An Evaluation of Fatigue and Performance Changes During Intermittent Overhead Work

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ABSTRACT

This study examined changes in task performance while conducting a fatiguing overhead-working operation. The study was performed with the goal of producing research that will lead to a better understanding of the relationship between fatigue development during overhead work and task performance. This research provides a strong foundation that can help support guidelines and can be put towards a reduction of work related shoulder musculoskeletal disorders. Industrial tasks that require the hands to be at or above shoulder level have been shown to be contributing factors to the development of these disorders. The body of research examining the effects of muscle fatigue on performance, however, is relatively small. This relationship is important, considering that performance changes, or decreases in task quality, have the potential for justifying and driving ergonomic changes that can help to improve worker safety.

Much of the previous research related to this area has focused solely on static exertions. For purposes of this study, an experimental work task was designed to mimic the dynamic conditions typically found in overhead working situations. Sixteen participants participated in eight experimental conditions (two levels of duty cycles, two work heights, and two hand positions). Four dependent measures based on subjective, objective, and physiological fatigue were used to quantify shoulder fatigue and were collected during the experiment. An overhead working task required participants to use a hand tool to strike targets at two reach distances above their head. Task performance was measured as a function of the closeness to the target center and the ability to apply a consistent force throughout the experiment. Participants provided ratings of perceived discomfort and performed maximum voluntary exertions at specific intervals to determine fatigue levels

Data collected in this experiment is intended to provide a research basis for creating design guidelines that will help maximize efficiency and quality while reducing the likelihood of developing shoulder fatigue. Experimental findings indicated that duty cycle had the greatest effect ($P<0.0001$) on the fatigue variables. The 40-second duty cycle conditions ended an average of 62 minutes earlier than the 20-second duty cycle conditions. Duty cycle had a significant effect on seven out of the eleven individual fatigue measures. Arm elevation was found to have significant effects ($P<0.05$) on fatigue development as measured using both ratings of perceived discomfort and tapping hand force. Hand position affected ($P<0.07$) ratings of perceived discomfort and average tapping hand force. Only one correspondence was found between a performance measure and either a physiological or subjective measure of fatigue. A relationship ($r^2=0.571$) was found when comparing the ranked condition end times for tapping hand force and maximum exertion for the anterior deltoid.

The results of this study have been compiled as tables that can be used by practitioners to design tasks that both minimize fatigue and optimize performance. Task factors did affect fatigue times and are summarized within the text. With the current experimental conditions a correspondence between changes in performance and task variables was not found. Task variables and endurance time had no substantial effect on the occurrence of performance errors. It was expected that evidence of performance decrements could be linked to quality metrics and used to supplement cost justifications for task redesign. At this time, the results of this study do not provide evidence to support a relationship between quality metrics and fatigue development. Full study results and limitations are discussed in the document.

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As one wise man once said tap, tap, tap-aroo!

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Chapter 1. Introduction

1.1 Motivation

A major movement within the rapidly emerging global market has involved a shifting focus from low cost products to high quality, high value products (Drury, 1996). Specifically in the automotive industry where competition is fierce, consumers are looking for value priced products that perform at a superior level. In addition to customer driven demands, companies are "being made more responsible for good working conditions on the floor by government regulations, tight labor markets, and recognition of the value of a good employee" (Tuinzaad et al., 2000). To meet these demands, automotive manufacturers must find a manufacturing method that meets or exceeds quality standards while decreasing costs through optimizing manufacturing productivity, efficiency, and safety. Ergonomics plays an important role in designing systems and tasks that are capable of meeting these manufacturing goals. Design of successful work methods requires the use of ergonomic principals that best match human capabilities with job demands. A mismatch of this interface can increase expenses, thus affecting the net profit by causing human operators to make mental mistakes, work inefficiently, or work beyond their physical capabilities to the point of injury.

Ergonomic efforts in recent years have focused on reducing the forces required to complete typical manufacturing jobs. The result has been work cycles that are often highly repetitive and involve low to moderate force levels. Jobs are designed to be easy and repeatable, maximizing the quality and the throughput of the parts being produced. While it was thought that reducing the amount of force required to perform a task would have a substantial effect on reducing the frequency of injuries, it seems to only have shifted the types of injuries that are being developed. Highly repetitious tasks, even ones that require low to moderate force levels, may lead to an accumulation of stress which in turn may increase the likelihood of developing muscle pain (Jonsson, 1982). Accumulation of muscle fatigue that results in chronic muscle pain is commonly considered a causative factor and as a result can be used as a surrogate measure of work related musculoskeletal disorders (Herberts et al., 1976, 1981). Back injuries have long been recognized as the most frequently injured area on the body, however Kvarnström (1983) found that in light assembly operations injuries to the neck and shoulder were even more predominant. While the prevalence of work related muscle disorders (WMSDs) in industry is well known, there is a relative lack of research describing the dose-response relationship between known risk factors such as excessive force, number of repetitions, posture, and task duration and the development of WMSDs. The specific causes of WMSDs are thought to be multi-factorial. Interactions among risk factors may have an effect on the likelihood of injury but this relationship is not well defined in the literature. Exposure levels that will cause one type of disorder in one person may have a different effect on another person. Along with job related factors, individual factors such as gender, strength, age and motivation can also influence the exposure levels that are likely to affect the dose-response relationship.

The present study is based upon the assumption of a direct relationship existing between muscle fatigue and the risk of developing a WMSD. The specific assumption is that continued work with chronically fatigued muscles will increase the risk of developing an injury. While this assumption is commonly acknowledged, there is a need to explore the quantitative relationship between fatigue and injury (Valencia, 1986; Öberg et al., 1994). At present, little is known regarding exposure limits that will prevent injuries. Time to develop an injury likely depends on the physical requirements of the task and the amount of recovery time between fatiguing exertions. Fatigue research has been generally focused in quantifying fatigue times while performing prolonged static exertions, with considerably fewer investigations of tasks that are dynamic and intermittent. Providing empirical work design guidelines is a step toward reducing the high occurrence of injuries caused by the accumulation of fatigue attributed to performing dynamic work tasks.

The present study was designed specifically to examine how localized muscle fatigue affects the performance of an overhead work task that is representative of those commonly found in an automotive assembly plant. Studies have shown that working with the hands elevated may be the greatest contributing factor to developing localized shoulder discomfort (Hagberg, 1981; Herberts et. al., 1981, 1984; Wiker et al., 1989). Bjelle et. al. (1979) studied the relationship between reported cases of upper extremity pain and working posture. They found that in the majority of cases, people complaining of shoulder pain worked at or above shoulder height. Previous work has also indicated that the prevalence of overhead work in the automotive industry is most likely a contributor to the development of shoulder disorders (Hagberg, 1981; Herberts, et al., 1981,1984; Wiker et al., 1989).

While the need for this knowledge is increasing, the availability of specific ergonomic design guidelines is scarce. In particular, little research has been performed in the area of overhead work and even less is known about the interaction between overhead work task demands and the output quality. Some recent studies have examined how performing a task in a fatigued or tired state affects performance in tasks that have a high risk associated with cognitive errors such as surgeons, truck drivers or airplane pilots (Hartley, 1995; Berninger, 1991). Errors in an industrial setting often do not compare to the risks associated with these jobs, however they can greatly impact the quality of a manufacturing system and in turn the cost of the product being built. The research in this study is aimed at identifying the point at which muscle fatigue has a negative impact on the task being performed and providing work design guidelines that consider the balance between muscle fatigue, risk of injury, and task performance. There is currently a need for research that examines the relationship between injury development risk factors and performance levels. One of the primary objectives of the present study is to develop a tool. The results of this research should enhance the ability to design jobs that minimize exposure to the known work related risk factors and result in the optimization of two goals: minimizing the risk of developing musculoskeletal disorders and maximizing performance (quantity and quality).

1.2 Industrial Ergonomics

High costs associated with the occurrences of WMSD highlight the importance of ergonomics but the correlation between good ergonomics and increased performance may provide an even bigger cost motivator. The field of industrial ergonomics uses knowledge of human capabilities to evaluate task demands, with the goal to design or redesign jobs so that they are kept within the range of human capabilities, thereby minimizing the risk of injury and maximizing the quality. Good job design can lead to a reduction of musculoskeletal disorders, which in turn will result in a decrease in workers compensation costs, increased productivity, a decrease in lost time cases, and also reduced employee turnover. The rising costs of injuries have resulted in an increased focus on reducing the bottom line impact to manufacturing costs. According to recent statistics, work related musculoskeletal disorders (WMSDs) are the leading cause of both lost workday injuries and workers compensation costs (OSHA, 1999). Each year WMSDs account for more than $20 billion in workers compensation costs, 1/3 of the total money spent on workers compensation (OSHA, 1999). Work related musculoskeletal disorders seem to be more prevalent in certain industries. In 1989, motor vehicle manufactures were among the three industries with the highest rates of WMSDs (NIOSH, 1995).

Implementing ergonomic solutions can often be difficult to “sell” by only using probable injuries as a cost justification. Often, through ergonomic improvements, operators are able to perform their job easier and more efficiently, which also has a positive impact on the quality of the parts being produced and line efficiency. These additional improvements can often more than pay for the work system improvements that minimize risk of injury (Deveraux et al., 1998). As with any engineering change, the best and most cost-effective method of implementing ergonomic solutions is to do so early in the design phase. Proactive ergonomics allows engineering controls to be implemented when it is still cost effective to make major design changes. Making a major design change in a reactive manner, once a product is in production, is often not feasible. This problem is especially apparent in the automotive industry, where the product life cycle is relatively short and design changes must have an immediate impact with a short payback period. Ergonomic issues resolved in a reactive manor often result in administrative controls like work rotation and worker selection. However, administrative controls limit the exposure to the risk factors and provide a fix when engineering controls are not feasible. Implementing an administrative control may result in a more cost-effective solution but it can also be ineffective if not designed around human capabilities. The general lack of knowledge describing the dose response relationship contributes to the difficulty of designing workstations to human capabilities.

1.3 Muscle Fatigue

Fatigued workers or workers who are recovering from injury may be at a higher risk for developing a WMSD than well rested healthy workers (Putz–Anderson, 1992). This fact contributes to the theory that muscle fatigue is an indicator of likelihood of developing a WMSD, and that minimizing fatigue will decrease the risk of developing a WMSD. It is commonly accepted that minimizing the effects of fatigue is a part of good work design, yet the point at which fatigue contributes to the development of WMSDs is unknown. Fatigue is thought by some to be the body's natural protection against serious damage (Chaffin et. al., 1999), and the perception of fatigue is a principal part of the feedback loop that provides information regarding how much is too much. Ignoring the signs of fatigue can be harmful to overworked muscles (Oberg, 1994). Through further examination of the relationship between fatigue and the development of WMSDs this point will better defined.

The term localized muscle fatigue is used to describe fatigue that limits the muscular capabilities of a single muscle or group of muscles performing the exertion (Rohmert, 1973; DeLuca, 1994). Chaffin (1973) characterized local muscle fatigue as the inability to sustain a desired force, the appearance of muscle tremor, and pain in a localized group of muscles. The pain and reduction in force generating capabilities associated with muscle fatigue results from a variety of physiological changes that occur within the muscle. Localized muscle fatigue may be a result of insufficient blood flow to muscles caused by an increase in intramuscular pressure (Rodbard et al., 1968; Chaffin, 1973;

Fitts, 1996). A reduction in blood flow decreases the supply of energy (oxygen) and leads to an accumulation of metabolites. Muscle fatigue develops gradually over time during a constant task using low to moderate force levels typical of those tasks found in modern assembly plants. The muscle is considered to have reached its failure point when it is no longer capable of maintaining a desired force (Rohmert, 1973). This failure point is well defined for static muscle loads, but considerably less is known about the development of muscle fatigue during low force intermittent and dynamic tasks. Fatigue of this type, however, is common in occupational settings and is characterized by long recovery times (Chaffin, 1973).

Existing literature provides fatigue curves, mostly for static postures, presented in terms of time until exhaustion (e.g. Putz-Anderson, 1992). Exhaustion times are generally not helpful for design purposes because often the level of discomfort reached before exhaustion will impede a workers ability to perform the task. Any damage caused by working with excessive fatigue may have already occurred before the exhaustion point has been reached. At the point of exhaustion, damaging micro traumas are likely to have already begun to accumulate and may result in a cumulative effect from repeated performance of a task. Valencia (1986) suggested that one method of preventing muscle fatigue is to provide guidelines in terms of work and rest cycles. If activities causing fatigue are continued without proper time to recover, chronic pain can develop (Chaffin et al., 1991). The body is generally able to recover from changes due to fatigue if given sufficient rest (Armstrong, 1993), but the amount of rest needed depends on the level of fatigue accumulated, task demands, and individual factors like fitness and motivation.

Optimal ergonomic guidelines will enable work designers to define tasks that will provide rest periods prior to reaching the exhaustion point. Rohmert (1973) quantitatively described the onset of muscle fatigue for static postures and constant loads. Rohmert’s curve (Figure 1.1) shows that exertions with a low level of exertion (15-18% of the maximum voluntary exertion, MVE) could be held for an indefinite amount of time. More recent research has shown that even low-level exertions have an endurance time (Corlett and Manenica, 1980). Chaffin (1973) showed that sustaining low-level exertions (15% of MVE) either with prolonged exertions, or with frequent contracts followed with very little rest, does result in a decrease of the force producing capabilities of that muscle group. Considerably less is known about the time to fatigue for intermittent low exertion level (10-20% MVE) dynamic movements. Sjøgaard (1986) found that even efforts as low as 5% MVE can lead to the onset of muscle fatigue. With the majority of work tasks being designed to use moderate to low force, it is clear that a better understanding of the development of fatigue in this region must be developed.

