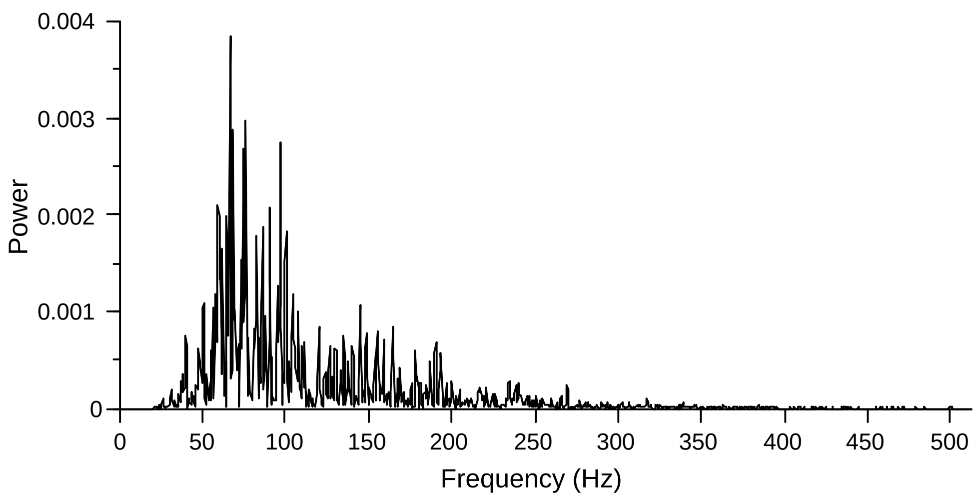


Figure 11. Frequency distribution for Mid Deltoid muscle. Within this sample, the Median Power Frequency was 123.5 Hz.

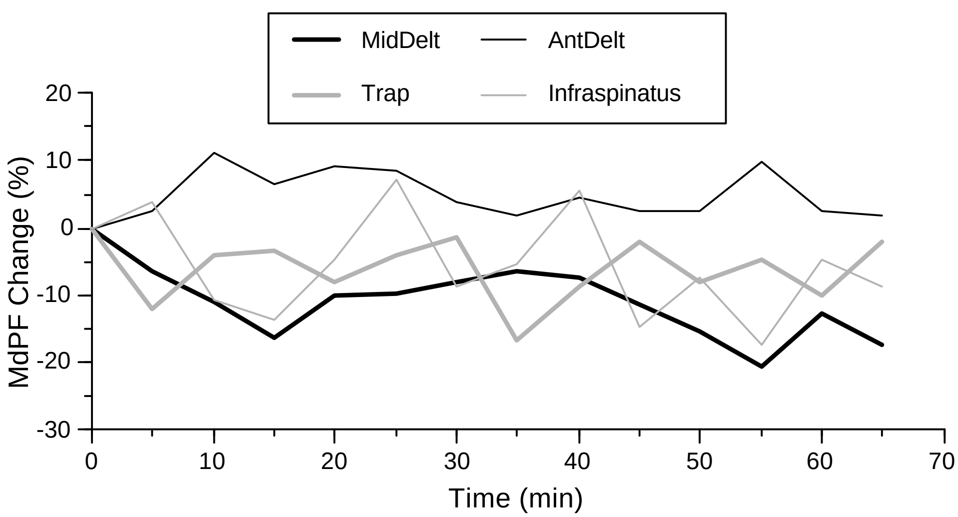


Figure 12. Changes in median power frequencies (MdPF) of the four shoulder muscles. The mid deltoid and infraspinatus muscles show evidence of gradually decreasing MdPFs.

4.3 Ratings of Perceived Exertion (RPEs)

RPEs were obtained for the shoulder and low back regions as well as the whole body at 5 minute intervals throughout each condition. The changes in RPE values are shown as a function of time (Figure 13).

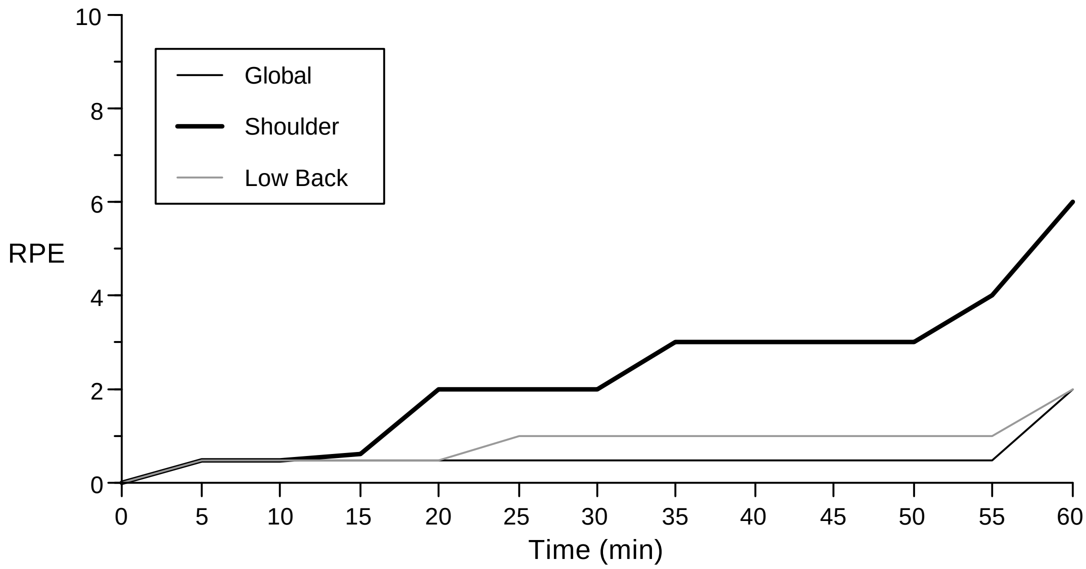


Figure 13. Changes in ratings of perceived exertion (RPE). The RPEs indicate the perception of increasing discomfort in the shoulder. This condition was terminated at 60 minutes when the shoulder RPE reached 6.

4.4 Tapping Force

Ten second samples of the impact forces were recorded from the two targets every five minutes during each condition (Figure 14). From each of these samples, the average, maximum, and variability (standard deviation) were calculated. The change in each of these values characterizing the impact forces is shown as function of time (Figure 15).

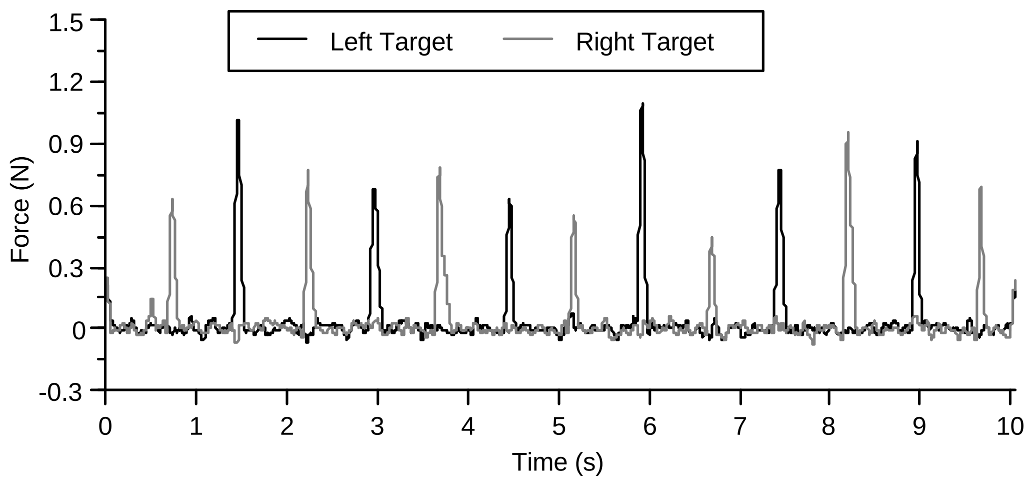


Figure 14. Target impact forces. Within this sample, the peak, standard deviation, and maximum forces were determined (1.3, 0.28, and 0.79 N respectively).

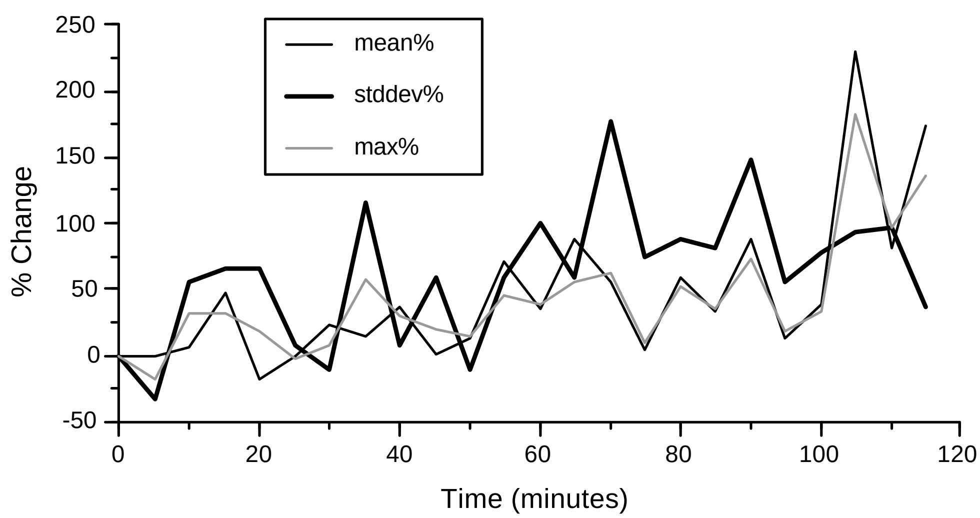


Figure 15. Target impact forces. Within each sample, taken every fifth minute, the mean, standard deviation., and maximum forces were compiled and the percent change (vs. initial sample) is shown. Linear increases in all three values are evident.

Chapter 5. RESULTS

The results were divided into five main categories based on the dependent measures discussed in the previous chapters. Each set of dependent measures was analyzed separately and is presented below.

5.1 Task Durations

Duty cycle was found to have a significant ($p<0.0001$) effect on task duration, as indicated by the time at which a person could no longer perform the task (failure point), the task was stopped because stopping criteria was met (time to fatigue), or a maximum time of three hours. When the one minute cycle time consisted of 20 seconds of work and 40 seconds of rest, the task was performed to completion (three hours) ten out of twelve times (Figure 16). However, when the cycle time consisted of 40 seconds of work and 20 seconds of rest, the task was never performed until completion. Average task durations for the 40/20 and 20/40 work/rest combinations were 53.33 and 172.5 minutes, respectively. Although the tool weight was not shown to have a significant effect on task duration, there was a trend showing a decrease in task duration as weight increased from 0.68 to 1.02 kg (W2 to W3).