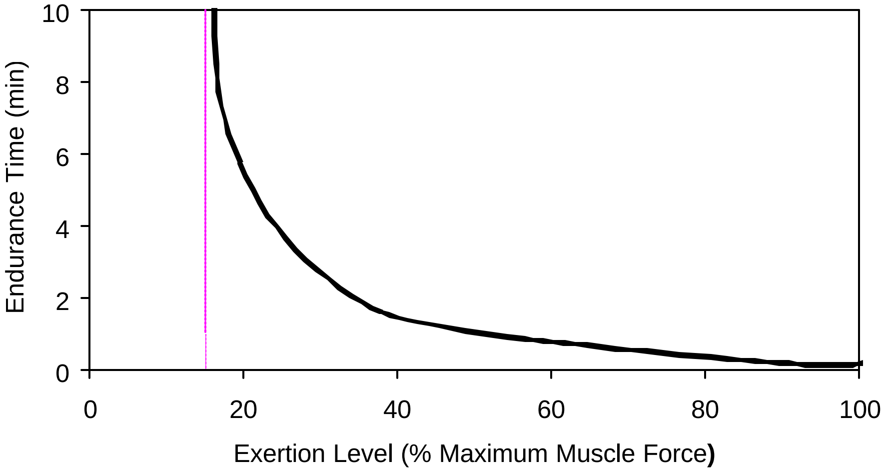


Figure 1.1. Rhomert's curve (from Rhomert 1968). A depiction of static muscle endurance as a function of percent of maximum exertion.

Results in the literature also show many variations on the mechanisms and definitions of fatigue (Vollestad, 1997). This lack of consistency leads to differing models, protocols, and methods for describing fatigue. As discussed above, fatigue can be defined as a reduction in the maximal capacity to generate force. The adverse effects of fatigue include discomfort, deterioration in skilled motor performance, increased risk for manual mistakes, and even accidents (Hagberg, 1981).

Bills (1943) classified fatigue into three different categories. The first category is subjective fatigue and is characterized with a decline of alertness, mental concentration, motivation, and other psychological factors. The first perceived symptom of muscle fatigue is typically discomfort (Valencia, 1986). Subjective measurement of muscular discomfort may thus be the most effective measurement of intermittent low-level tasks (Borg, 1970; Öberg et al. 1994). Muscular discomfort may also lead to the adoption of postures that pose a secondary risk for developing a WMSD. Putz-Anderson (1992) found that people experiencing localized muscle fatigue would adapt their work postures in an attempt to displace the workload from the overworked muscles to less fatigued tissues.

Bills' second category of fatigue, objective fatigue, is characterized by a decline in work output. There have been relatively few research studies done using performance measures to quantify fatigue, though it may have the greatest impact on industry. A reduction in performance can result in quality problems thus directly affecting the end product. Correlating fatigue development to a decrease in performance will provide a method of predicting cost benefits for ergonomic improvement. Lance et al. (1971) showed that muscle fatigue had negative effects on task performance. In their study, it was found that performing a precision task required increased time in a fatigued state, participants overestimated light loads, and limited participant's ability to accurately hit targets (target overshoot). These performance changes were attributed to the development of muscle tremor, an involuntary response to physiological changes in the muscle brought on by fatigue. Laursen et al. (1998) showed that increased precision demands caused increased loads on the muscles involved, particularly on stabilizing muscles. They suggested this was because movements made when precise accuracy is needed are more jerky than when little accuracy is needed. Hammarskjöld et al. (1992) concluded that after having participants perform a fatiguing arm exercise there was no effect on the amount of force applied to perform a familiar task, the pace of the task slightly changed, but the quality of the work performed in the fatigued state was inferior. Hammerskjöld et al. (1992) also found that the effects of cumulative muscle loading impacted a participant's performance of precision movements.

The third category of fatigue that Bills describes is physiological fatigue, characterized by physiological changes in the muscle activation process. One common method of objectively measuring physiological fatigue is to use electromyography (EMG). Fatigue generally manifests in spectral shift in the EMG and can be observed as a decrease in the mean power frequency and an increase in the signal power (De Luca, 1984). A second method to measure physiological changes in the muscle brought about by fatigue is to measure maximum force generating capabilities. As fatigue accumulates the tension producing mechanisms in the muscle deteriorate and cause a decrease in the maximum tension that the muscle can produce (Chaffin, 1973).

1.4 Shoulder Disorders

While costs associated with low back and wrist pain may account for the majority of injury costs, shoulder disorders are becoming more prevalent (Herberts et al., 1984) and rank behind only neck and back pain in clinical frequency (Cailliet, 1981). Movements and postures common to performing overhead work can lead to the localized shoulder fatigue (Hagberg, 1981; Herberts et al., 1981,1984; Wiker et al., 1989). It is believed that accumulation of fatigue can lead to injury development. Bjelle et al. (1979) studied the relationship between reported cases of upper extremity pain and working posture. They found that in the majority of cases, the people complaining of shoulder pain worked at or above shoulder height. As discussed previously the amount of ergonomic risk is determined by the interaction of the force, posture, and repetition needed to perform the task. Injury development during overhead work may be more influenced by certain task requirements more than others. Arm posture can be considered a major risk factor for developing shoulder fatigue because arm postures contribute to increased muscle load independent of the hand load. Repetitive arm elevations and the degree of upper arm elevation, not necessarily hand load, seem to be the most significant factors influencing shoulder muscle load (Hagberg, 1982; Selvick, 1974). With an increase in muscle load there is a corresponding increase in the probability of developing chronic shoulder pain (Herberts, 1984).

Kadefors et al. (1976) studied localized shoulder muscle fatigue in a group of welders, to identify causative factors in the development of chronic muscle fatigue. Three groups of welders were studied: inexperienced, experienced, and elderly. During work at shoulder level there was no evidence of fatigue found in any group. In overhead work, however, there was significant fatigue found in the inexperienced welder's deltoid, supraspinatus, and trapezius muscles. The experienced and elderly workers also showed fatigue in the supraspinatus muscle. This led to the conclusion that through training and improved work techniques welders were able to perform a task with less muscle fatigue than inexperienced welders. Even with proper work techniques, muscle fatigue is still prevalent in this type of overhead work. Fatigue developed by the experienced and elderly workers can be attributed to the difficulty of the task and not due to improper work methods.

1.5 Fatigue Measurement

In this experiment, fatigue has been measured in three ways: subjectively through the use of rating scales, with changes in task performance, and objectively through physiological changes in the muscle. Due to the complexity of the fatigue process, it is difficult to define fatigue using only one measurement. Therefore, fatigue as measured in this study, will be classified into three different categories (Bills, 1943):

1. Subjective Fatigue: feeling of discomfort and pain.
2. Objective Fatigue: changes in work output.
3. Physiological Fatigue: physiological changes in the muscle activation process (the ability to generate a maximum force).

The following sections discuss common measurement methods for each of these three fatigue classifications.

1.5.1 Subjective Fatigue: Ratings of Perceived Discomfort

Psychophysical methods of quantifying task demands are common in the field of ergonomics. There are typically difficulties in directly assessing the levels of exertions for manual work tasks due to the complexity of movements and a lack of exposure guidelines. Objective measures of fatigue are often more difficult to collect and interpret while providing little difference in the quality of the data (Grant et al., 1994; Borg, 1970). In addition to being easy to collect and interpret, changes in discomfort may be the first indicators of fatigue and occur prior to physiological changes (Valencia, 1986). Borg (1970) also noted that subjective ratings were important because perception of discomfort may result in performance changes regardless of whether the discomfort has manifested in physiological changes within the body. Subjective fatigue measures may even be the preferred method of gauging a global shoulder fatigue due to the complex structure of the shoulder girdle (Putz-Anderson, 1993).

Borg (1982) developed a 10-point rating scale with ratio properties (Figure 1.2), which is commonly used in a variety of situations to facilitate quantifying subjective perceptions of discomfort. The scale has numerical ratings as well as verbal anchors. Advantages of the scale include the ease of use, effectiveness in evaluating intermittent tasks (Borg, 1970), repeated reliability, and correspondence with effort level.

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 1.2. Borg General Scale (From Borg, 1970)

The disadvantages associated with this scale are inherent to most subjective measurement devices. Participants are often not able to differentiate between the variable being measured and the entire work task. For example, recent research has found that ratings are influenced by previous experience and motivation (Kilbom, 1990) and that highly motivated participants tend to underestimate their exertion level. Individuals may also interpret the scale differently making it difficult to compare intersubject data. However the high correlation rate (r = 0.92) between mean power frequency shifts (an objective measure of muscle fatigue) and measures of perceived exertion provides evidence for the validity of the scale (Hasson et al, 1989).

1.5.2 Objective Fatigue: Performance

The use of measures of performance to quantify fatigue is not as common in the literature as the other two fatigue measurement methods. There have been studies that have recognized that cumulative muscle loading can inhibit the dynamics of future movements, but provided little quantitative data (Heide and Molbech, 1973; Jaric et al., 1988). Studies have found that the onset of localized muscle fatigue lowered a person’s ability to perform a skilled motor task (Lance et al., 1971; Grandjean, 1969; Sharum et al., 1970). A loss of precise and coordinated movements can often result in a negative impact on the output quality. Typical performance decreases that have been associated with localized muscle fatigue are an increase in the amount of time it takes a person to perform a variety of tasks and an increased likelihood of overestimating light loads (Chaffin, 1973). Chaffin (1973) also suggested that a clear relationship between localized muscle fatigue and an effect on performing manual tasks is not well defined.

Hammarskjöld et al. (1992) had participants perform a fatiguing arm exercise at 70-80% of their maximum effort and then perform a carpentry task that was measured on time and quality. This experiment used a fatiguing task that was independent of the performance evaluation task. The number of errors committed and the amount of time it took to perform the task were measures of quality. Three physical work tasks, hammering, screw driving, and sawing, were analyzed. Participants performed these tasks on a regular basis and were considered expert users. After performing a fatiguing exercise, participants made more misses while nailing and deviated more frequently from the pre-markings during the sawing task. There was no change in the screw-driving task during the fatigued condition. Previous research (Carlsöö, 1986; Hammarsköld et al., 1990, 1992) has found that participants used the same amount of force in the fatigued and prefatigued conditions.

Performance measurement has the advantage of providing data that can be directly translated to key measures that will help to justify ergonomic improvements in addition to injury avoidance. Performance decrements can affect the quality of parts leaving the workstation and have an impact on the entire work system (efficiency, defects, scrap rate, etc.). One disadvantage associated with this data collection method is that changes in accuracy may represent psychological fatigue changes derived from boredom (De Luca, 1984). Lack of interest in the task may show similar performance changes that could also be attributed to a deterioration of the muscle condition. A second disadvantage is performance-based measurements of fatigue may be difficult to collect and interpret for certain tasks. Data collection methods may require expensive and inhibiting motion analysis systems. Hammarskjold's (1992) study provided very distinct and narrow quality acceptance criteria, however, many quality issues can prove to have less concrete definitions for failure, thus making it more difficult to interpret the data. For example, in the Hammarskjold study the task was designed such that operators were given real-time continual feedback, but in a typical manufacturing environment an operator may be given a task with less concrete quality parameters. A typical assembly task may be to attach two clips to make an electrical connection. Without use of a computer, the operator has no way of ensuring the connection has been properly seated. When quality targets are difficult to receive feedback on operators may use force that is greater than necessary, or may push the connection together multiple times to ensure a proper connection. Performance data taken on a system with little continual feedback will provide more realistic data.

1.5.3 Physiological Fatigue: Maximum Voluntary Exertion (MVE)

An MVE can be defined as the maximum force generated while an individual is encouraged to perform at a maximum level. Measuring MVE is a direct measurement of localized fatigue and is generally accepted as a standard (even 'gold' standard) method of measuring fatigue (Vøllestad, 1997). On a cellular level, fatigue can be caused by the impairment of action potentials to elicit a muscle twitch (Fitts, 1996). Byproducts in the form of lactic acid inhibit the amount of calcium ions released at the sacrolemma, and therefore fewer cross-bridges are formed which results in decreased tension generating capability (Fitts, 1996). With the onset of localized muscle fatigue, the muscle is not capable of generating as much force, thus maximum exertion capabilities are reduced. This fact is particularly important for work designers to keep in mind while designing tasks that work at a certain percentage of the MVE. A task that is designed to work in the 20% MVE range during hour two of the workday will require a greater percentage of MVE to perform the same task in hour seven of the workday due to the onset of fatigue and reduced strength capabilities.

Maximum force generating abilities can vary greatly depending on individual factors, such as motivation (Vøllestad, 1997). To control for this, participants should be encouraged to perform at their highest level and encouragement should remain constant through out the entire testing condition. Due to the quick (within 2 minutes) recovery of force generating capabilities (Fitts, 1996), it is important to obtain the measurement directly after performing the task. This is often difficult due to necessary controls noted above. Resting time between the exertions may provide the muscle with enough time to increase blood supply and delivery of nutrients to the muscle, thereby minimizing the fatigue effects. However, when the effects of fatigue accumulate, the amount of rest needed to recover increases. The physiological changes in the muscle fibers due to fatigue result in decreases in the maximum force generating capability of a muscle. When participants are given adequate practice, motivation, and occur directly after the task, MVEs provide a reliable method of evaluating the maximum force generating capabilities of the muscle with low intrasubject variability (Bigland-Ritchie et al., 1983).

1.6 Gaps in the Literature

Existing research has provided relatively little information in three main areas: development of fatigue while performing intermittent work, overhead work guidelines, and the effect of fatigue on task performance. This study is aimed at bridging those gaps and creating a body of research to help create practical work guidelines for intermittent overhead work. Discussed below is the most relevant current research in these areas.

Fatigue Development with Intermittent Work

There is a great deal of literature relating endurance time with sustained isometric exertions (e.g. Rohmert, 1960; 1973; Björksten et al. 1977). This research, however, leaves a large void in describing muscle fatigue caused by the low to moderate exertion levels (10-20% MVE) that are common to most industrial tasks. Low level, long lasting, intermittent or dynamic exertions have been suggested to be non-fatiguing when the tension exerted is less than 10-15% of MVE. Rohmert's early work has been interpreted to suggest that intermittent tasks at this level, common in today's industry, are non-fatiguing (Jonsson, 1978; Petrofsky and Phillips, 1982). More recent research suggests that even minimal loads (5-10% of MVE) cannot be sustained past one hour without rest breaks (Sjøgaard et al., 1986). It is evident with the prevalence of work related muscle fatigue, that an accurate work design tool is not available. The relationship between the duration of intermittent low level tasks and recovery time is not well defined. Thus, localized muscle fatigue has not been quantified in a format where industry has been able to make a positive impact on the design of work systems.

Overhead Work

The risks of overhead work are well known in the literature, however many industries still rely heavily on manual overhead work in the assembly process. Wiker et al. (1989) lists a number of studies that have shown shoulder abduction and flexion, movements common to overhead working postures, to be the most significant factor related to the development of shoulder disorders in industrial workers. Practical data is needed that will allow industries to evaluate specific overhead working situations. There is a general lack of knowledge relating the dose of overhead work and the development of a WMSD. Much of the research generated to develop design tools has used muscle fatigue as an indication of the likelihood of developing a WMSD. Previous overhead fatigue research has been focused on static postures making it difficult to generalize the results to more realistic dynamic work situations. This study will provide information relating work postures, work height, work duration, and recovery times during intermittent overhead work with the likelihood of developing localized muscle fatigue and the effects of fatigue on performance.

Task Performance with Fatigue Development

Information showing the effects of fatigue on performance is relatively scarce. One possible explanation is that the evaluation of performance is somewhat subjective. For example, it is difficult to quantify the performance of a painter or to account for all of the variables involved with installation of an exhaust system. Performance data can also be unrealistic unless a realistic work situation is simulated with actual acceptance/failure tolerances. Previous studies involving the measurement of performance have had the fatiguing tasks be performed prior to, and independent from, the task being used to measure performance. In more realistic situations, the fatiguing task will be the task that is quality dependent. For example if an operator is working overhead performing hose connections, the fatiguing task (working overhead) and the quality dependent task (ensuring hoses are connected) are occurring at the same time. By simulating real work situations, practical data can be obtained to design work systems aimed at minimizing the risk of developing shoulder fatigue and increasing the quality of the task being performed.

Previous research has supported that precision abilities decreased, even prior to fatigue development, while working in conditions above the shoulder (Wicker et al, 1989; Lance et al., 1971; Grandjean, 1969; Sharum et al., 1970). Other researchers have found no difference in task performance between work performed at waist level and work performed at chest height (Konz, 1967; Barnes’s, 1940; Ellis, 1951) however few have examined this relationship at differing work heights above the shoulder. Astrand (1968) expanded on the earlier work performed by Konz, and found that when the work surface was raised above the shoulder there were more substantial precision decrements than were found at chest height. Results produced from the present experiment further examined the effects of fatigue on performance while working above shoulder height.

Chapter 2. Research Objectives

2.1 Rationale for the Study

This study was designed to examine the relationship between the development of localized muscle fatigue and the effect it has on task performance, specifically during overhead work. With a more defined relationship between performance decreases and an increase in risk, work design practitioners will be able to more easily justify ergonomic fixes through positive impacts on multiple key measures. Repetitive work with the arm extended overhead, even with light loads, can contribute to localized shoulder muscle fatigue. While the exact cause of WMSDs cannot be identified, it is recognized that localized muscle fatigue has a strong relationship to the development of these injuries. Therefore, muscle fatigue can be viewed as a surrogate measure of injury risk and efforts should be made to minimize the risk of developing localized muscle fatigue in designing work systems. This study provides data describing the relationship between task duration and the onset of muscle fatigue. Multiple independent measures of fatigue were used to quantify the development of fatigue. Subjective fatigue evaluations, physiological changes in the muscle, and performance output were all used as fatigue measures. Significant changes in these measures identified work durations, under specific task characteristics, that are likely to contribute to WMSD development or have negative effects on quality.

The study was designed to simulate the actual working conditions present in an automotive assembly plant. Repetitive overhead work is common in the automotive industry and has been identified as a likely contributor to the development of shoulder WMSDs. Overhead working conditions in the automotive industry were studied to determine typical work surface heights, work postures, work cycle durations, and recovery times. It is expected that the automotive industry, along with others, can use the data collected in this study to optimize overhead work systems to minimize the risk of injury development and maximize output quality. Quantifying this relationship will help to provide a correlation between a decrement in work capacity (onset of fatigue) with a decrement in work output (performance). Results from this experiment can also be used as initial data describing the relationship between exposure to WMSD risk factors common in overhead work tasks, and the probability of developing muscle fatigue. Expanding these initial findings will provide data to generate practical guidelines that can be used for design and evaluation of overhead work system.

2.2 Experimental Goals

This study was performed with two main goals. The first goal was to provide an initial quantification of human capabilities in performing overhead work. The study specifically addresses overhead working conditions that are present in modern automotive assembly plants. Work tasks were characterized in terms of work height, posture, and work to rest ratio. Using this data, work systems can be designed and evaluated based on human capabilities. In the future, this will help reduce shoulder muscle fatigue attributed to working overhead. The second experimental goal was to evaluate the effects of fatigue on performance. Industry may consider performance to be the most significant measure of fatigue because it has a direct impact on quality. At the beginning of the experiment it was expected that the onset of fatigue would have a measurable effect on task performance and that results from the study would quantify the relationship between fatigue development and performance decrement. The study specifically tested two hypotheses:

Hypothesis #1: Task factors (duty cycle, hand orientation and arm elevation) will affect fatigue times for one or more measures of fatigue.

It was expected that fatigue would happen earliest in conditions that contain a 67% duty cycle, arm elevation at 75%, and hand position supinated. Analysis of variance testing was performed to test for an effect caused by the task variables. An affect is considered significant when $P \leq 0.1$.

Hypothesis #2: Changes in task performance will correspond with changes in fatigue measures.

It was expected that objective fatigue measures of task performance, would show correspondence with subjective and physiological fatigue measures. As fatigue accrues it was expected that performance decrements would increase. Performance decreases would be shown with the increase in the number of errors and an increase in the amount of force used to perform the task. Regression analysis was performed to test this effect.

Chapter 3. Experimental Methodology

An experiment was designed to mimic the dynamic and intermittent overhead working conditions that are present on automotive assembly lines. The task was intermittent, paced, and lasted no longer than three hours. The main task had participants perform a tapping motion with a small hand tool between two overhead targets. Data was collected at specific intervals while the task was being performed. Performance (task accuracy), subjective reports of fatigue, and physiological changes in the muscle were all measured and used as indicators of fatigue.

3.1 Participants

The participants in the study consisted of 16 participants, 8 male and 8 female. Participation in the experiment required extreme time demands so efforts were made to minimize the number of participants. With the use of 16 participants a Latin Square design could be used to provide treatment order conditions. Due to equipment limitations only right-handed people were included. All participants were between the ages of 18-22 and were recruited through advertisements on the campus of Virginia Tech. Participation was restricted to those who had a moderate level of athletic activity determined by a questionnaire. Perspective participants with extremely low or high activity levels were not used because they were not representative of the target population. Participants must have been free of recent (within two years) injury and pain in their shoulders and backs. A diagnosis of abnormal physical conditions like heart conditions, diabetes, high blood pressure, etc. made a person ineligible for the subject pool. Participants completed a Subject Survey (Appendix 2) stating they complied with all of the above conditions. Participants were paid six dollars per hour at the end of each session with a $20 bonus after the completion of all nine conditions (1 training, 8 testing). Descriptive data for the participants is provided in Table 1. All participants completed an informed consent procedure approved by the VT IRB.

Table 1. Participant anthropometric data and target heights.

	Stature (cm)	Body Mass (kg)	Shoulder Height (cm)[1]	Arm Reach (cm)[2]	Target Height: 50% (cm)	Target Height: 75% (cm)
Mean	171.6	69.4	144.8	211.1	187.7	204.3
Std. Dev.	9.7	12.0	8.9	16.9	12.4	14.5
Range	158.5-187.5	50.0-89.0	133.5-159.0	190.0-253.5	172.5-216.3	186.3-240.0

[1] measured from the floor to superior aspect of acromion

[2] measured from the floor to the center of a thin hand held rod with the arm fully extended overhead

3.2 Tapping Task

Participants were asked to alternately tap two overhead targets. Participants held a small wand-like tool (Figure 3.1) in their right hand. The tool had a mass of 0.36 kg, comparable to the smallest tools that are typically used on assembly lines. Two targets were mounted on a wall, parallel to the floor, and represented by circles with a diameter of 3.3 cm. Targets were placed 50cm apart, a distance equal to average shoulder span. The vertical height of the targets was normalized to an individual's actual height and overhead reach (Appendix 3). Tapping heights were varied between 50% and 75% of the overhead arm reach. The task was paced with a computer-generated tone that signaled every 0.75 seconds. MTM standards based on target size and distances were used to generate task pace. Participants were instructed to tap on the tone and to hit the center of the target represented by a small dot.

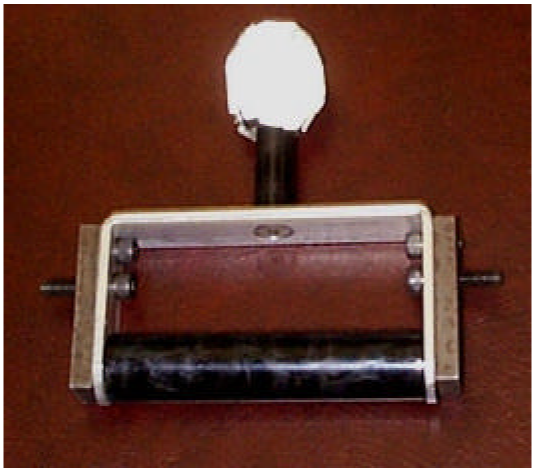


Figure 3.1. Tapping tool, made of plastic and aluminum. Weights were placed on the sides and a reflective marker was placed at the tip.

3.3 Experimental Design

Data collection and testing was conducted in the Industrial Ergonomics Lab at Virginia Tech. The experimental design employed the use of two Latin squares, one for each gender, to assign treatment order. Tasks were modified by manipulating three independent variables (1) target height, (2) hand position, and (3) duty cycle, each at two levels. Use of a Latin square design, where each level of a treatment both proceeds and follows each level of treatment an equal number of times, allowed for control of potential confounding due to treatment order. A work cycle of one minute was used to replicate those typical in automotive assembly plants. The work rest ratio (duty cycle) was either 67% or 33%.

3.4 Independent Variables

Variables were manipulated to account for and represent the variety of conditions common in overhead assembly tasks and to create an initial database of differing overhead-working conditions. Table 2 presents the eight treatment conditions with the corresponding independent variable levels.

Table 2. Experimental Conditions

Treatment Condition	Arm Extension	Hand Orientation	Duty Cycle (work duration)
1	50%	Pronated	67%
2	50%	Pronated	33%
3	50%	Supinated	67%
4	50%	Supinated	33%
5	75%	Pronated	67%
6	75%	Pronated	33%
7	75%	Supinated	67%
8	75%	Supinated	33%

Participants worked at a height that required their arm to be extended either 50% or 75% of their overhead reach (Figure 3.2). The arm extension variable provided data to characterize human capabilities at differing working heights. This height was calculated from the height of the acromial process to the overhead grip of a small rod (Figure 3.3). Hand orientation was either supinated, with the right hand rotated so that the palm is facing the participant, and pronated, with the right palm facing toward the wall. Pronation is common in tasks such as installing wire harnesses or simply holding a part overhead, and supination is more common when a tool is used. These two positions were chosen as representing the postural extremes that are present in overhead assembly tasks. The third independent variable was the duty cycle that varied between 33 and 67% of the work cycle. These ratios were chosen to reflect those typically found in automotive assembly tasks. They also provided anchors at the extremes of the exposure scale, 33% relatively low exposure limits and 67% relatively high exposure limits.

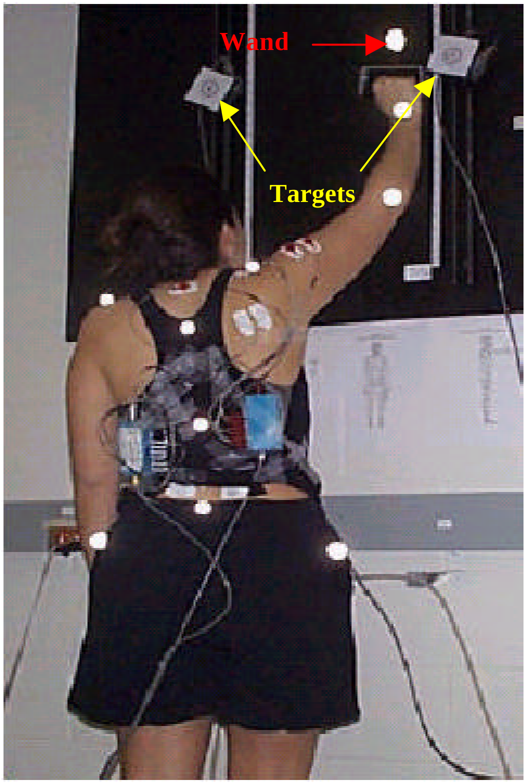


Figure 3.2. Participant performing the tapping task at 75% arm elevation with a pronated hand posture.