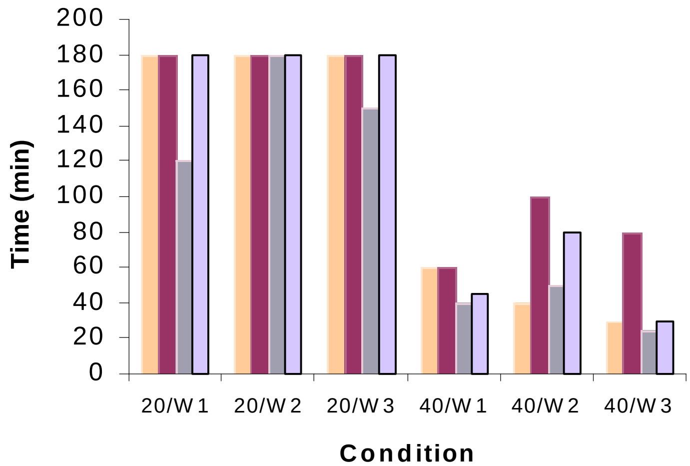


Figure 16. Task duration for all subjects as a function of task condition. Each different shaded bar represents a different subject. The x-axis labels indicate the duty cycle (20 or 40 seconds) and the weight used (0.34 kg, 0.68 kg, or 1.02 kg).

5.2 Maximum Voluntary Contractions

Changes in maximum voluntary contraction values for the infraspinatus were significant with respect to duty cycle (p = 0.0425) and changes for the mid and anterior deltoid were shown to approach significance with respect to duty cycle (p = 0.1326 and 0.1675 respectively). Time to fatigue for all four muscles was less for the 40 second duty cycle than for the 20 second duty cycle. Although time to fatigue for the trapezius was not statistically significant, the same trend was observed. Figure 17 depicts this relationship, while Figure 18 shows the average time for each shoulder muscle to fatigue for each subject over all conditions. No trends were observed for time to fatigue with respect to weight. However, it should be noted that the pattern for time to fatigue for each muscle was relatively consistent with regard to subject. For example, Subject 2 always fatigued last while Subject 4 always fatigued first.

During the 40 second duty cycle, the mid deltoid appears to fatigue first, while the trapezius, anterior deltoid and infraspinatus fatigue shortly thereafter (Figure 17). However, for the 20 second duty cycle, the mid deltoid and anterior deltoid appear to fatigue first, at about the same time, while the trapezius showed fatigue slightly later and the infraspinatus did not show fatigue until the task was approximately 75% completed.   Time to fatigue, as determined by changes in maximum voluntary contractions, was 25-60% sooner in the mid deltoid, anterior deltoid, and infraspinatus in the 40 second duty cycle condition than in the 20 second duty cycle condition.

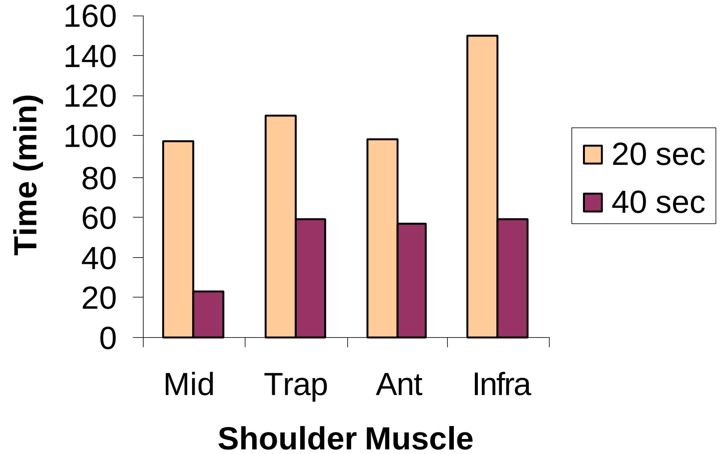


Figure 17. Average time to fatigue(based on decreasing MVC) for three shoulder muscles of all subjects as a function of duty cycle (20 seconds of work and 40 seconds of rest or vice versa).

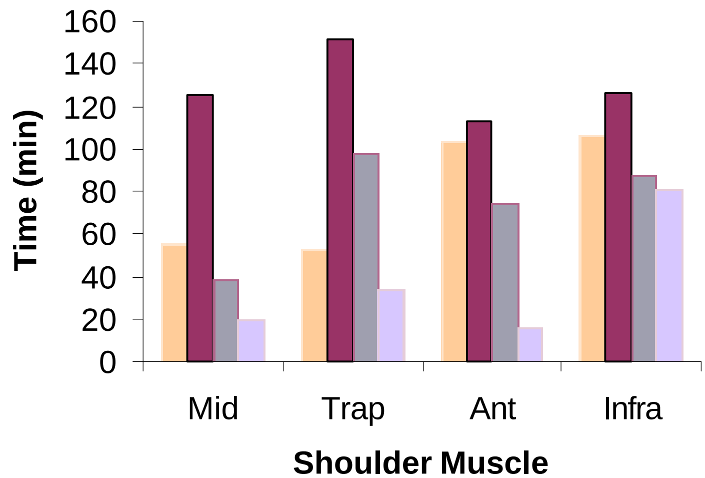


Figure 18. Average time for each shoulder muscle to fatigue for each subject, over all conditions. Each different colored bar represents a different subject.

5.3 EMG Power Spectra

Time to fatigue for the mid deltoid as determined by changes in the median frequency of the EMG power spectrum was shown to change significantly (p=0.0249) with change in weight (Figure 19). A clearly decreasing trend can be observed between weights two and three. A decreasing trend also exists between weights one and two, although it is not as obvious upon observation of the data. Post hoc tests showed that time to fatigue for the mid deltoid was not significantly different between weights one and two (p>0.1), but was significant between weights two and three (p=0.058) and between weights one and three (p=0.032). These trends existed for three of the four subjects (Figure 20).

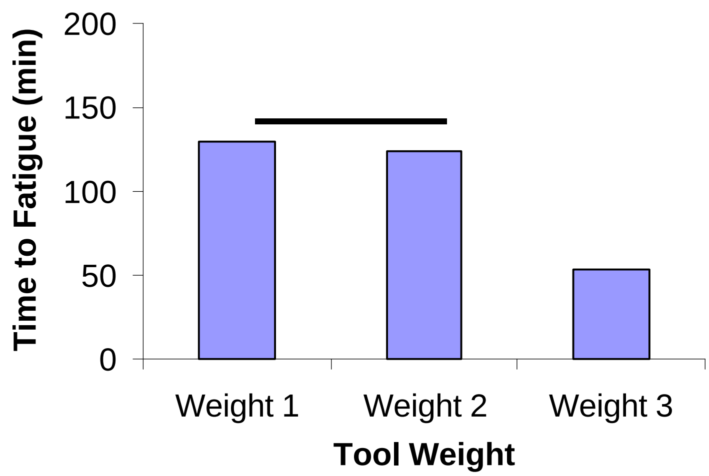


Figure 19. Mid deltoid average time to fatigue with respect to weight (weight 1 = 0.34 kg, weight 2 = 0.68 kg, and weight 3 = 1.02 kg), based on changes in MdPF.

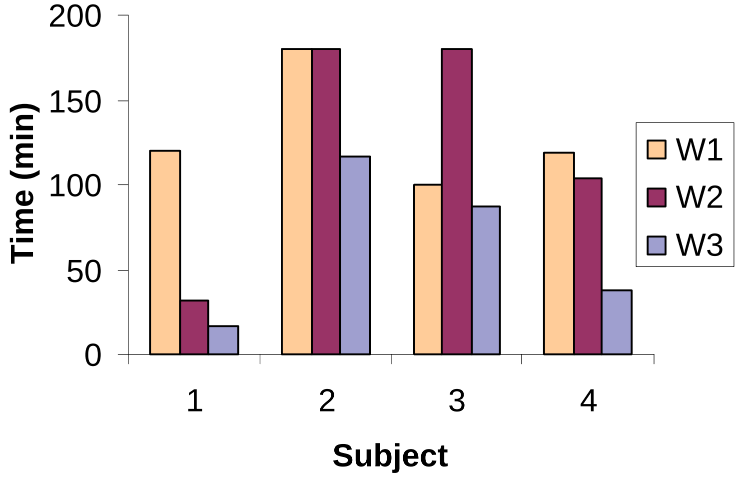


Figure 20. Mid deltoid average time to fatigue with respect to weight for each subject.

Time to fatigue as shown by changes in the median frequency of the trapezius approached significance (p=0.1271) with respect to duty cycle (Figure 21). The minimum time for any shoulder muscle to fatigue was also shown to significantly change (p=0.0323) with respect to duty cycle (Figure 22).

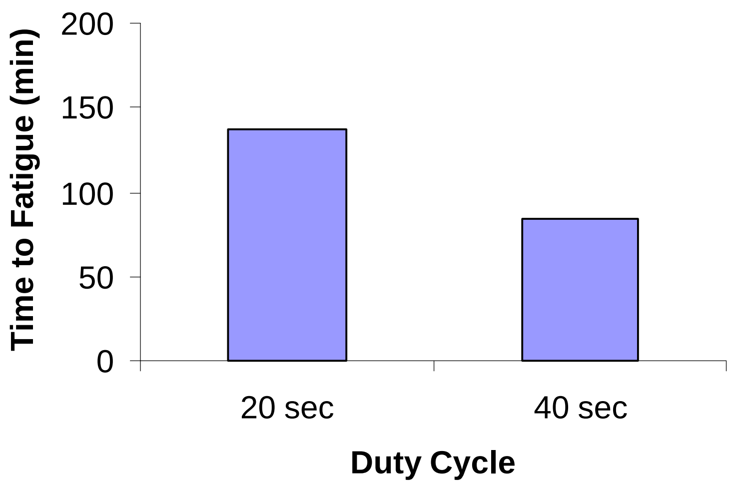


Figure 21. Average time to fatigue with respect to duty cycle as determined by changes in the trapezius EMG power spectrum.