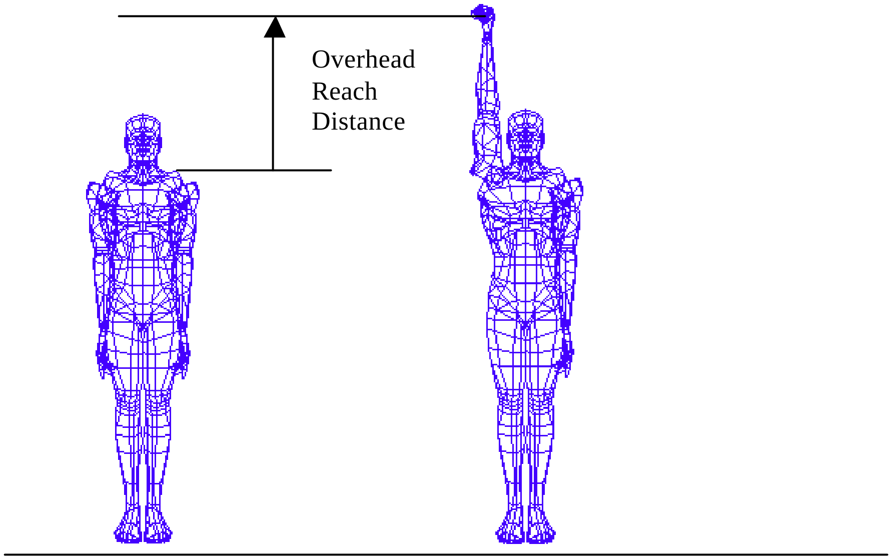


Figure 3.3. Postures and distances used in determining target height.

3.5 Dependent Variables

Multiple measures of fatigue were used to provide a comprehensive indication of fatigue. Dependent variables were used to quantify three different aspects of fatigue; subjective measures, physiological measures, and objective measures (performance). In addition to these, maximum endurance time was recorded as a dependent variable.

3.5.1 Subjective Measures

Subjective fatigue was measured based on Borg's General Scale (Borg, 1970; Figure 1.1). Participants assessed their level of fatigue by giving their Ratings of Perceived Discomfort (RPD). Prior to starting the task on each testing day participants were instructed to give RPDs. If the values were not zero and the reason was due to an acute injury or residual fatigue participants were asked to reschedule the session. Participants were instructed to orally provide ratings of their level of localized right shoulder discomfort. RPDs were recorded after every fifth cycle (5 minutes), and were given as numbers based on the Borg General Scale (Borg, 1970, Figure1.1). Decimal values were encouraged to provide a more accurate rating of subjective fatigue. Participants were instructed that each subjective rating should be independent from previous cycles and testing days.

3.5.2 Physiological Measures

Maximum force generating capabilities were measured by having participants perform maximum voluntary exertions (MVEs). MVEs were performed and measured prior to work cycle one, at the end of every tenth work cycle (ten minutes), and at the end of each testing day. Participants were constrained in a fixture (Figure 3.4) where their posture (Figure 3.5) was controlled to obtain the isometric MVE for the following right shoulder muscles: middle deltoid, trapezius, anterior deltoid, and infraspinatus. These muscles were chosen because a literature review suggested that they were among the primary muscles used in overhead work. Pilot studies showed general discomfort and physiological signs of fatigue in these areas. In addition, these muscles were chosen for their ability to be isolated during the MVE exertions, and because each muscle controls a different degree of freedom in the shoulder joint. The anterior and middle deltoid along with the trapezius are the primary movers of the upper arm and enable the shoulder joint to have a wide range of motion with three degrees of freedom. Testing the middle deltoid allowed evaluation of changes in the muscle caused by arm abduction. Changes in the anterior deltoid quantified the muscle fatigue attributed to shoulder flexion. Muscle fatigue caused by shoulder elevation (shoulder shrug) was measured through changes in the trapezius muscle.

On the training day the general procedure for performing MVEs was explained and practiced. After the tenth work cycle participants were asked to move quickly to the propositioned fixture to perform a set of MVEs (one exertion per muscle). Participants were instructed to gradually ramp up to a maximum, and then once they have attained their peak value gradually ramp down. Exertions were sustained for between three and five seconds. It was also emphasized that there should not be any jerking motions (slope to reach maximum was too steep) to allow for an accurate reading of the maximum strength capabilities. Forces were monitored on-line and if the exertion was too short, a clear peak was not obtained, or a jerky motion was used, the exertion was repeated after a brief rest break. Prior to each exertion, verbal encouragement was given to exert the maximum efforts at each MVE trial. MVEs were performed for each of the four shoulder muscles in the same order each time 1) middle deltoid, 2) trapezius, 3) anterior deltoid, 4) infraspinatus. Exertions that were repeated were performed after the initial four exertions were completed.

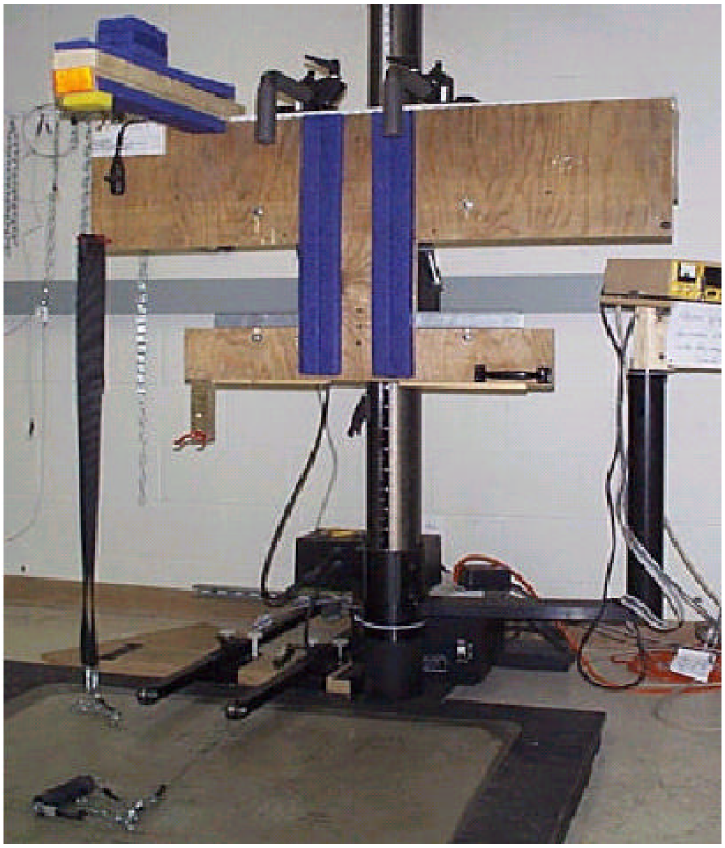
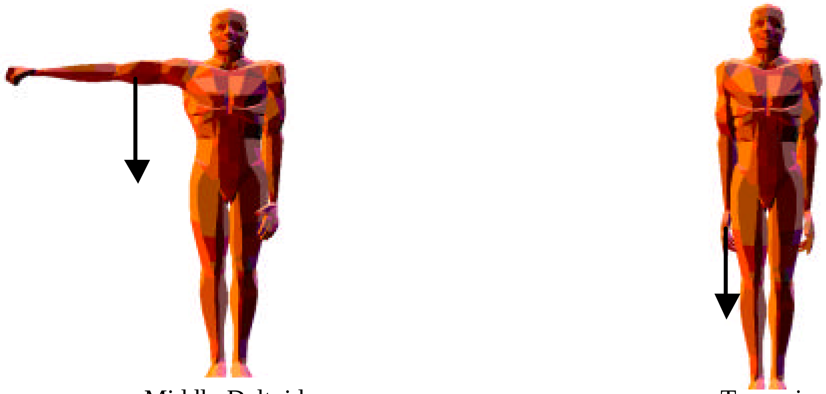


Figure 3.4. Testing fixture. The height adjustable fixture was designed to hold the shoulders against the rigid backboard. A system of straps, chains, and pulleys were used to connect handles to force transducers.



Middle Deltoid

Trapezius

Anterior Deltoid

Infraspinatus
Arrow direction is into the page

Figure 3.5. Isometric Postures for MVE testing.

3.5.3 Objective Measures

Performance was measured to quantify the quality of work output. Performance was described by two dependent variables, task accuracy and tapping force. Task accuracy was measured with a spatial positioning system. Cameras tracked the position of the wand relative to the targets and measured the difference in the wand location and the center of the target. Tapping force was recorded with force transducers mounted behind each of the targets. Procedures and systems for measuring target and wand position are described below.

3.5.4 Endurance Time

Endurance time is the amount of time the participant performed the experiment without out feeling significant, prolonged localized discomfort in the shoulder (participant chose to stop due to level of discomfort). Each session lasted a maximum duration of three hours. If a participant was able to perform the task for three hours it was assumed that the participant could perform that task for an indefinite amount of time. Endurance times were also determined at the time the participant stopped the session. Guidelines for stopping the sessions are discussed in section 3.8. Specific statistical procedures (i.e. non-parametric tests) were used in order to evaluate the data based on the fact that there was an artificial limit (3 hours, as described below) set due to experimental limitations.

3.6 Experimental Procedures

The experimental design required participants to come into the laboratory a total of nine times, one training day session and eight testing day sessions. Information collected on the training day was used to determine the configuration of the workstation that was used on testing days.

3.6.1 Training Day

Participants completed a short survey regarding previous injury (Appendix 2). It was explained that they were free to withdrawal at any time for any reason without penalty. Participants were asked to change into the clothes that were provided at the beginning of each testing session. Anthropometric data was taken and recorded on standardized forms (Appendix 3). A specialized fixture was fit to the individual and positions were recorded to allow for setup prior to subsequent testing days. Maximum voluntary exertions (MVEs) were measured and were used to compare with the data collected on testing days. The simulated work task was explained and practice was provided so the participant had a clear understanding of expectations during testing days.

3.6.2 Testing Days

Testing days began with the participant performing a set of baseline MVEs, following which they started the tapping task. A work cycle consisted of a one-minute interval where the subject performed one segment of tapping overhead (either 20 or 40 seconds) and then rested for the remaining cycle time (either 40 or 20 seconds respectively, Table 3). Subjective fatigue ratings and performance data was collected during every fifth work cycle. MVEs were recorded after every tenth work cycle. Participants were free to stop the task at any time due to physical discomfort, but experimenters stopped the task after 3 hours or if safety criterion described in section 3.8 had been met.

Table 3. Description of Work Cycles

Work Cycle Number	Work Cycle Description
1	Tapping task Rest
2	Tapping task Rest
3	Tapping task Rest
4	Tapping task Rest
5	Tapping task Applied force measurement and spatial positioning recording the last ten seconds of the task Rating of Perceived Exertion Resting
6	Tapping task Rest
7	Tapping task Rest
8	Tapping task Rest
9	Tapping task Rest
10	Tapping task Applied force measurement and spatial positioning recording the last ten seconds of the task Rating of Perceived Exertion Maximum Voluntary Exertions
Go To 1	Repeat unless: 1. Subject feels they can no longer continue 2. MVE <75% of starting value 3. RPDs >6 4. 18 groups of ten work cycles completed

3.7 Apparatus and Materials

The testing apparatus was composed of two different testing areas, the task workstation and the MVE fixture. All data was collected and concurrently evaluated using National Instruments™ hardware and Labview™ Virtual Instrumentation software. The spatial positioning data was collected using a Qualisys™ MacReflex™ system.

3.7.1 Workstation

Participants were asked to stand at a comfortable distance from the wall. Two force transducers were attached to the wall 50-cm apart on parallel tracks that were perpendicular to the ground. Paper targets were placed on the force transducers with a large 3.3 cm diameter circle and a small 0.6 cm dot to indicate the center of the target. The targets were manipulated on the tracks to position them at the respective heights of 50 or 75% over arm reach height. Participants were able to grasp the tool handle with a power grip in either the supination or pronation positions. Target impact forces were sampled at a rate of 512 Hz, and then passed through a low pass filter (F_c = 20 Hz). The subjective ratings scale was placed at the workstation allowing participants to refer to the numbers and anchors at all times. A bench was provided to allow participants an option to sit or stand during the rest period.

3.7.2 Strength Testing

The MVE fixture (shown in Figure 2) was used to control for posture during MVE tests. Cloth straps were placed at the epicondyle and connected to force transducers attached to the wall through a pulley for the middle deltoid, and anterior deltoid exertions. Handles extended from wires were connected to force transducers attached to the wall through a pulley for the infraspinatus and trapezius exertions. Participants pulled against the straps and handles in an isometric position during exertions. The MVE signal was sampled at a rate of 100 Hz for an eight second interval for each muscle and then smoothed through a low pass filter (Fc=10 Hz).

3.7.3 Marker Tracking System

A four-camera MacReflex system was used to record the 3-D spatial position coordinates of the wand. A reflective marker with a diameter of 3.3 cm represented the end of the tool and was used for striking the target. Prior to testing, the locations of the targets were recorded. This information was used to determine the target accuracy information. Spatial position data was recorded during the last ten seconds of tapping at the end of every fifth work cycle. The sample was recorded at a rate of 60 Hz and then smoothed through a low pass filter (F_c = 10 Hz) to eliminate high frequency noise.

3.8 Safety Measures

Testing sessions were scheduled 48 hours apart to minimize the cumulative effects of fatigue. Prior to starting an experimental session, participants were told that the experimenters would most likely not stop the experiment. However, if they felt uncomfortable, they were free to stop the experiment at any time. There were three conditions that caused the experimenter to stop the experiment, even if the participant was willing to continue. These criteria were developed to prevent participants from becoming overly fatigued and to avoid injury. The experiment was stopped if any one of the following was true:

1) A participant gave two consecutive RPD ratings of six or greater.
2) A participant performed two consecutive MVEs with a greater than 30% drop from the baseline MVEs.
3) The task was performed for 180 cycles (3 hours).

Chapter 4. Data Analysis

Dependent measures that could be directly analyzed include the time at which the experiment was terminated (endurance time) and the time at which the RPD rating reached a value of one. Non-parametric tests were performed to account for the non-normality of this data. All other data was analyzed over time to show the percentage of change as a function of time. Comparing the percent change provided a normalization factor that allowed for comparison between participants and across conditions. Normalizing the data also provided a control measure for intra-subject variability between various testing days. Sample data for each fatigue measure is given in the sections below.