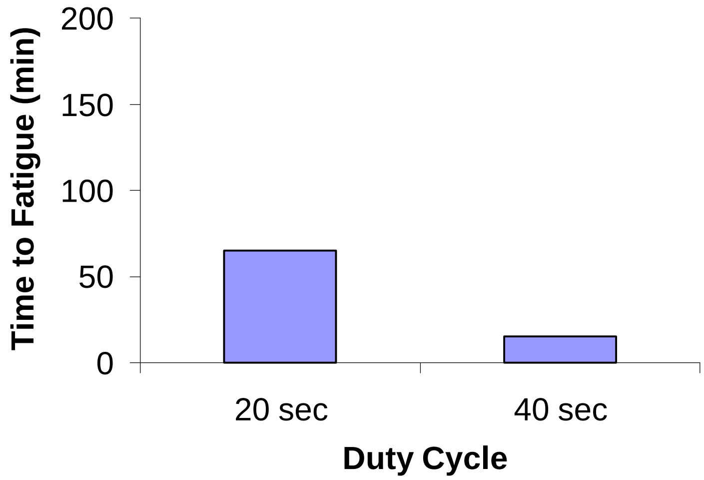


Figure 22. Average minimum time for any shoulder muscle to fatigue with respect to duty cycle as determined by changes in MdPF.

5.4 Ratings of Perceived Exertion

Times to fatigue based on RPEs were found to approach significance (p=0.1210) with respect to duty cycle (Figure 23). Shoulder RPEs reached a value of one much more quickly when the task required the more strenuous duty cycle (40 seconds of work and 20 seconds of rest. It appears as though subjects perceived a linear increase in fatigue with respect to time after RPE rises above one. However, large intersubject variation was observed and is evidenced by the difference in the slopes of linear trend lines, which represent a change in RPE/% task duration (Figure 24).

Although weight did not prove to be a significant variable with respect to RPE, it was discovered that in most cases, time to fatigue was smaller at weight 3 than weight 2 (Figure 25). It should be noted that the times at which RPEs reached six are usually equal to the total task time for each condition. Sessions were almost always stopped because the RPE reached six unless the participant worked the entire three hours without ever reaching that value.

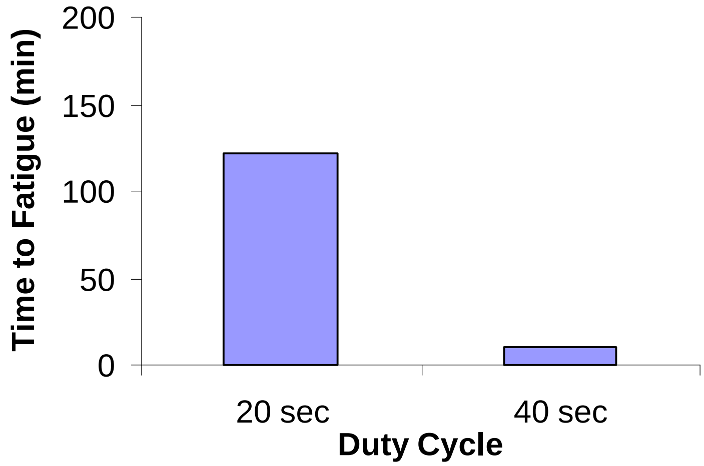


Figure 23. Average time to fatigue based on shoulder RPE = 1 with respect to duty cycle for all subjects and all conditions.

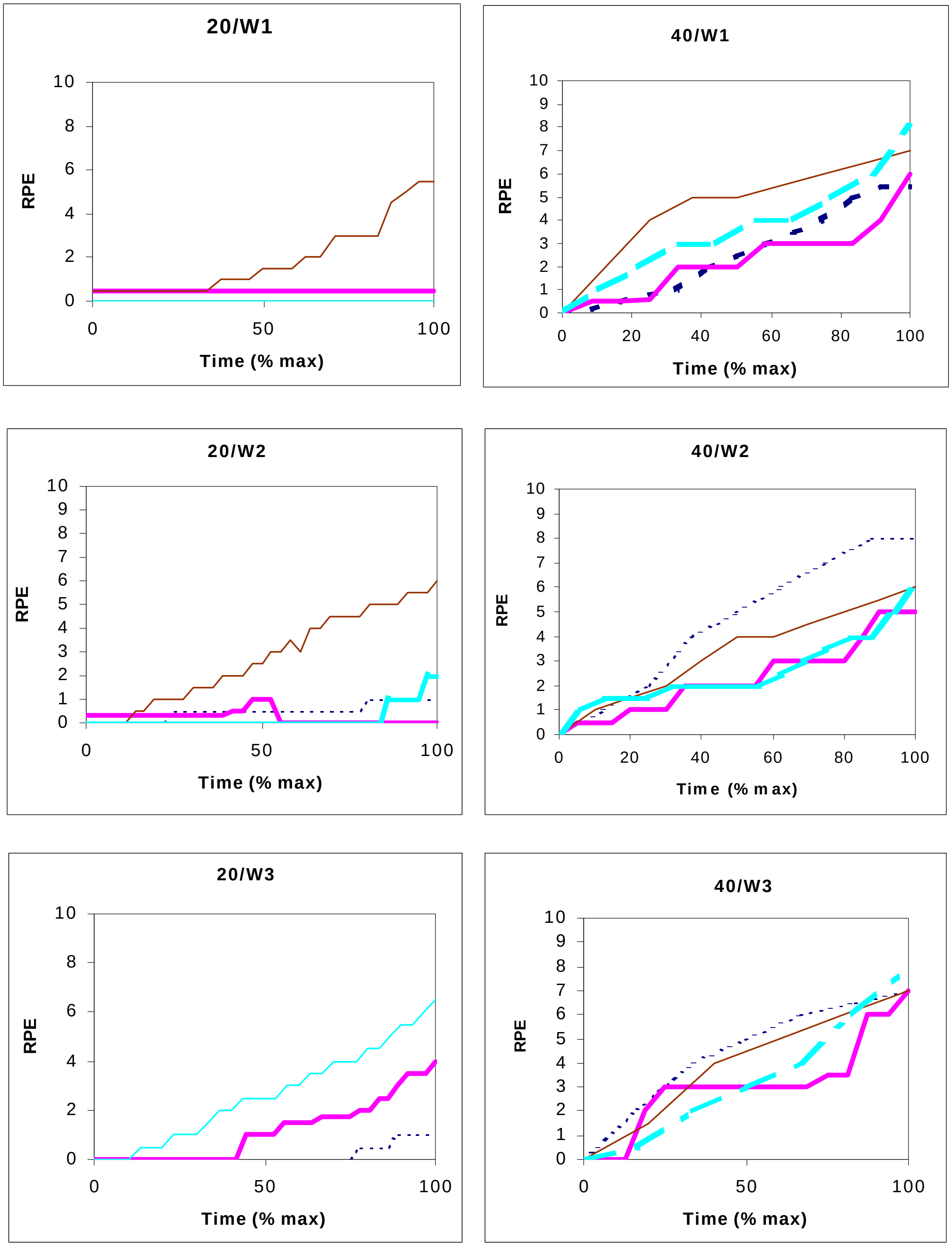


Figure 24. Shoulder RPE as a percent of total task time for all subjects, all conditions.

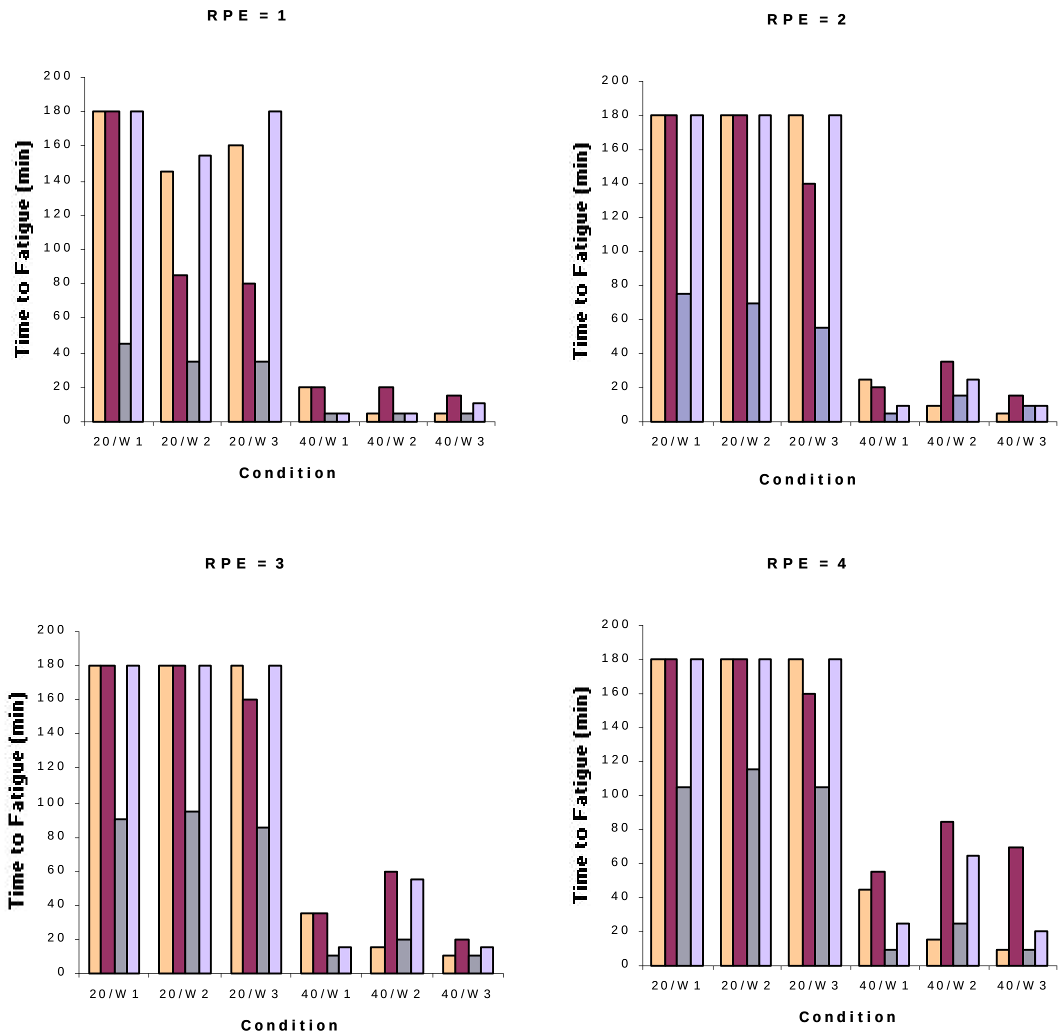


Figure 25. Time to fatigue based on shoulder RPE = 1, 2, 3, or 4 for all subjects, all conditions. Each different colored line represents a different subject.

<u>5.5 Target Tapping Forces</u>

Time to fatigue with respect to tapping force was analyzed according to changes in three parameters, each of which was determined from ten second samples taken every ten minutes throughout the task: average, standard deviation, and maximum (Figure 26). Average tapping force was shown to approach significance with respect to weight (p=0.1710). It should be noted that all three measures used to determine time to fatigue for tapping force were very consistent, that is, time to fatigue as determined by a significant change in average, maximum, or the standard deviation of tapping force occurs at approximately the same point in time. Figure 27 shows the relationship between average tapping force and time to fatigue for each weight class.