Each fatigue measure was analyzed to show independent measures of "time to fatigue". Time to fatigue was identified when there was a significant change in the performance level for all dependent variables except for ratings of perceived exertion (subjective measurement) and endurance time, which had clearly defined fatigue points (point task could no longer be performed, and RPD value equal to one). For these variables there is no acceptable standard for deciding when fatigue has occurred or for identifying significant changes in performance. Analysis of linear regression trends provided a method of identifying significant changes in the data. The residual variation ($\sigma = \sqrt{MSE}$) about the linear regression line was determined. As described in Nussbaum et al. (2001), it was assumed that when the dependent measure exceeded the $\sigma/2$ level, this indicated the task time where a significant level of change had occurred (Figure 4.1). The time at which this significant change in performance occurred was recorded as the time to fatigue for that fatigue measure. Once all fatigue times had been determined for all participants, all conditions, and all fatigue measures, a standard analysis of variance (ANOVA) was used to identify significant effects of independent variables on each of the dependent measures. ANOVA analysis first tested for effects on time to fatigue due to the order of condition presentation. Additional ANOVA tests were used to test for effects on the independent task variables (height of target, hand orientation, and work ratio).

For several conditions, the predicted time to fatigue exceeded the three-hour time limit. In these cases, the time to fatigue was set to three hours. There were also data sets that showed a change in fatigue in the opposite direction, indicating that participants were becoming less fatigued as the experiment continued. It was assumed that, in these cases, participants were not fatigued due to a lack of change and the maximum fatigue time was also set at three hours. Standard Student's t-tests were used to determine significance using a criterion of $P<0.1$. Since many of the dependent measures used an artificial maximum (maximum fatigue time set to three hours) much of the data was not normally distributed. To adjust for this fact, additional non-parametric tests (Wilcoxon/Kruskal-Wallis) were run to first identify if there were differences between the 8 conditions. Subsequent tests (ANOVA) identified any two-way interactions of the independent variables due to rank.

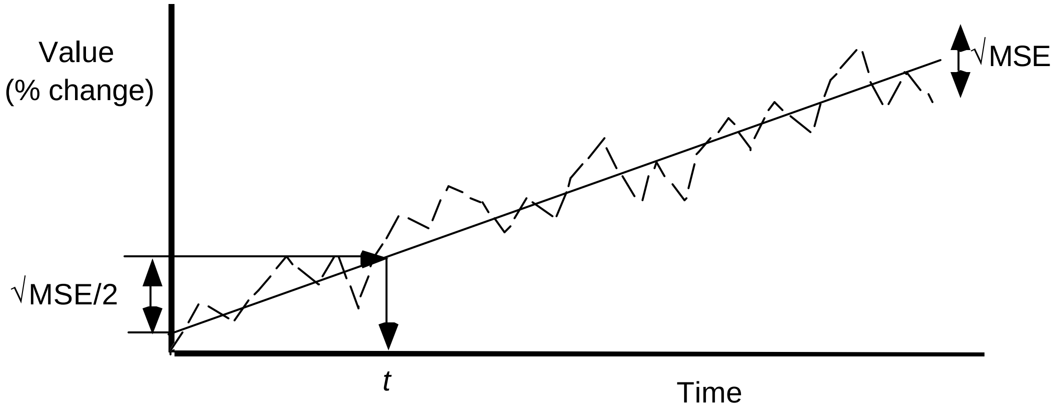


Figure 4.1. Determination of fatigue, using linear regression parameters.

4.1 Ratings of Perceived Discomfort

The change in RPD values was analyzed as a function of time. The time to fatigue was identified when the shoulder RPD reached a value of one, corresponding to very weak pain. RPD is the only measurement that did not use percent change to show significance. Figure 4.2 shows an example of data collected for Subject 5, Condition 1.

All three RPD rating gradually increased in a stepwise function during the 60-minute trial time.

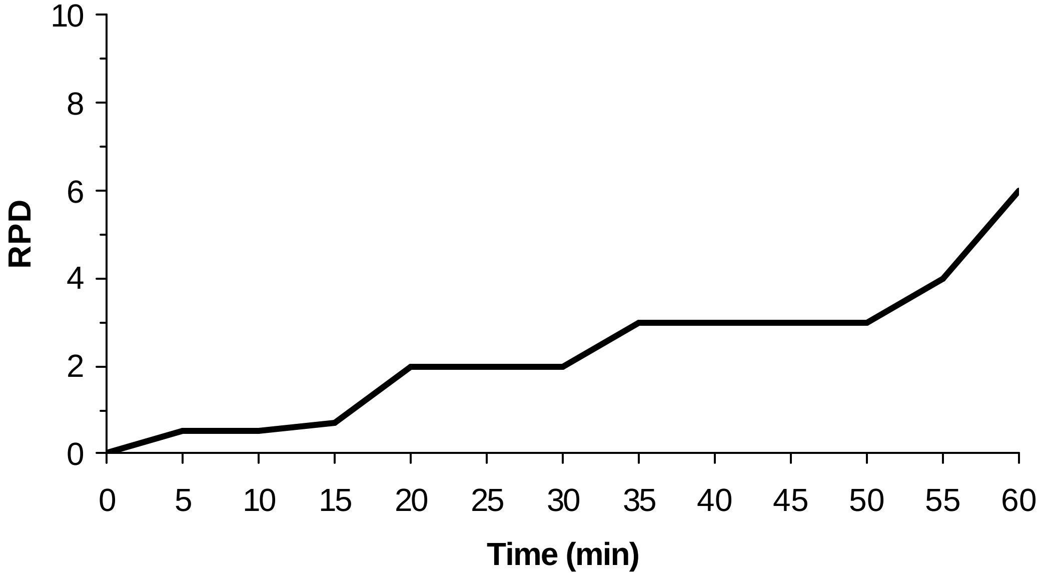


Figure 4.2. Changes in shoulder RPD values for Subject 5 Condition 1. RPD values were collected at every fifth work cycle and after the last cycle.

4.2 Maximum Voluntary Exertions

Maximum voluntary exertion data was recorded every tenth cycle for four different muscles. Raw data was interpreted to obtain the peak value during each exertion. Changes in the peak values were evaluated to show significant changes in strength, thus indicating a fatigued state. Gradual decreases in force generating capabilities are evident for the Mid Deltoid and Trapezius muscles (as described above). The time to fatigue measures ($TMVE_{MID}$, $TMVE_{TRAP}$, $TMVE_{ANT}$, and $TMVE_{INFRA}$) were determined from significant decreases in MVE (as described above) or was set to three hours if the condition was completed without indication of fatigue.

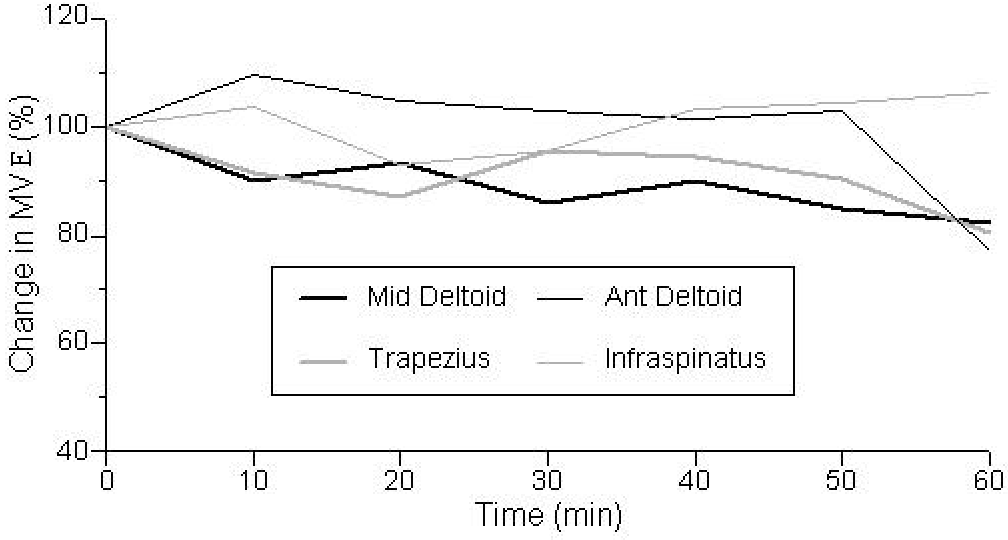


Figure 4.3. Changes in MVE values for Subject 4 Condition 1. MVE values are normalized at t = 0 and graphed at as a percent change.

4.3 Target Accuracy

A two dimensional analysis of the wand location was used to determine target accuracy. Wand location was recorded for ten seconds every fifth cycle. The wand path was then compared to the target locations that were recorded prior to beginning the testing procedure. The difference in horizontal distance between the wand and the targets was used to determine the peak and mean magnitudes of error. The change in error is shown as a function of time for each subject and condition (Figure 4.4). In the example shown, the data suggests that the increases in both peak and mean error indicate a decrease in tapping accuracy (Figure 4.5). Fatigue times (TTA_{AVG} and TTA_{MAX}) were determined from significant increases in tapping errors (as described above) or were set to three hours if decreasing error trends were found.

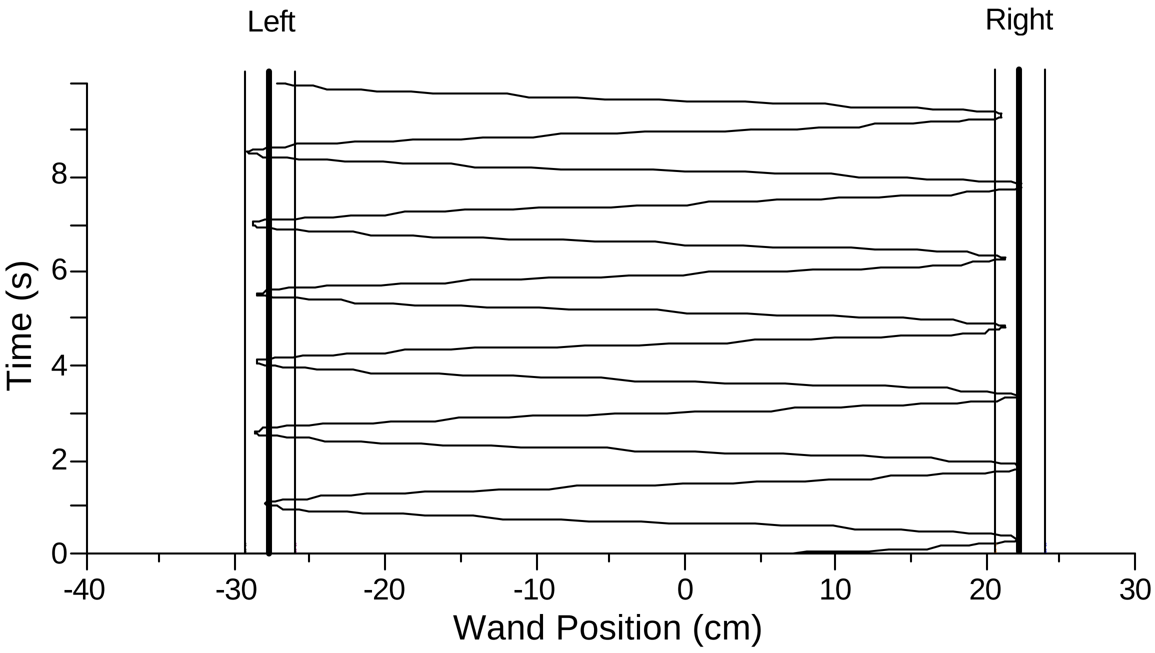


Figure 4.4. Target tapping accuracy for Subject 1 Condition 3 Sample 1. This figure shows the path of the wand in relation to the target position over time. The thin lines represent the outside diameter of the targets and the bold line represents the center point of the target.

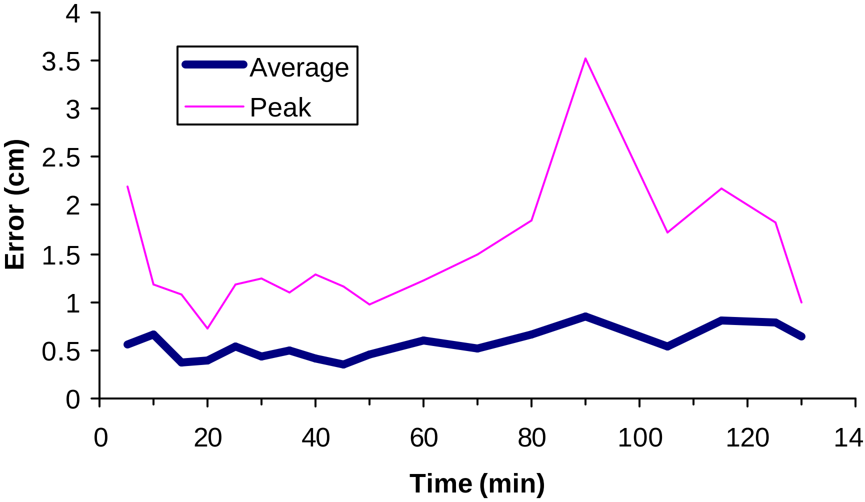


Figure 4.5. Changes in target tapping accuracy (Subject 1 Condition 8). This graph shows the work cycle average and peak error values for wand positioning with respect to the target.

4.4 Tapping Force

Ten-second samples of the force applied to each target were recorded every fifth cycle. A sample of the raw data collected during these trials can be seen in Figure 4.6. For each testing day, the change in mean, standard deviation, and maximum value were all calculated as a function of time. Figure 4.7 shows an example of the data that was collected. Fatigue times (THF_{AVG}, THF_{SDV}, and THF_{MAX}) were determined from significant increases in tapping force values (as described above) or were set to three hours if values were decreasing.

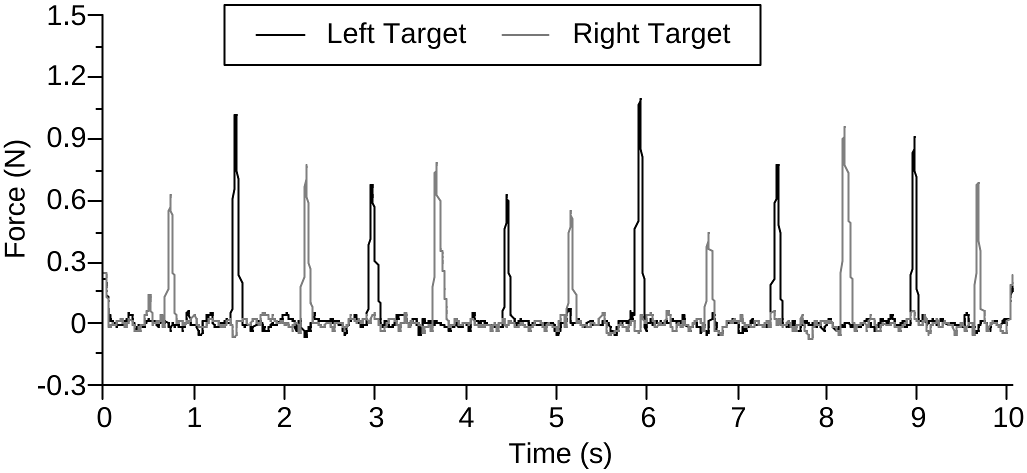


Figure 4.6. Applied target force data (Subject 1, Condition 1, Sample 1). This data was interpreted to gather average, standard deviation and peak forces per trial.

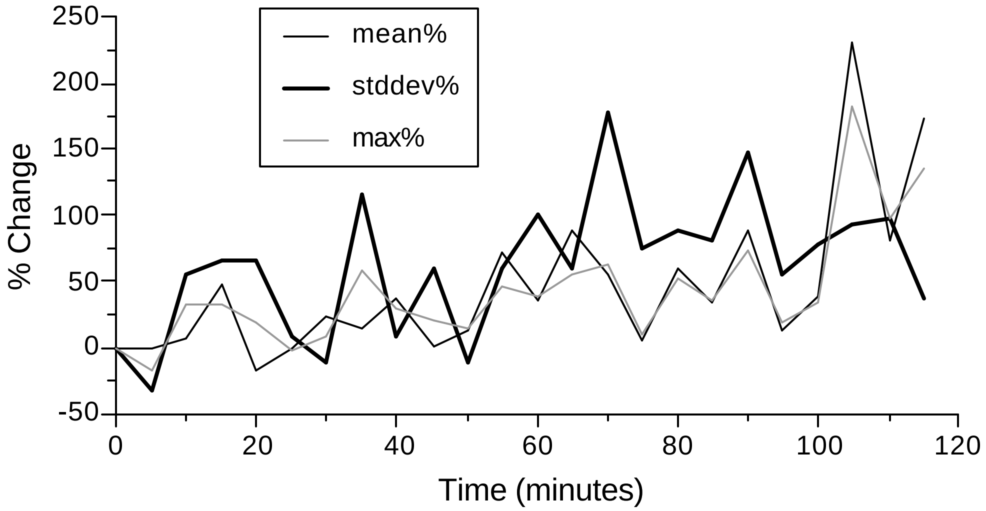


Figure 4.7. Applied target force data statistical analysis (Subject 1 Condition 1). This condition shows an increasing trend for the percent change in force applied to the target for all three values.

Chapter 5. Results

Data was collected for the five dependent variables discussed in the previous chapters. Fatigue times for the various dependent variables were calculated and analyzed (Table 4). Variances were considered significant when $P \leq 0.1$. Endurance time (T_{END}) and rating of perceived discomfort (T_{RPD}) were determined directly from recorded times during the experiment. The time to fatigue based on the percentage change during the experiment as discussed previously, will be used for the remaining variables: maximum voluntary exertions ($TMVE_{MID}$, $TMVE_{TRAP}$, $TMVE_{ANT}$, $TMVE_{INFRA}$), target hand force (THF_{AVG}, THF_{SDV}, THF_{MAX}), and target tapping accuracy (TTA_{AVG}, TTA_{MAX}). Tapping force data from one condition (S15C6) and target accuracy data from three conditions (S1C2, S6C4, and S8C1) were lost during the data collection. One experimental condition (S2C3) was terminated after 10 minutes. This did not provide enough data to conclude trends and was excluded from the data analysis section of the experiment (data for endurance time and RPD at this condition was still used).

Table 4. Descriptions of multiple fatigue measures obtained.

Measure	Name	Description
TEND	Endurance Time	Indicates the stopping point of the condition (maximum three hours)
TRPD	Ratings of Perceived Discomfort	The time at which an RPD rating reached a value of one
$TMVE_{MID}$	Maximum Voluntary Exertion – Middle Deltoid muscle	The time the middle deltoid has reached a significant change in performance
$TMVE_{TRAP}$	Maximum Voluntary Exertion – Trapezius muscle	The time the trapeziuz has reached a significant change in performance
$TMVE_{ANT}$	Maximum Voluntary Exertion – Anterior Deltoid muscle	The time the anterior deltoid has reached a significant change in performance
$TMVE_{INFRA}$	Maximum Voluntary Exertion – Infraspinatus muscle	The time the infraspinatus has reached a significant change in performance
THF_{AVG}	Tapping Hand Force – Average	The time the average hand force applied to targets has reached a significant change
THF_{SDV}	Tapping Hand Force – Standard Deviation	The time the standard deviation of the hand force applied to targets has reached a significant change
THF_{MAX}	Tapping Hand Force – Maximum	The time the maximum hand force applied to targets has reached a significant change
TTA_{AVG}	Target Tapping Accuracy – Average	The time the average target tapping accuracy has reached a significant change
TTA_{MAX}	Target Tapping Accuracy – Maximum	The time the maximum distance from the target center has reached a significant change

5.1 Order and Gender Effects

The presence of order effects signify a possible learning process where participants perform better in conditions that are presented in the later part of the treatment order. Using ANOVA (with participants and order as the main effect) all dependent variables were tested for significant order effects. With the exception of average tapping force ($P=0.057$) there were no significant order effects found for times to fatigue. Average THF has a decreasing trend, for conditions that were preformed later in the treatment order reach T_{HF} earlier (Figure 5.1). Significant ($P<0.09$) gender effects (Subject [Gender], Condition) were present for TEND, TRPD, $TMVE_{Ant}$, $TMVE_{Infra}$, THF_{Avg}, THF_{SDV}, THF_{Max}, and TTA_{Avg} dependent variables. Females as a group reached TEND later in all but one condition and lasted an average of 20% longer for all of the conditions (Table 5). On average females reached T_{RPD} later in every condition. Female TRPD occurred an average of 44% later in each condition. Since gender cannot be a considering factor when designing jobs, it was not considered as a factor in later statistical models.

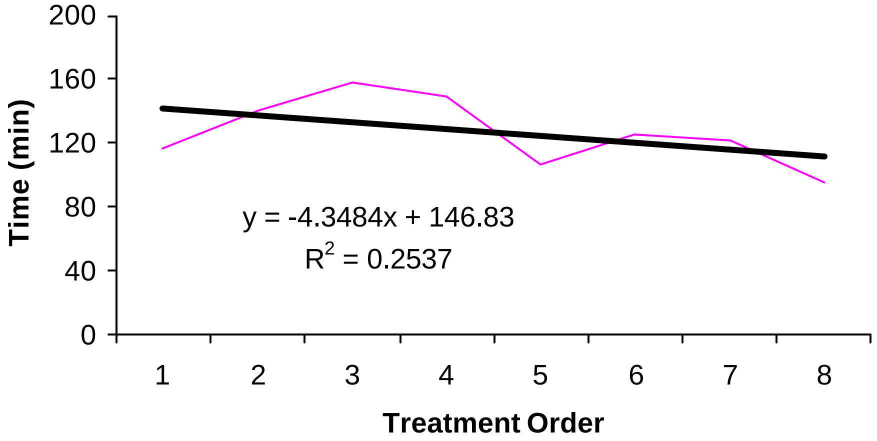


Figure 5.1. The trend for THF_{AVG} as a function of treatment order. The average tapping hand force decreased during later treatment presentations.

Table 5. Gender as a main effect

Factor	P Value	Female Avg (min)	Female SDV (min)	Male Avg (min)	Male SDV (min)
TEND	0.001	143	41	118	40
TRPD	0.0013	77	51	47	38
$TMVE_{ANT}$	0.0897	93	62	61	24
$TMVE_{INFRA}$	0.017	134	56	95	22
THF_{SDV}	0.0055	146	48	146	52
THF_{MAX}	0.0354	114	67	119	71
TTA_{AVG}	0.0042	94	68	110	69

5.2 Task Duration (TEND)

Condition as a main effect was found to be significant (P<0.0001) with respect to the task duration (Figure 5.1). Duty cycle also showed a significant effect on TEND (P<0.0001). Participants reached TEND earlier for the 40-second work cycles compared to the 20-second work cycles with respective average TEND times of 99.5 min and 161.3 min. Degree of arm elevation and hand position did not show a significant main effect (P>0.7). Arm height x duty cycle and hand orientation x duty cycle interactions were found to be significant (P<0.08). TEND during the 20-second cycles decreases when comparing 50% overhead reach and 75% overhead reach while the trend is increasing for the 40-second conditions (Figure 5.2). Working at the higher elevation resulted in the ability to work for longer periods of time compared to the lower elevation during the long duty cycle but the endurance time was reduced for the short duty cycle. The same significant (P=0.08) effect was seen for the hand orientation x duty cycle interaction (Figure 5.3).

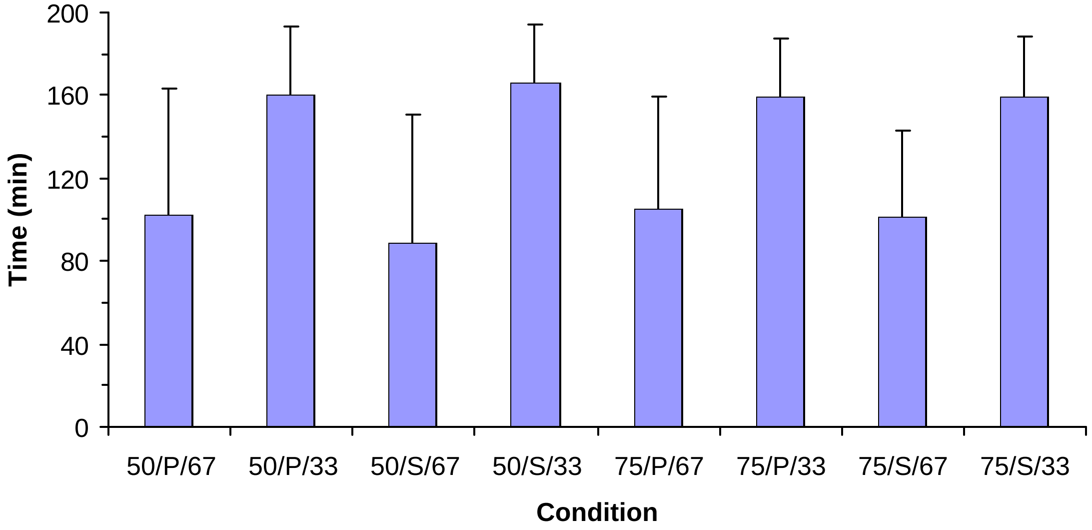


Figure 5.2. The average task duration for each condition. X-axis labels show % Arm Elevation , hand orientation, and % duty cycle)

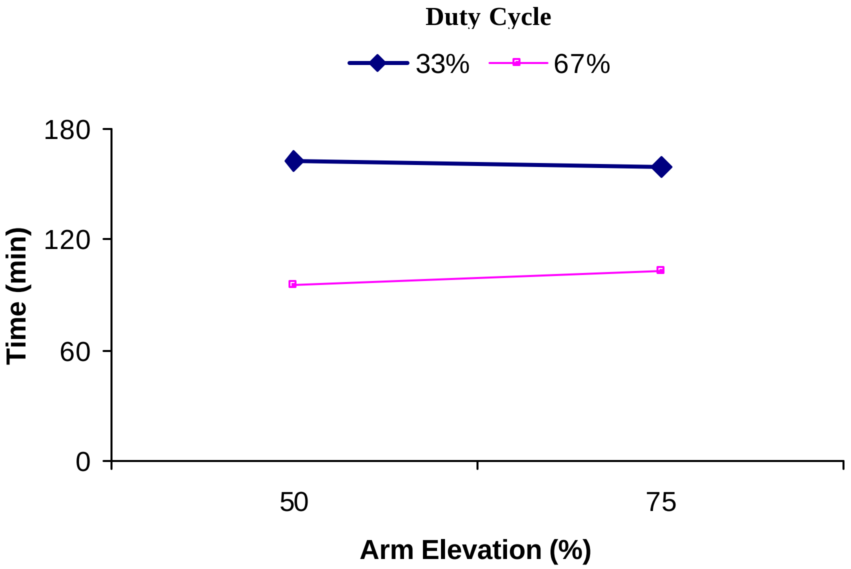


Figure 5.3. Arm Elevation x Duty Cycle interaction. Endurance time (T_{END}) for each arm elevation (%) and duty cycle.