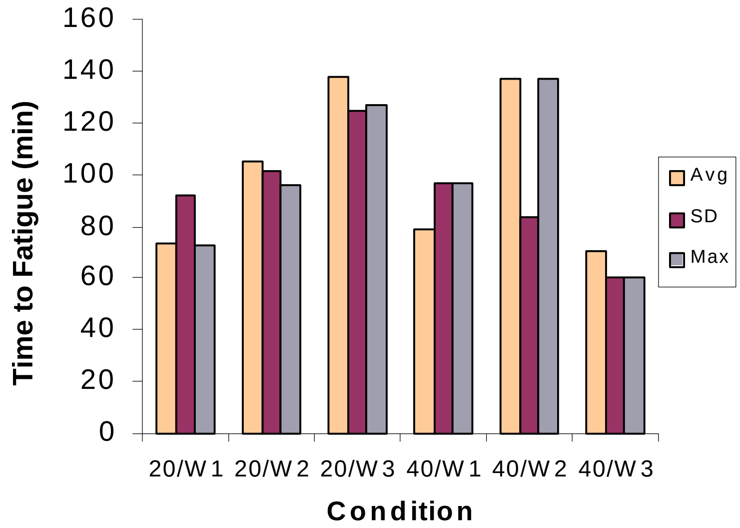


Figure 26. Time to fatigue determined using changes in tapping force.

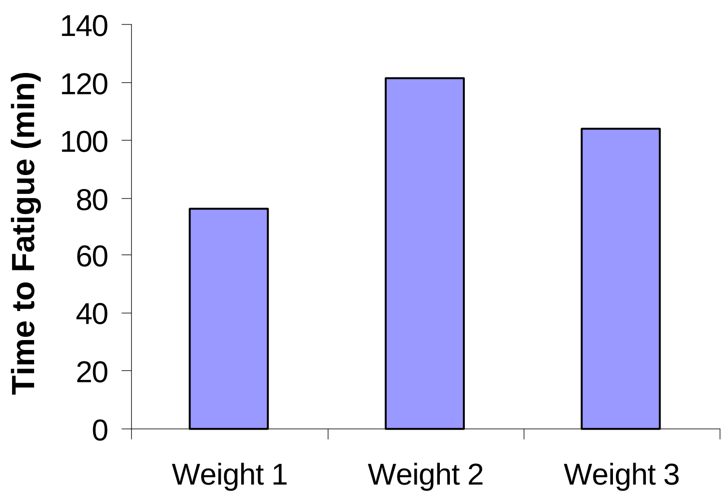


Figure 27. Time to fatigue with respect to weight for average tapping force.

5.6 Overall Time to Fatigue

Graphs depicting fatigue times were derived from the experimental data and indicate the times during performance of the overhead task at which various signs of muscle fatigue are expected to become evident. Comparison of the times derived from the various measures shows considerable variability (Figures 28 and 29).

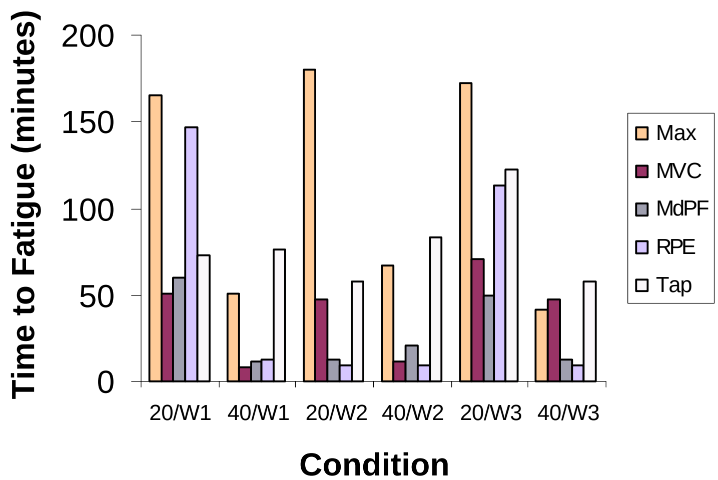


Figure 28. Time to fatigue based on different dependent measures, grouped by weight. Max: total task time; MVC: strength; MdPF: EMG spectra; RPE: subjective shoulder discomfort; Tap: task performance (force).

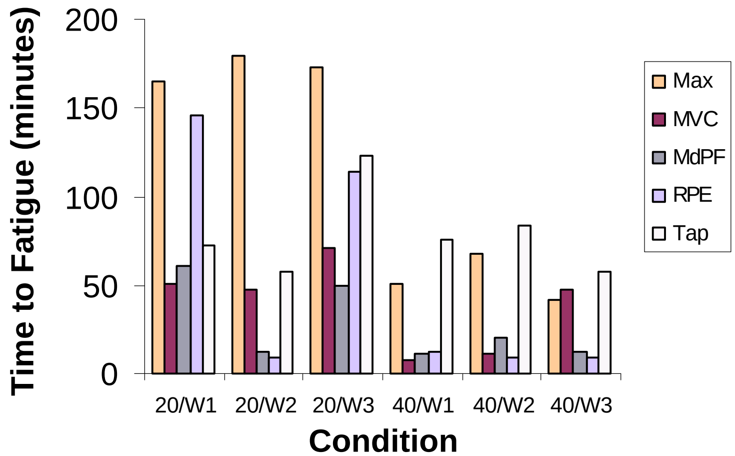


Figure 29. Time to fatigue based on different dependent measures, grouped by duty cycle. Max: total task time; MVC: strength; MdPF: EMG spectra; RPE: subjective shoulder discomfort; Tap: task performance (force).

As can be seen from the graphs, MVC, RPE, and MdPF appear to be the three earliest indicators of fatigue. Overall, change in MVC seems to be the earliest predictor, as it is always the first or second indicator in five out of six conditions. It is believed that change in MVC was not an early indication in the weight 3, 40 second condition because this condition was extremely difficult, and therefore very short. The trials did not last long enough to observe significant change in MVCs. In very difficult trials (both heavier weights and 40 second duty cycles) RPE was the earliest predictor of time to fatigue. This was not the case in easier (20 second duty cycle) trials. In addition, MdPF was a consistent measure of time to fatigue. It was always in the top three earliest predictors for all conditions. As weight increased, time to fatigue as indicated by MdPF appeared earlier than other predictors.

Chapter 6. DISCUSSION

6.1 Overview

This study was performed in order to address the effect of hand held weight on fatigue over a range of common part and tool weights as overhead work was executed. Work tasks that resulted in the development of localized muscle fatigue, as determined by a variety of measures, were considered to pose additional risk of musculoskeletal injury in the shoulder mechanism. Although an exact quantitative relationship between fatigue and injury has not yet been established, there is a general consensus within the body of scientific literature available that fatigue has a direct correlation with increased injury risk. For the purposes of this study, it was assumed that fatigue could be used as a surrogate measure of injury risk, but does not necessarily equate directly to injury risk. By determining the times at which fatigue became evident in the experimental trials, it was intended that the task variables causing fatigue could be identified and used to generate initial data towards the development of ergonomic guidelines. In the future, these guidelines could be used by practitioners as a practical design tool to evaluate current overhead work operations and as a predictive tool to evaluate overhead work at the design phase.

In order to achieve this goal an overhead assembly task consisting of a paced point to point tapping task between two elevated circular targets was simulated in a lab environment. The task was selected to allow for quantification of several different measures of fatigue and for its similarity to actual overhead assembly work in terms of postures, repetitiveness, and stereotypical required movements. Three levels of tool weight and two levels of duty cycle were used as independent variables. These variables were selected for examination based on the results of a previous study on overhead work conducted in the same laboratory which suggested that overhead reach height (target height) and hand position (prone or supine) were not significant variables in time to fatigue. A total of 4 subjects were used due to the large amount of testing time required. These subjects had participated in the previous overhead work study prior to participation in this study. Data from two conditions tested in the earlier study were also used in the present analysis.

6.2 Determination of Time to Fatigue

As fatigue has been researched, it has undergone a significant change in definition. Fatigue was traditionally thought of as a failure point, or the point at which a given physical exertion could no longer be maintained. However, a growing body of research evidence supports the more current definition of fatigue as a continuous and cumulative process. According to this explanation, there is not a specific identifiable time at which it can be said that fatigue occurs, which can present difficulties in calculating a time to fatigue for a given task. There are currently no measures available to indicate that fatigue is occurring at a particular time. Fatigue as a failure point is typically distinctly observable and therefore relatively easy to measure. Yet the use of this definition is of little use in work design because fatigue is detected after it occurs. From a health and safety standpoint, it is desirable to have indications that precede failure in order to remedy the situation. It is not advantageous to design tasks so that workers are at or near their failure points, for obvious reasons.

If fatigue is defined as an ongoing and gradual process, and it is assumed that fatigue and injury risk are directly related, then it can also be inferred that injury risk should grow continuously as a task progresses. It then becomes necessary to make a decision as to what level of fatigue is acceptable, a difficult and somewhat arbitrary decision at best due to the lack of empirical evidence available and the wide variety of potential fatigue measures that may be obtained. In this study a variety of measures were obtained to address the objective (physiological), subjective, and performance changes that occur during a fatiguing task. Failure points were identified in this study as the times at which the experiments were terminated (based on several stopping criteria). Time to fatigue was interpreted as the time at which the change in the fatigue measure had become significant, with this significance in turn obtained as a function of the rate of change of the measure and inherent variability in the data. This approach was justified by the observation that confidence that a measure has changed is higher when low variability exists. However, when a measure is highly variable, confidence that a change has occurred is lower. An alternative method that could have been used would be to say that fatigue had occurred at a predetermined level of change, e.g., 20%. Differences in variability found for the different fatigue measures suggested that this approach was not optimal. The results are therefore limited by their dependence on the operational definition used for time to fatigue.

Many intramuscular changes occur at the biochemical or cellular level with fatigue. For example, Fitts (1996) describes a reduced isometric twitch force and a decreased rate of force development due to a reduction in the rate at which contractile proteins bind to each other. McArdle et al. (1994) discuss intracellular changes such as oxygen deficit, lactic acid accumulation, and an increase in the H^+ concentration in an active muscle that may cause interference in the contractile process. However, it is still unclear which of these changes are related to injury. Multiple measures were used in this experiment to determine the secondary or macro effects of underlying processes occurring in the muscle. In addition, the use of multiple measures in assessing fatigue allowed for the examination of both the physiological signs of fatigue (which may be related to injury risk) and of the impact of fatigue on performance. For example, it would not be said that changes in tapping force demonstrate an increased risk of injury. The point of performance measures is to demonstrate that the performance effects of fatigue are often undesirable, in addition to the increased risk of injury. For example, Hammarskjold et al. (1992) found that after an arm fatiguing exercise, precise work was perceived as being harder, movements slowed, and more mistakes were made, resulting in inferior quality.