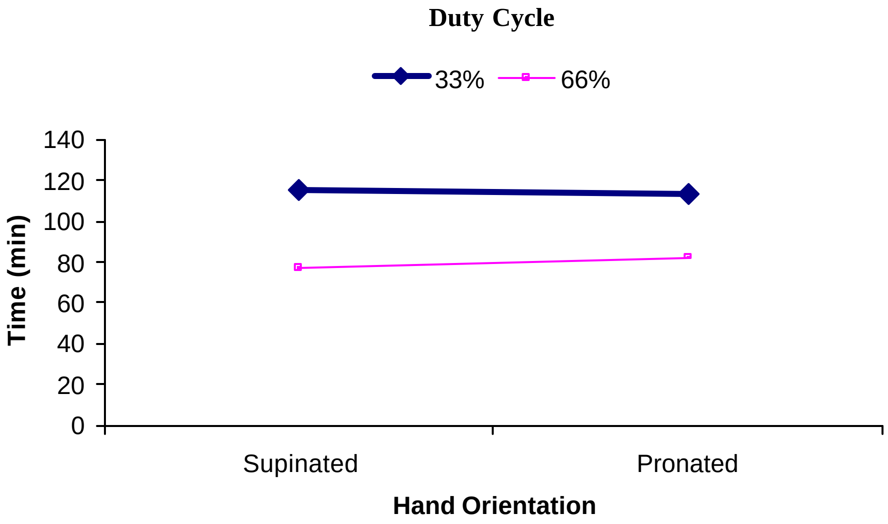


Figure 5.4. Hand Orientation x Duty Cycle interaction. Endurance time (TEND) for each hand orientation and duty cycle.

5.3 Ratings of Perceived Discomfort

Experimental condition had a significant effect ($P<0.0001$) effect on T_{RPD} (Figure 5.5). Shoulder RPD values reached a rating of "one", corresponding to very weak pain, significantly ($P<0.0001$) earlier when the duty cycle was 67% compared to 33%. The average T_{RPD} for the 33% and 67% duty cycles were 24 and 101 minutes, respectively. The degree of overhead arm reach was also a significant ($P=0.04$) factor with respect the T_{RPD}. Shoulder RPDs reached a rating of "one" earlier in the conditions where the degree of arm elevation was 75 percent compared to the other conditions that required work at 50 percent arm elevation (57 and 66 minutes respectively, Figure 5.6). The arm height x hand orientation interaction was also significant ($P=0.03$, Figure 5.7). While working in a pronated hand position participants were able to perform the task longer in the 50% reach position while hand orientation had almost no effect in the extended (75%) reach conditions.

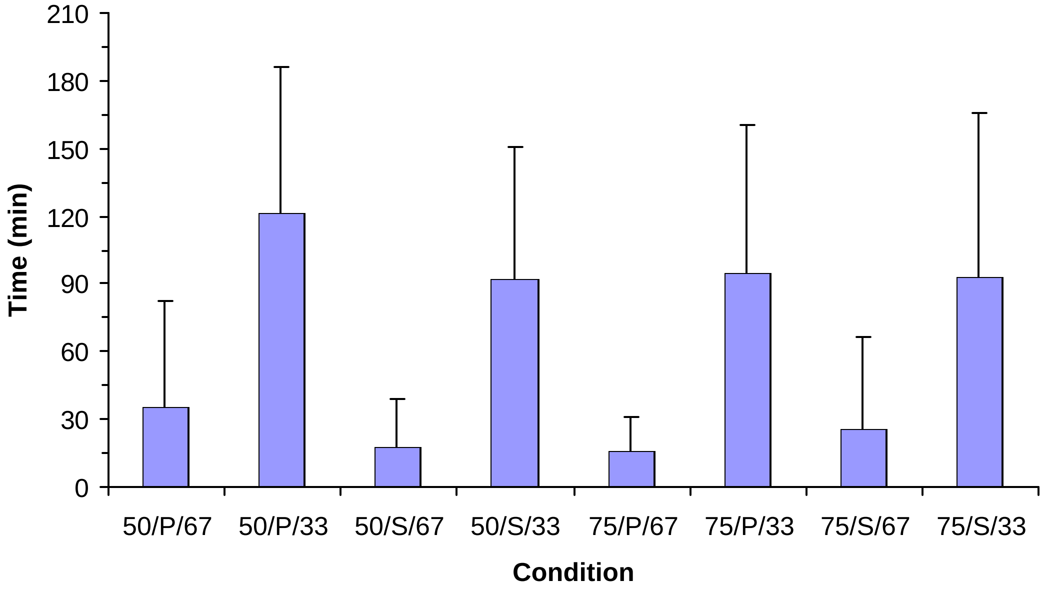


Figure 5.5. Average time to reach subjective shoulder ratings of RPD=1 for each condition. X-axis labels show % arm elevation, hand orientation, and % duty cycle.

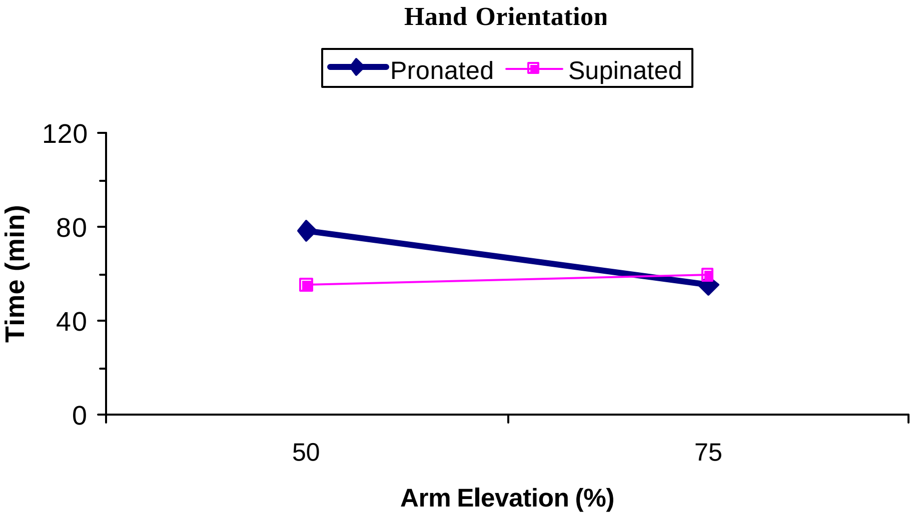


Figure 5.6. Time to fatigue for Ratings of Perceived Discomfort (TRPD) for arm elevation and duty cycle.

5.4 Maximum Voluntary Exertions

The overall trend for the time to fatigue based on MVEs showed that as time increased MVE capability decreased. On average, the Mid Deltoid had a decreasing trend for 85% of the conditions. MVEs for other muscles showed decreasing trends a majority of the time as well (Trapezius 74%, Anterior Deltoid 80%, and Infraspinatus 59%). The Mid Deltoid fatigued the fastest at a rate of 0.13%/minute. The Infraspinatus showed the slowest rate of fatigue with an MVE Reduction rate of 0.03%/minute (Table 6).

Experimental condition as a main effect was significant (P<0.099) for all four muscles. The Middle and Anterior Deltoids were generally the first muscles to show fatigue (Figure 5.7). In all but one condition, (75/S/40), the infraspinatus was the last muscle to show the signs of fatigue. All four muscles showed significant (P<0.003) differences in TMVE between the duty cycles (Figure 5.8). TMVE occurred an average of 30% earlier during the forty-second trials. TMVE_{MID} was significantly (P=0.035) lower in the 50% vs. 75% arm reach conditions (22% lower). Hand orientation had a significant (P=0.04) effect with respect to $\text{TMVE}_{\text{INFRA}}$. Conditions that were performed with a pronated hand position reached $\text{TMVE}_{\text{INFRA}}$ later than when the conditions were preformed with a supinated position. Arm elevation x duty cycle interaction for Mid Deltoid and Trapezius were found to be significant (P<0.015, Figure 5.9).

Table 6. MVE slopes (% change/min). The mean and median slope distribution is given for each muscle as well as the percentage showing significant negative changes (-), non-significant changes (0), or significant positive changes (+).

	Middle Deltoid	**Trapezius**	**Anterior Deltoid**	**Infraspinatus**
Mean	-0.13	-0.08	-0.11	-0.03
Median	-0.07	-0.05	-0.06	-0.02
-/0/+	64/54/9	49/72/6	49/73/5	36/74/17

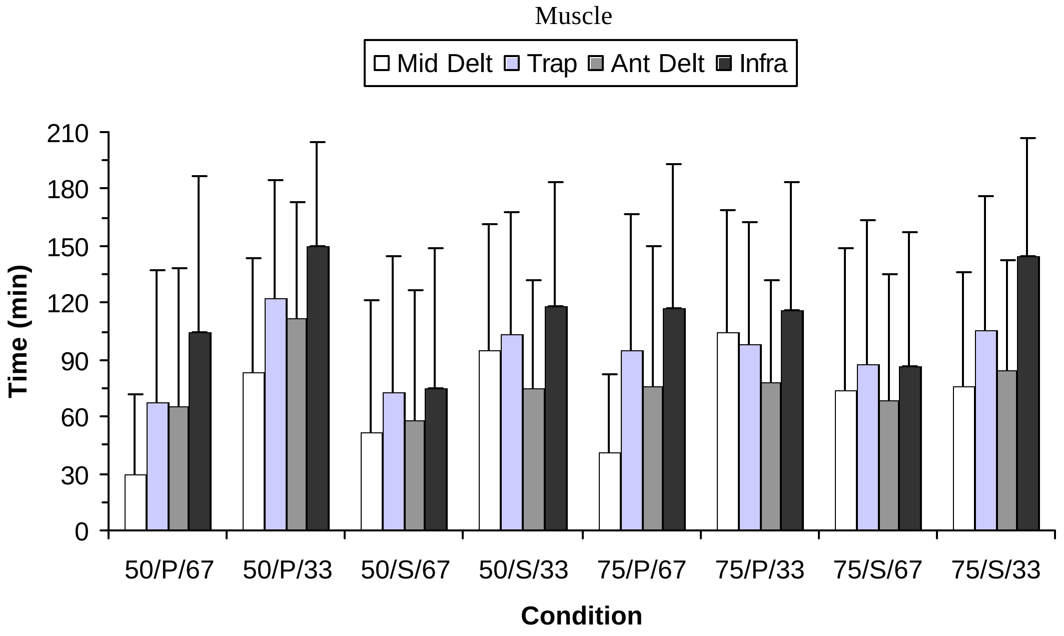


Figure 5.7. Average time to fatigue based on maximum voluntary exertion for each condition. X-axis labels show % of arm elevation, hand orientation, and % duty cycle.

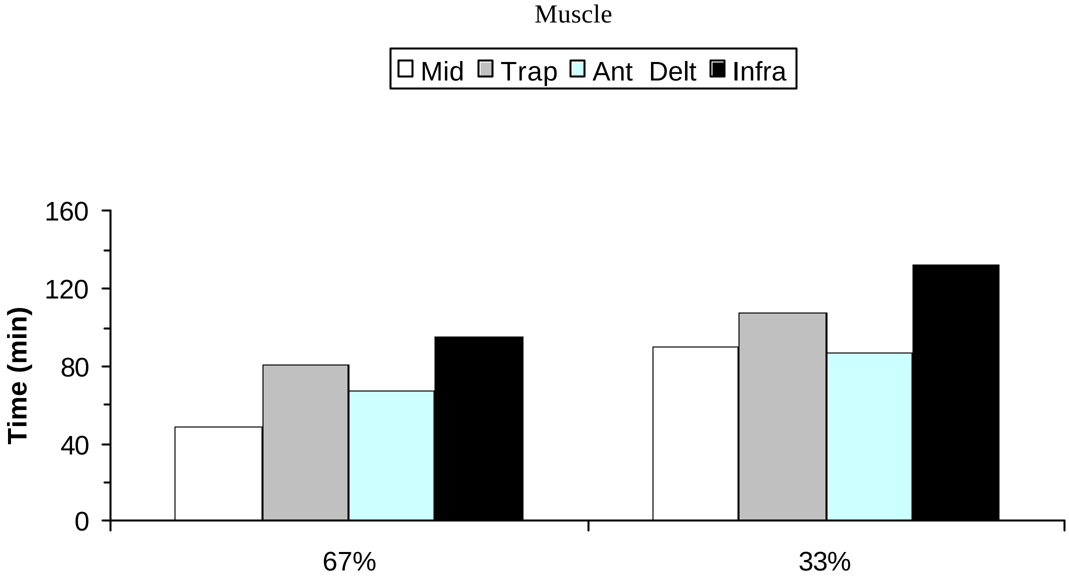


Figure 5.8. Average T_{MVE} for each muscle and duty cycle. X-axis labels show % duty cycle.

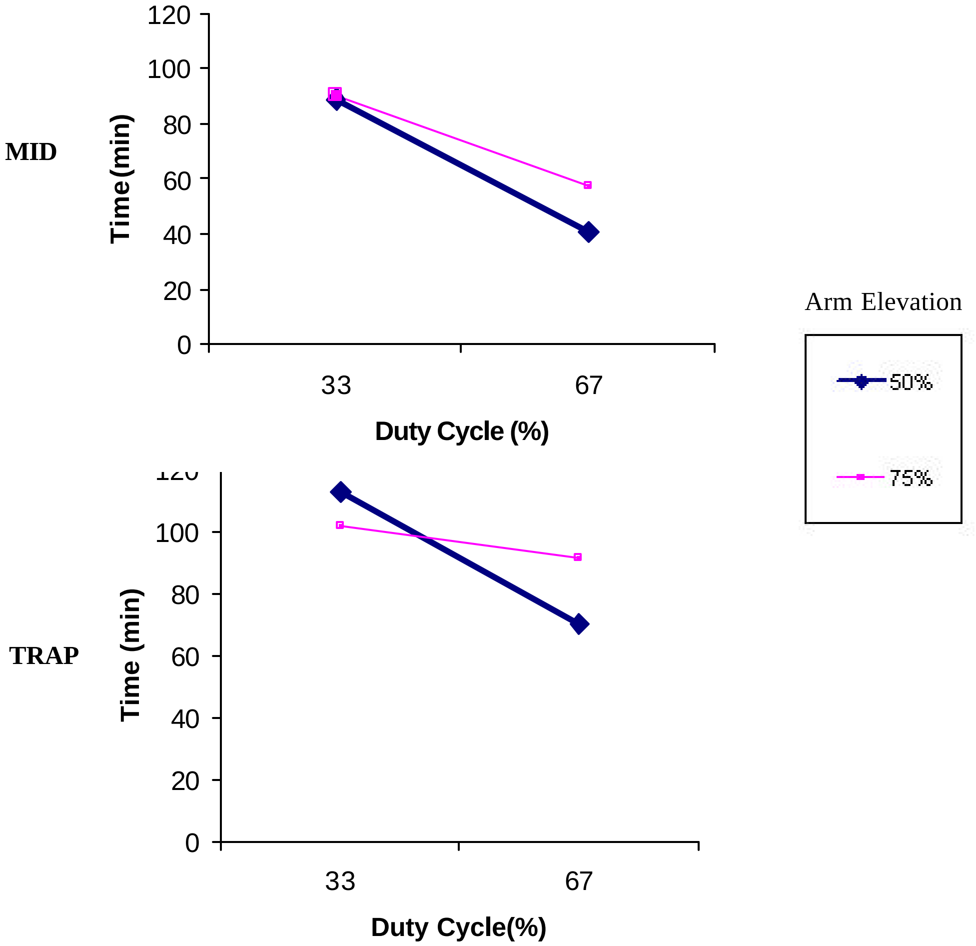


Figure 5.9. Time to fatigue based on MID and TRAP MVE for each Duty Cycle and Arm Elevation.