6.3 Hypotheses

Three hypotheses were developed as a result of observations from pilot studies and were examined after the data collection and analysis procedures were complete.

Hypothesis #1: The effect of increased hand tool weight on time to fatigue will be nonlinear (Figure 30).

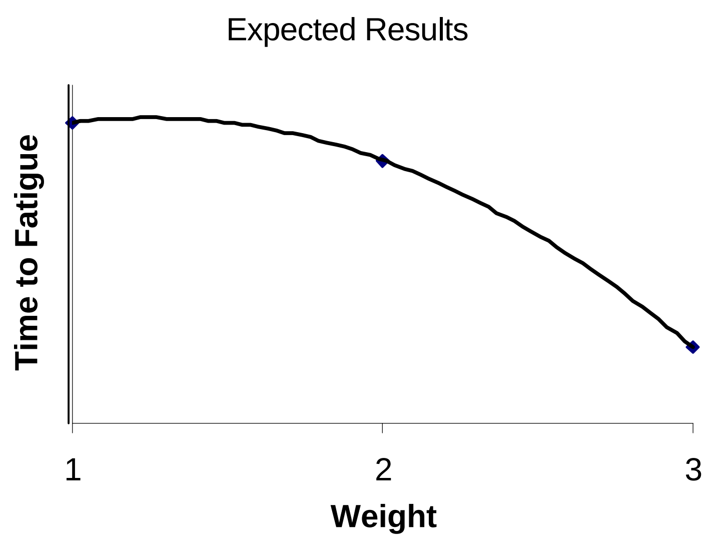


Figure 30. Expected effect of hand tool weight on time to fatigue for any dependent measure.

This hypothesis was formulated based on pilot data and on the Rohmert Curve (Rohmert, 1973), which shows the relationship between a person's ability to maintain a given static muscular force and the magnitude of the force (Sanders and McCormick, 1993). The Rohmert Curve shows large drops in performance with small increases in effort. Maximum endurance time decreases exponentially as percent exertion increases for static tasks (Chaffin, 1991). Maximum static efforts can be maintained only briefly while tasks requiring less than 25% of maximum effort can be maintained for an extended period. However, the Rohmert Curve is not considered to be accurate at very low effort levels.

For repetitive, dynamic work, the combination of both force and repetition determines the length of time an activity can be endured (Rodgers, 1997). Therefore, in the experimental task, it was expected that time to fatigue, or maximum endurance time, would decrease as tool weight, or the magnitude of the force, increased, and as duty cycle increased. Due to the nature of pilot data collected, it was expected that lower level changes in weight (i.e., W1 to W2) would not have a large impact on time to fatigue. Observations suggested a critical level at which fatigue became more substantial. Therefore, it was expected that the effect of weight on time to fatigue would be similar to the effect of force on endurance in Rohmert's Curve, but the size of the effect would differ. It was expected that time to fatigue would begin to decrease more rapidly as the handheld weight increased to higher levels.

The results of the study did not support this hypothesis. In many cases, the results actually showed an increase in time to fatigue from weight one to weight two, that is, it took longer for the dependent measures to change to a significant degree, for a heavier weight (Figures 28 and 29). It is believed that this was largely due to an unanticipated learning effect that occurred because the subjects participating in this study had previously taken part in a similar study from which some data was used in the present analysis. This learning effect was not likely due to physical training, that is, the participants did not actually get stronger or increase in endurance as a result of participating in the previous experiment (see Figure 31). If MVCs did increase slightly in some cases, it could be the result of practice effects and increased familiarity with the equipment and postures. However, this subtle effect would not explain large differences in time to fatigue as a result of an increase in physical strength. MdPFs, which are objective measures, also showed increases in times to fatigue for weight 2 conditions than weight 1 conditions.

In fact, the participants did appear to be more comfortable with the task each session. They became increasingly familiar with the expectations of the experimenters and the task demands. In some cases, participants may have even adopted more efficient methods of performing the task , such as assuming certain postures. The learning effect was especially evident in the 20 second duty cycle conditions, where participants were aware of the comparative ease of the task to the 40 second duty cycle tasks. It is possible that they were prepared to work through the maximum duration of the task (three hours) and did not expect to become fatigued.

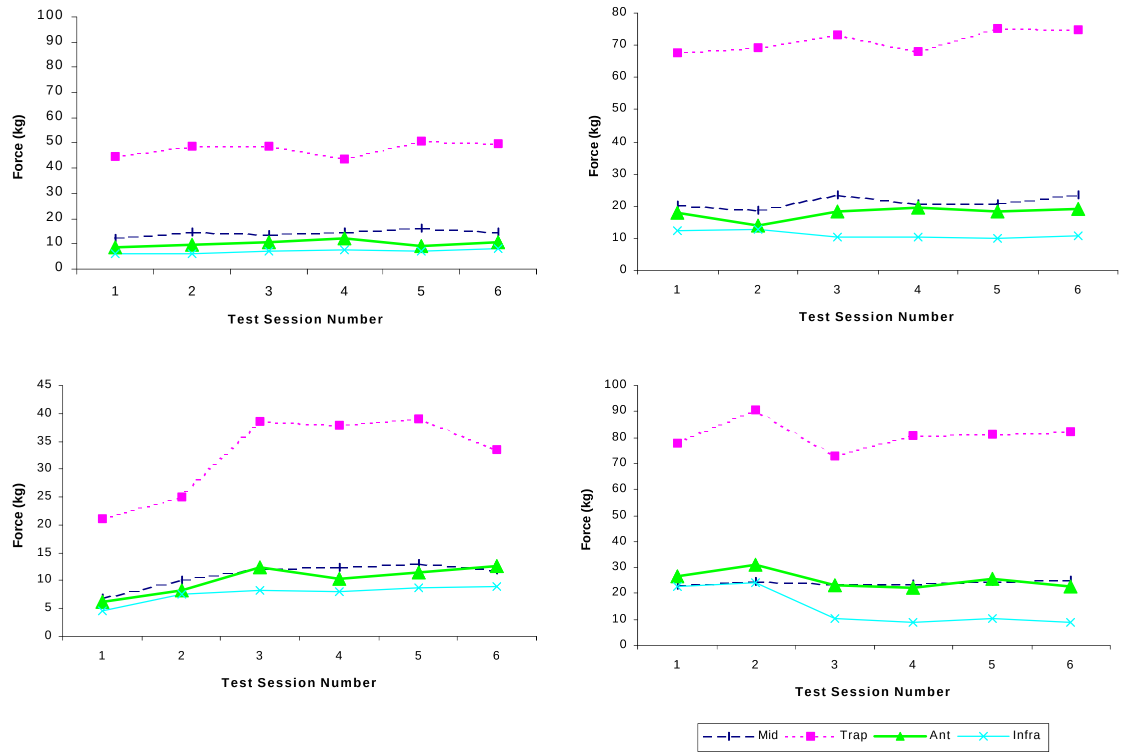


Figure 31. MVC values for all muscles tested at the beginning of each testing session. Each graph represents values for a different subject. The x-axis labels indicate test session number (not condition number).

Hypothesis #2: The effect of increased hand tool weight on time to fatigue will differ depending on task parameters. For example, it was expected that time-to-fatigue would decrease at a faster rate as the percentage of cycle time worked increased (Figure 32).

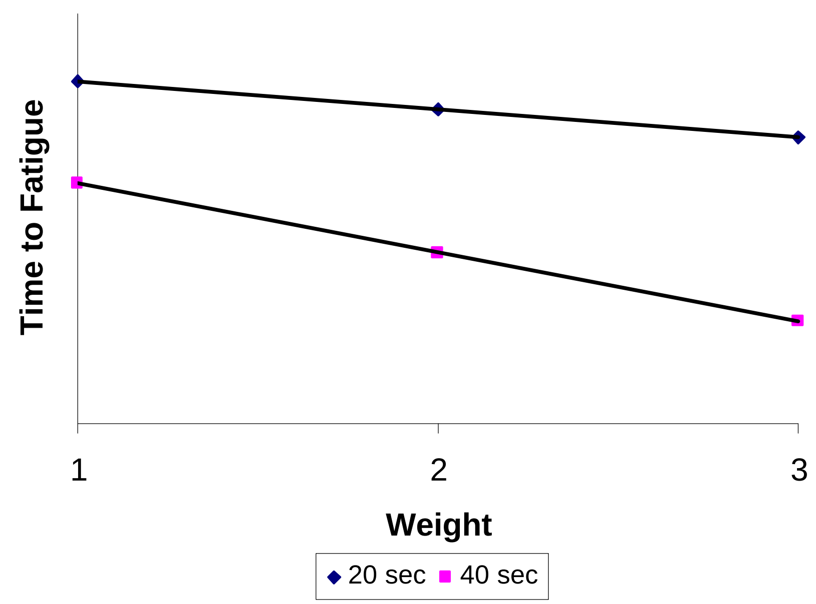


Figure 32. Expected effect of hand tool weight on time to fatigue with respect to duty cycle.

This hypothesis was not supported by the data as no interactions between duty cycle and weight were statistically found. In addition, time to fatigue actually decreased as tool weight increased in many cases, especially between weights 1 and 2. This was most likely due to the learning effect described previously. However, the expected trend was observable between weights 2 and 3 in some cases. Particularly good examples of this trend are observed when time to fatigue is determined using myoelectric patterns in the anterior deltoid (Figure 33), maximum voluntary contractions in the trapezius (Figure 34), and maximum task duration (Figure 35).

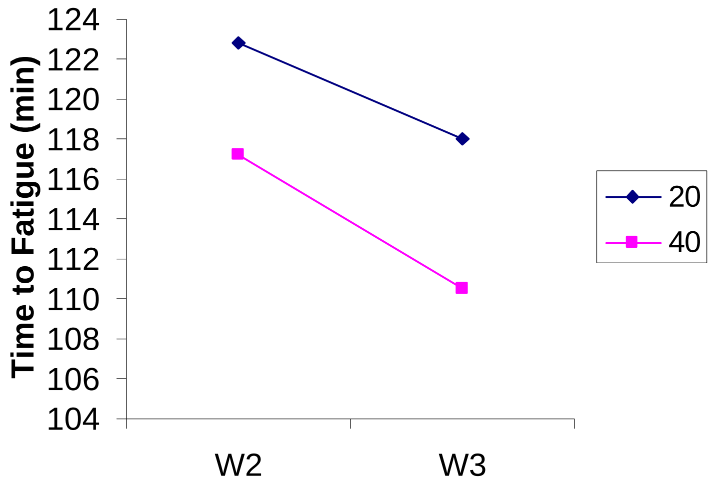


Figure 33. Time to fatigue as determined by MdPF changes in the anterior deltoid.

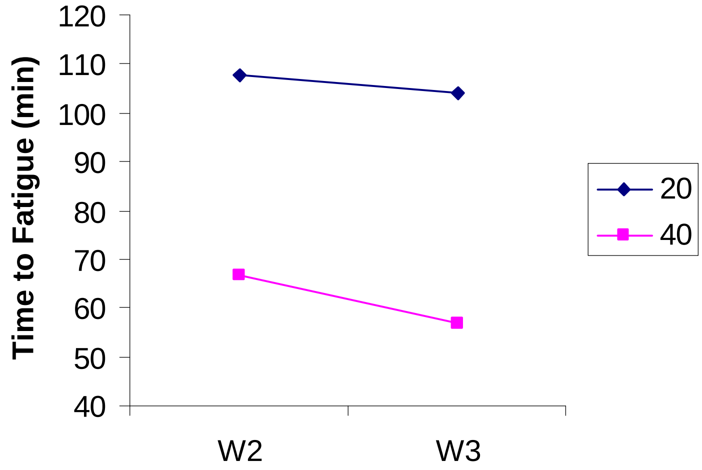


Figure 34. Time to fatigue as determined by trapezius MVC.

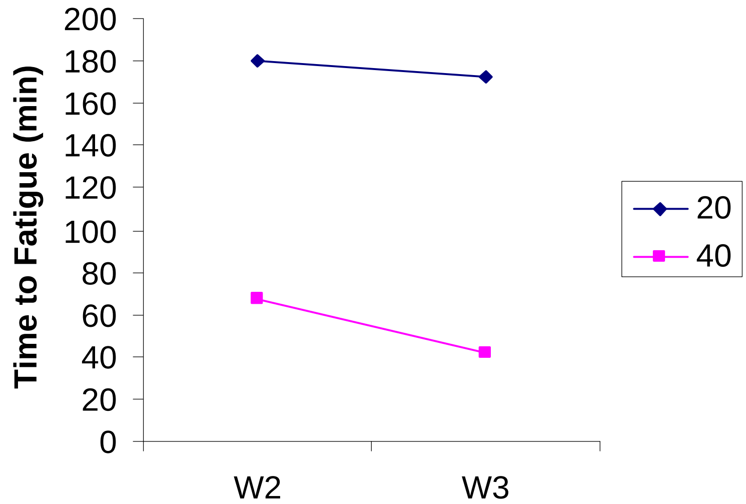


Figure 35. Time to fatigue as determined by maximum task duration (weights 2 and 3).

Hypothesis #3: The effect of increased hand tool weight will differ depending on how fatigue is measured.

Times to fatigue calculated for this experiment were based on different dependent measures and differed widely from one another in absolute value. For example, time to fatigue as determined by maximum task duration was consistently higher than time to fatigue as determined by other measures. However, within the 20 second and 40 second duty cycles, the trends looked similar for some measures (Figures 36, 37, 38, and 39). For the 20 second duty cycle, trends for the maximum task duration and MVC data are similar (relatively flat) and trends for the RPE and MdPF data are similar (V-shaped). For the 40 second duty cycle, trendlines for the different dependent measures appear relatively flat; however, the maximum task duration and MdPF data both show small peaks at weight 2. Although these trends are observable, it is difficult to say whether or not they have practical significance. The fact that many of the trendlines appear relatively flat may suggest that the differences between the tool weights selected were not large enough.

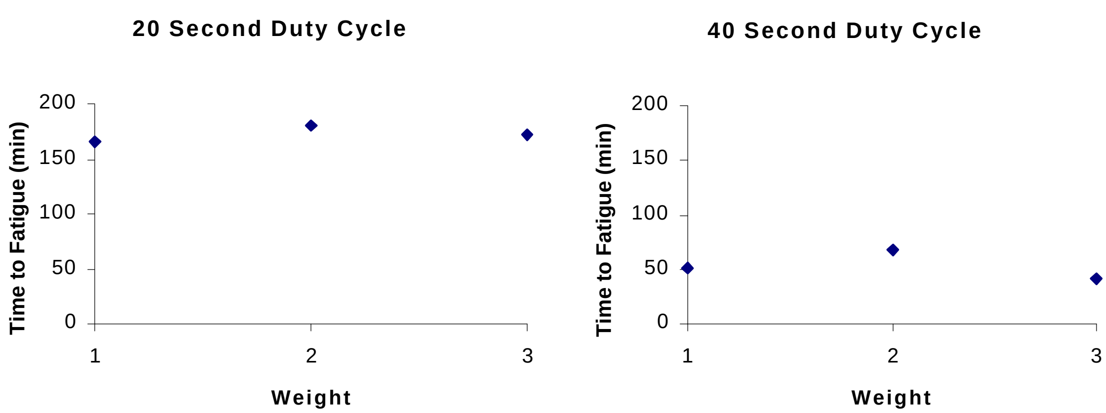


Figure 36. Time to fatigue as determined by maximum task duration.

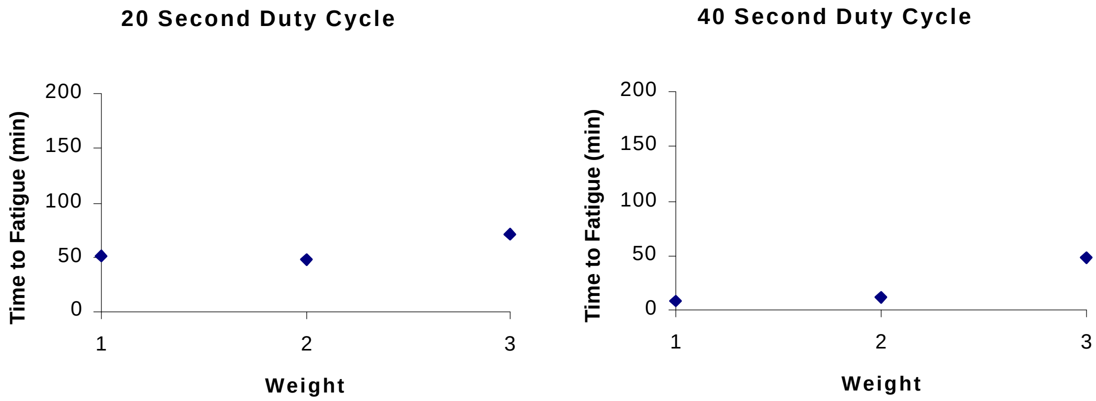


Figure 37. *Time to fatigue as determined by changes in maximum voluntary contractions.*

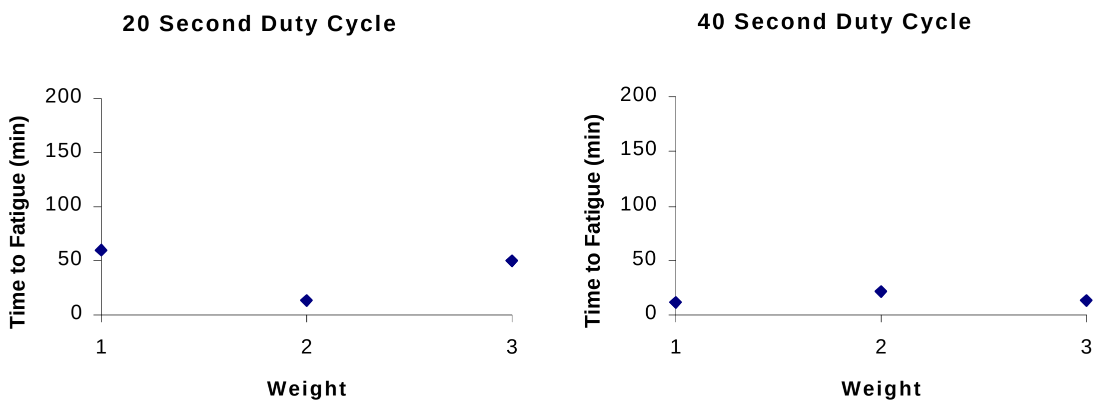


Figure 38. *Time to fatigue as determined by changes in MdPF.*

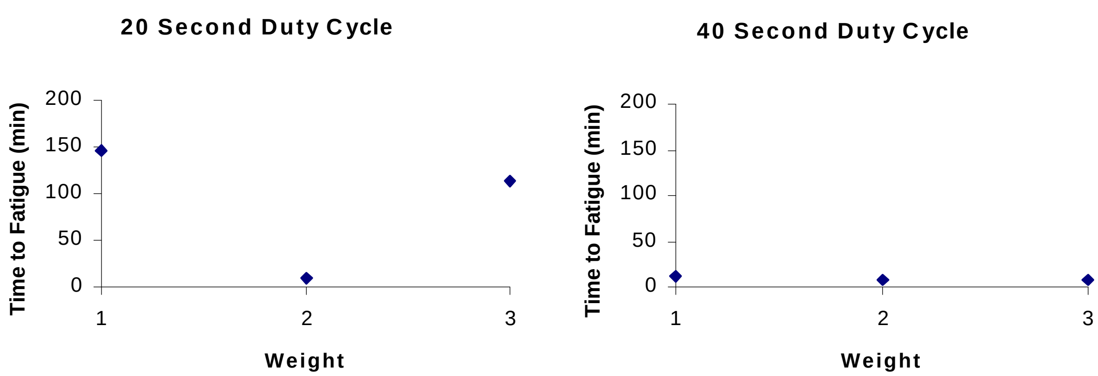


Figure 39. *Time to fatigue as determined by changes in RPE.*

6.4 Study Limitations

The two most important limitations in this experiment were the use of only four subjects and a potential unanticipated training effect. Such a small sample size makes statistical significance difficult to establish, and allows outliers to have a large effect on data analysis. These subjects were recruited from a previous study conducted regarding overhead work, so they were familiar with the procedures and requirements of the experiment. Two experimental conditions (those using the lightest weight) were taken from this previous experiment for use in the data analysis. It was not expected that a conditioning effect would be present due to the fact that the previous experiment took place weeks prior to the current experiment. However, it is believed that a training effect did in fact exist. This was evidenced by the fact that almost all measures of time to fatigue, including MdPF, an objective measure, indicated a slightly longer time to fatigue for the second heaviest weight than for the lightest weight. In addition, data analysis showed that the subjects did not actually increase in physical strength (Figure 31).

In order to determine the true size of the effect or to eliminate a learning effect, an alternative experimental design should be used. For example, a between subjects design in which each subject recruited only completed one condition could be used. Benefits of this type of design would be the elimination of learning effects and a much lower demand on the subject's time. However, this type of design would require a larger number of subjects, which requires greater amounts of resources such as money, lab usage, and staff availability. A mixed design could used in which weight is a between-subjects variable and duty cycle is a within-subjects variable, as the effect of duty cycle has already been established as large. One group of subjects would run three conditions with a 20/40 duty cycle and three weights while another group would run three conditions with a 40/20 duty cycle and the same three weights. Another alternative would be to rerun the experiment, again using a within-subjects design, but using naïve subjects and presenting all trials within a close time frame. A minimum of six subjects would need to be used in order to completely randomize condition order. Other options include training subjects for a period of time before beginning to run conditions in an attempt to eliminate learning effects, or to run one subject through the same conditions a few times to see what the learning curve, if any, looks like.

Performance results based on tapping force were highly variable and not necessarily consistent with the expectation that force magnitude and variability would increase as subjects fatigue and lose fine motor control. The experimental conditions may not have been controlled to a level that would allow these changes to be observed. It may be necessary to provide more detailed instructions to the subjects, for example, how hard they should hit the target.

The experimental task realistically simulates an industrial tapping task in the sense that it is a repetitive overhead task requiring stereotyped movements. Some minor differences include the requirement for subjects to pay close attention to pacing and accuracy, while real tasks may or may not have this requirement. Also, subjects have little freedom of movement whereas actual workers may have more freedom. An additional limitation relates to subject motivation and stimulation level. This is an individual factor that is difficult to control. Attempts to control this variable included providing a consistent environment with minimal distractions. Experimenters also periodically reminded and encouraged subjects to attend to the task, and try their hardest.

The major difference in the laboratory task from an actual industrial task involves the task interruptions that were necessary to take MVC measurements. It may be questioned whether these interruptions could have biased fatigue measurement by either contributing to fatigue or alleviating fatigue by providing a rest from overhead work. However, the MVC measurements were not considered to be a biasing factor, because pretests on the mid deltoid muscles of 6 subjects revealed no signs (myoelectric spectral shifts) of fatigue when performing exertions up to 30% of MVC every 5 minutes. These results and the low frequency with which MVCs were performed suggest minimal bias.

An additional limitation of the experiment was that subjects worked for less time per cycle than would generally be required of a manufacturing assembly job. In reality it would be rare for an actual worker to only work 40 seconds, let alone 20 seconds out of a one minute cycle. However, this limitation was not considered critical to the outcome of the experiment because in an actual work situation workers may not be doing only overhead work for the complete cycle but overhead work combined with some sort of other task. An additional task could result in two different outcomes: giving the worker a break from the overhead work, providing recovery time, and slowing MSD onset or could introduce additional risk factors such as twisting motions/awkward postures, heavy weightbearing, etc. which could interact with the overhead work to actually speed the onset of a MSD. However, this experiment sought to isolate only the effects of overhead work on time to fatigue. Forty seconds was near the maximum time feasible because of the need to take static EMG measurements after each tapping exercise. The task was terminated after three hours although some subjects showed few signs of fatigue and could have easily continued working. This was justified because in reality an assembly line worker would rarely work for more than three hours without the opportunity for some sort of rest or break.

Duty cycle and weight were the two independent variables chosen for investigation in this study, although there are actually a large number of task parameters and levels of these parameters that may be varied for an overhead work task. The two parameters chosen were based on the results of a previous overhead work study which suggested that overhead reach height (target height) and hand position (prone or supine) were not significant variables in time to fatigue. However these variables may be tested with different weights to see if an interaction does in fact exist.

The use of surface EMG was also a constraint as only certain muscles accessible by surface EMG could be studied. Underlying, unaccessible muscles may also contribute to fatigue, discomfort, and ultimately injury. For example, supraspinatus muscle activity, which has been implicated in shoulder fatigue and injury (Armstrong et al., 1993; Wiker et al., 1989), cannot be observed through surface EMG. In addition, EMG itself as a fatigue factor is controversial. As Vollestad (1997) points out, the underlying cause for the decrease in MdPF often associated with fatigue is still unresolved and no straightforward relationship between shifts in EMG power spectrum and fatigue currently exist. Wiker et al. (1989) also note that the recovery of EMG spectral shifts upon cessation of exertion has been shown to be rapid, especially when levels of fatigue are small. In this experiment, substantial variability in MdPFs were found despite the attempt to obtain unbiased spectral indicators through highly controlled test contractions. MdPFs often remained stable or even increased while other signs of fatigue were obvious and apparent (i.e, tremor, lowered MVC values, increased RPE values). This finding may be due to factors beyond experimental control, such as the presence of excess subcutaneous tissue. There is a possibility that intermittent work is associated with different patterns of muscle recruitment than that which occurs during static work. In a prolonged static effort, a consistent group of motor units may be recruited, and as these units fatigue, the expected (typical) spectral changes occur; however, in dynamic work, new motor units can be recruited. Therefore the observed spectral changes may be in any direction as some units fatigue and fresh units are recruited (Luttmann et al., 1996). The use of intermittent test contractions may not suitably isolate the motor units of interest (those undergoing fatigue). In light of this theory, a high risk of type II error may exist when using EMG to determine time to fatigue, that is, the failure to find localized muscle fatigue when it in fact exists.

Chapter 7. CONCLUSIONS

7.1 Summary of Findings and Use of Data

This data should be considered preliminary information about the effect of weight on overhead work. Some conclusions can be drawn regarding the consistent and large effect of duty cycle on fatigue. In addition, the fact that the mid deltoid appears to fatigue first in most conditions as indicated by change in MdPF could be important for future research. Instead of testing all muscles, just the mid deltoid could be tested and resources could be saved. However, it is also possible that this assumption may only apply to the specific types of tasks studied in this experiment, where the mid deltoid was especially activated. It should be also be noted that the perception of fatigue, which results in an RPE increase, appears to be a step function. As the subjective measure of RPE was used to infer something physiological, this observation could indicate that the onset of fatigue is also a step function. This observation is consistent with the results of the EMG and MVC measures, which also show subjects experiencing different levels of fatigue while performing the same task.

Hesitation in establishing even general ergonomics guidelines from the results of this study stems from the fact that only four subjects were used and an unexpected training effect was discovered. The results with regard to weight were highly unexpected, for example, time to fatigue was longer for weight 2 (0.68 kg) than for weight1 (0.34 kg) which resulted in no significant weight effects for a variety of measures, most notably, maximum task duration. The results of this study should be used to design studies with a refined experimental design and more participants.

7.2 Future Research

The most straightforward extension of this research would be to run naïve subjects under the same experimental protocols as used in this work, at the expense of large amounts of time and resources. However, this would likely contribute to increased statistical significance of the results and potentially find significance where this experiment has found none. Different work/rest cycles, arm elevations, hand positions, tool shapes, worker age, and amount of work experience could also be investigated. Work experience and age may show a great deal of influence on time to fatigue as workers generally experience some level of 'work hardening' and the typical industrial worker is older than the participants used for this study.

Additional fatigue measures may also be considered, such as the use of indwelling electrodes to measure the myoelectric activity of those muscles, such as the supraspinatus, not accessible by surface EMG. This could help determine if deeper muscles fatigue faster than surface muscles. Perhaps objective measures could also be used to determine the extent of fatigue in other parts of the body besides the shoulder. Subjective reports in this study indicate that the neck and low back may also have undergone fatigue during the overhead task.

In this experiment maximum muscle capacity was measured through voluntary exertions, however, a higher level of objectivity can be achieved when assessing muscular strength with the use of external stimulation. This approach uses controlled electrical shocks to determine muscle force capability. This technology is readily available and easy to use but does impose some level of discomfort on the subjects.

Future researchers may also wish to simulate a more realistic manufacturing assembly task by requiring the use of a commonly used tool such as an air gun to shoot bolts overhead or by requiring subjects to lift a part overhead and place it on a fixture. Subjects could also be required to route wires or perform other more complicated assembly tasks overhead. Times to fatigue resulting from these types of tasks or from actual field studies could be used to validate predictions obtained from fatigue times generated from more general task simulations.

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APPENDIX 1 – INFORMED CONSENT FORM

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

Informed Consent for Participants of Investigative Projects

Title of Project: "Quantifying Time to Fatigue During Short Cycle Overhead Work Operations"

Principal Investigators: Dr. M. A. Nussbaum, Assistant Professor, ISE
Dr. L. L. Clark, Research Associate, ISE
Hardianto Iridiastadi, Graduate Research Assistant, ISE

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a study investigating potential muscle fatigue during overhead work (tasks which involve lifting one arm above head level). The purpose of the study is to develop knowledge concerning muscle fatigue in overhead work operations which can be used to design safer and more productive work conditions. It is anticipated that approximately four subjects total will be participating in the study.

II. PROCEDURES

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

1) You will have electrodes placed on several muscles which move your right shoulder and on two muscle areas in the lower back. These electrodes are used to collect information from the muscles which can indicate fatigue levels. The procedure for each electrode involves cleansing a small patch of skin over the muscle area. The electrodes are then placed on the skin and remain in place with a safe adhesive.
2) You will be fitted with special nonreflective clothing. The investigator will then place reflective markers over specific landmarks on the clothing. These markers will be used to track motions and record the motions in a computer. Cameras located in the testing area only view these reflective markers, they will not record any images of you.
3) The investigator will demonstrate the data collection procedures which involve tapping a wand back and forth between two targets, exerting specific muscles in static postures, and providing verbal feedback concerning the level of experienced fatigue.
4) You will be secured next to the apparatus used for collecting data.
5) You will exert several sets of muscles separately for short durations.
6) You will conduct a simulated overhead work task in short cycles with rest periods after each exertion. The work task involves tapping a wand back and forth between two targets.
7) Occasionally, the investigator will interrupt the work cycle to repeat steps 4 and 5.

8) Eight series of these work cycles will be completed with a minimum one day rest period between each set of work cycles.

The total estimated time of participation is twenty-five hours. This time will be divided over nine separate testing days. If the collected data does not fit the required profile, the experimenters may find it necessary to terminate your participation prior to the completion of nine testing days. In this case you will be compensated for your time up to the point of termination.

III. RISKS AND BENEFITS OF THIS RESEARCH

Your participation in this study will provide information that will be used to develop design guidelines for overhead work. It is the objective of this study to contribute design information for improving worker safety, comfort, and productivity.

The primary focus of the study is to measure muscle fatigue. Therefore, you may experience some discomfort related to extended use of some muscles. The muscle fatigue will be due to use over a long period with regular breaks, and not due to generation of large forces. Also, an investigator will continuously monitor your condition to minimize any opportunity of strain.

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

It is the intent of the investigators of this project to report the findings of this study. The information you provide will have your name removed and only a subject number will identify you during analysis and any written reports of the evaluation.

V. COMPENSATION

If you decide to participate in this study, you will be paid $6.00 per hour for the time you participate. The evaluation is expected to last approximately 25 hours total. You will be paid at the conclusion of each of nine testing sessions to take place on nine separate days. Upon completion of the study, you will be paid a bonus of $20 in addition to the hourly pay.

If the collected data does not fit the required profile, the experimenters may find it necessary to terminate your participation prior to the completion of nine testing days. In this case you will be compensated for your time up to the point of termination.

VI. FREEDOM TO WITHDRAW

You are free to withdraw from this study at any time 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 project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, and by the Department of Industrial Engineering.

VIII. PARTICIPANT'S RESPONSIBILITIES

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

- To notify the investigator at any time about a desire to discontinue participation.

- To notify the investigator of any medical conditions which may be negatively influenced by extended muscular exertion. This may include heart disease, conditions influenced by blood sugar levels, or any other medical problems that may interfere with results or increase the risk of injury or illness.

IX. PARTICIPANT'S PERMISSION

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the 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 above and on the following page (please repeat for your copy).

Signature Page

I have read a description of this study and understand the nature of the research and my rights as a participant. I hereby 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 research team for this experiment includes Dr. Maury A. Nussbaum, Assistant Professor, Dr. Laura L. Clark, Research Associate, and Hardianto Iridiastadi, Graduate Research Assistant. Research team members may 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 2 – SUBJECT SURVEY

Subject #: _______ Date: _______

Gender *(please circle one)*	: 1. Male 2. Female
Address	: ____
Phone # and email	: ____
Date of Birth	: _______________
What is your present work?	: _______________
How long have you been doing it?	: _______________
Handedness *(please circle one)*	: 1. Right 2. Left

How would you describe your level of physical activity? *(please circle one)*

1. Minimal 2. Moderate 3. Average 4. Above Ave. 5. Every Day

Have you at any time during the **last 12 months** had **trouble** (ache, pain, discomfort) in: *(please circle)*

Neck	1. No	2. Yes
Shoulders	1. No	2. Yes
Elbows	1. No	2. Yes
Wrist/Hands	1. No	2. Yes
Upper Back	1. No	2. Yes
Lower Back	1. No	2. Yes
Hips/Thighs	1. No	2. Yes
Knees	1. No	2. Yes
Ankles/Feet	1. No	2. Yes

If yes, please describe time, type, extent, duration, limitations on activity

____

____

APPENDIX 3 – ANTHROPOMETRIC DATA COLLECTED

Subject #: _____ Date: _______

Anthropometric Measures:

gender(M/F)	___________
stature (cm)	___________
weight (kg)	___________
wrist thickness (cm)	___________
elbow thickness (cm)	___________
knee thickness (cm)	___________
ankle thickness (cm)	___________
shoulder width (bi-acromial) (cm)	___________
trunk length (T1->L5) (cm)	___________
leg length (hip->ankle) (cm)	___________
inter asis (cm)	___________
biiliocristale (cm)	___________
upper arm link length (cm)	___________
lower arm link length (cm)	___________
included elbow angle (deg)	___________
forward arm reach (cm)	___________
standing shoulder height (cm)	___________
overhead arm reach (cm)	___________

APPENDIX 4 – BORG CR-10 RPE SCALE INSTRUCTIONS

All subjects were given the same instructions on the use of the Borg Scale. These instructions were repeated at the onset of each condition.

Instructions

Every five minutes, you will be asked for a global, shoulder, and low back rating of exertion and/or fatigue. For the global rating, you should consider your entire body as a whole and not focus on one specific area that may be fatigued, although if one such area exists, you should tell the experimenters. For the shoulder rating, you should focus only on the right shoulder. For the low back rating, you should focus on your entire low back.

The scale goes from 0 to 10, where 0 stands for "nothing at all", meaning that your body, shoulders, and low back feel as though you have done no work at all. In other words, if 0 is how you normally feel, then a rating of 0 would indicate no deviation from your normal state. You are permitted to use decimals. Be aware that ratings for any trial do not depend on previous ratings (later ratings do not necessarily need to be higher than earlier ratings).

When using the rating scale, always start by looking at the words to the right of the numbers and pick the word that describes the workload. Choose the number that goes with the word you picked. Tell the experimenter the number. Be as honest as possible.

Do you have any questions about using the scale?

APPENDIX 5 – TRAINING DAY PROTOCOLS

Subject #: ____ ***Date:*** _______

1.0 Forms, trial lists, and prepare payment ❏
2.0 Cut a 3-foot white paper for marking feet and fixture locations ❏
3.0 Strain Gauge calibration ❏
4.0 Configure Labview programs ❏
5.0 Check EMG amplifier (time constants = 110 msec) ❏
6.0 Informed Consent and Pre-test Questionnaire ❏
7.0 Clothing ❏
8.0 Anthropometric Measurements ❏
9.0 Fixture setup, positioning, and feet location ❏
10.0 Electrode prep, mark, and placement *(see Diagram)* ❏
11.0 Check interelectrode resistance (<10KΩ) ❏
12.0 Warmup exercises (~2 minutes + 2 minutes rest) ❏
13.0 Lumbar *RAMP* MVCs ❏
    13.1 Shallow breaths during rest trials
    13.2 Fold arms during torso extension, measure moment arm
14.0 Shoulder *RAMP* MVCs ❏
    14.1 Rest after trapezius trial
15.0 Practice Trials ❏
16.0 Redo Shoulder RAMP MVCs whenever needed ❏
17.0 Instruct subject about marks and exercise ❏
18.0 Schedule testing days ❏
19.0 Pay subject ❏
20.0 Calculate Test Weights ❏
21.0 Calculate Target Locations ❏

APPENDIX 6 – TESTING DAY PROTOCOLS

Day __ __ __ __ __ __ __ __

Subject # _______ **Date** __ __ __ __ __ __ __ __

Condition __ __ __ __ __ __ __ __

1.0 Lab Preparation

- 1.1 Forms, trial lists, fees for subject, etc. ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 1.2 Strain Gauge calibration ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 1.3 Fixture setup and positioning ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 1.4 Configure Labview programs ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 1.5 Prepare buckets and weights ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑

2.0 Subject Preparation

- 2.1 Verify no soreness or abnormal activities ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 2.2 Clothing ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 2.3 Electrode placement *(see Diagram)* ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 2.4 Check resistance ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑

3.0 Pre-testing

- 3.1 Subject bathroom break ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 3.2 Verify interelectrode resistance (<10KΩ) ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 3.3 Set EMG amplifier gains ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 3.4 Rest (>5 min) ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑

4.0 Testing

- 4.1 Warmup exercises (~ 2 min) ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.2 Baseline RPE values ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.3 Baseline MPF values using test weights (x3) ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.4 Lumbar rest &*RAMP* MVCs (Record force & RMS; x1) ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.5 Shoulder rest &*RAMP* MVCs (Record force & RMS; x1) ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.6 Run Task Configuration ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.7 Stop when any of MVCs is <75% or RPE >6 ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 4.8 Final Shoulder *RAMP* MVCs ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑

5.0 Post-Testing

- 5.1 Electrode marker instructions ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 5.2 Avoid abnormal shoulder activity and rest ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑
- 5.3 Confirm next session and pay subject ❑ ❑ ❑ ❑ ❑ ❑ ❑ ❑

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VITA

EDUCATION:

08/97 - 05/99 Virginia Polytechnic Institute and State University, Blacksburg, VA
M.S., INDUSTRIAL AND SYSTEMS ENGINEERING
Human Factors and Safety Option
Degree: *December, 1999*
GPA: 3.97

08/92 - 12/96 State University of New York at Buffalo - Buffalo, NY
B.S., INDUSTRIAL ENGINEERING
Degree: *May 1997*
GPA: 3.6

POSITIONS HELD IN COLLEGE:

08/98 - 12/98 Virginia Polytechnic Institute and State University, Blacksburg, VA
GRADUATE TEACHING ASSISTANT
Responsible for homework grading for Industrial Engineering undergraduate Work Design course. Clarified students' questions concerning engineering design problems or lecture material.

PROFESSIONAL EXPERIENCE:

06/99 - present Honda of America Manufacturing, Marysville, OH
CORPORATE ERGONOMIST
Participating in design and implementation of extensive ergonomics audits for two assembly plants. Participate in Ergonomics for Engineers training courses and Natural Teams training courses in which cross functional Teams analyze problem jobs and develop cost effective countermeasures. Learned to conduct four hour safety orientation course for new hires. Participate in design review activity for new models.

08/98 Titmus Optical, Petersburg, VA
ERGONOMICS CONSULTANT
Conducted an ergonomic audit in the manufacturing floor of a 300+ employees company. Suggested improvements to then current workstations and manufacturing problems. The suggestions resulted in the

creation of “operator-friendly” workstations and reduced the probability of product damage.

05/97 - 08/97 Delphi Harrison Thermal Systems, Lockport, NY
INDUSTRIAL ENGINEERING INTERN
Worked with joint programs (UAW-GM) to evaluate work systems and reduce/eliminate potential risks. Developed a QS9000 Ergonomics procedure for high risk job identification and correction. Assisted in development of Transitional Work Center for rehabilitating workers.

RESEARCH EXPERIENCE:

08/98 - 05/99 Virginia Tech, Blacksburg, VA
THESIS RESEARCH
Developed and conducted a study to determine effects of overhead work on a variety of subjective and objective fatigue measures. The thesis intends to provide a basis for further research in the factors related to the development of musculoskeletal disorders associated with overhead work in industry. Responsible for recruiting, scheduling, and coordinating participants and research assistants and for data collection using MaxReflex motion analysis system, LabView software, and surface EMGs.

PROFESSIONAL SOCIETIES:

- Human Factors and Ergonomics Society, *Virginia Tech Student Chapter*
  Treasurer *08/97 - 12/98*
- Institute of Industrial Engineers
- American Society of Safety Engineers

HONORS:

- United Parcel Service Fellow: *08/97 - 05/99*
- Alpha Pi Mu, *Virginia Tech Student Chapter*
- Tau Beta Pi, *New York Nu Chapter*

PUBLICATIONS:

Kirst, M., and Saleem, J. (forthcoming). An examination of the cognitive processes involved in mail sorting. Accepted for publication by Ergonomics in Design.