5.5 Target Tapping Accuracy

Table 7 displays the overall results for target tapping accuracy. The time to fatigue based on the tapping accuracy (TTA_{AVG}, TTA_{Max}) was not found to be significant with respect to condition (Figure 5.10). TTA_{AVG} was significant (P=0.04) with respect to hand orientation. Variance in average target accuracy was reduced in a supinated hand orientation (Figure 5.11). The target tapping errors increased in a majority of conditions at rates of 0.17%/min and 0.15 %/min for average and peak errors respectively (Table 7).

Table 7. Descriptive data for slopes (%change/min) of tapping accuracy changes versus time. The numbers of conditions yielding decreases in accuracy, no change, and increasing accuracy trends are shown. The mean and median of the slope distribution is shown along with the number of conditions show in significant decrease in accuracy (-), no significant change (0), and significant increase in accuracy (+).

	Average	Peak
Mean	0.17	0.15
Median	0.095	0.125
-/0/+	3/92/28	3/96/25

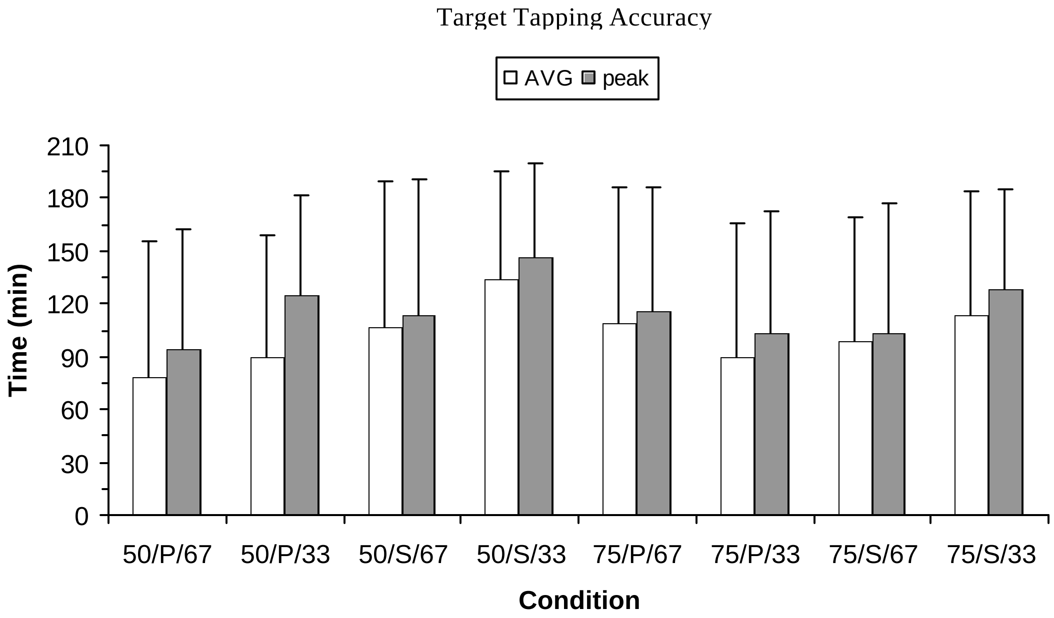


Figure 5.10. Average time to fatigue based on the average and peak distances from the center of the target are shown as a function of each condition task descriptions. X-axis labels show % of arm elevation, hand orientation, and % duty cycle.

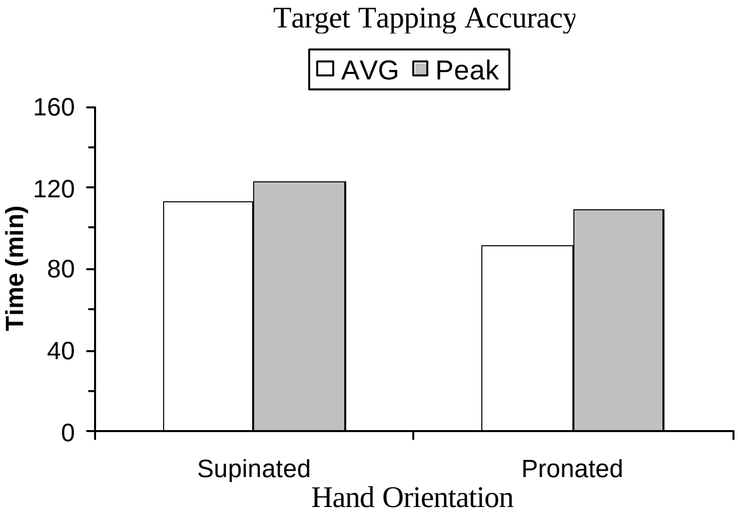


Figure 5.11. Average time to fatigue based on target tapping accuracy (average and peak errors) for all participants shown with respect to hand orientation. X-axis labels show hand orientation.

5.6 Target Tapping Hand Force

The average hand force (THF_{AVG}), standard deviation (THF_{SDV}), and peak forces (THF_{MAX}) were all used to describe the target tapping force measure and the majority of experimental conditions produced an increase in all three categories (Table 8). For all measures tapping force increased at a rate of 0.07-0.19% per minute (4-12% per hour). Significant changes happened at a similar frequency as non-significant changes (40-60%). When significant changes did occur, increases were more common than decreases.

There were no significant changes in hand force due to condition (Figure 5.12). Significant increases in force were more common than decreases. THF_{AVG} and THF_{MAX} occurred significantly ($P<0.1$) earlier in the 40-second duty cycle conditions. The average differences in THF_{AVG} and THF_{MAX} between the respective 40 and 20-sec duty cycles were 118 vs. 133 minutes for THF_{AVG} and 121 vs. 141 minutes for THF_{MAX} (Figure 5.13). Arm height had a significant effect on THF_{MAX} (P=0.02) and THF_{STD} (P=0.05) and approached significance with THF_{AVG} (P=0.11) variable. All three measures had a THF that occurred earlier in the 50 percent arm reach conditions (Figure 5.14).

Table 8. Descriptive data for slopes (%change/min) of tapping hand force changes versus time. The number of conditions yielding decreases in hand force, no change, and increasing hand force trends are shown. The mean and median of the slope distribution is shown along with the number of conditions show in significant decrease in hand force (-), no significant change (0), and significant increase in hand force (+).

	Average	**Standard Deviation**	**Peak**
Mean	0.07	0.19	0.12
Median	0.01	0.07	0.02
-/0/+	29/61/36	11/90/25	22/75/29

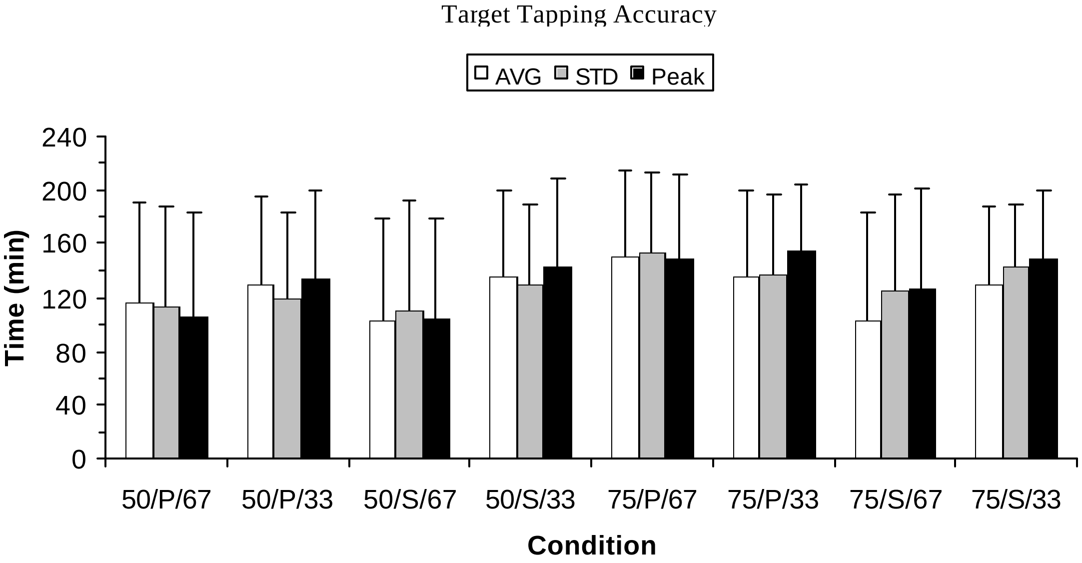


Figure 5.12. Average time to fatigue based on tapping force measured as a function of the condition task descriptions. The tapping force measures used were average force, standard deviation, and peak force. X-axis labels show % of arm elevation, hand orientation, and % duty cycle.

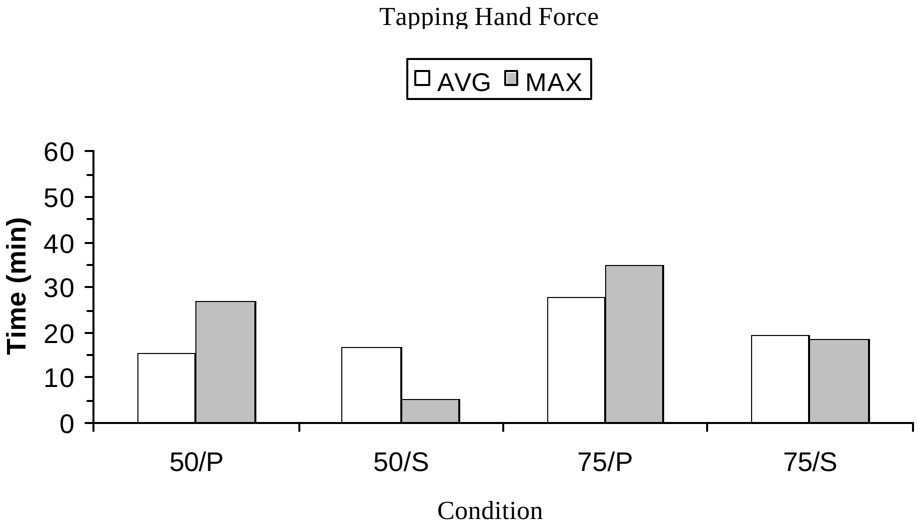


Figure 5.13. Average time to fatigue based on Target Hand Force for all participants shown with respect to arm elevation and hand orientation. X-axis labels show % of arm elevation and hand orientation.

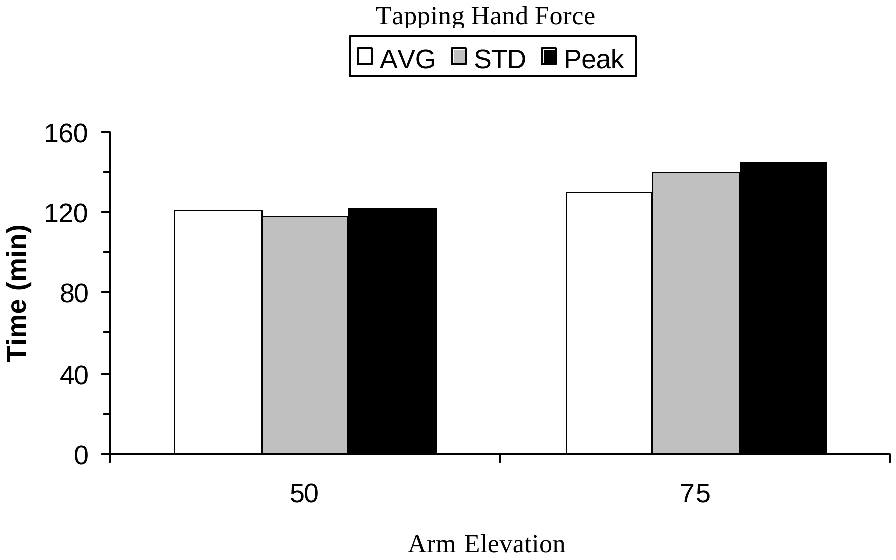


Figure 5.14. Average time to fatigue based on target tapping force for all participants shown with respect to degree of arm elevation. X-axis labels show % of arm elevation.

5.7 Fatigue Time

Each measure for time to fatigue was averaged across participants and is shown with respect to condition (Figure 5.15). Time to fatigue based on a shoulder RPD rating of one occurs the earliest in seven out of eight conditions. Endurance was the dependent measure that occurred the latest in all 20-second duty cycle conditions. During the 40-second duty cycle condition, fatigue time, as defined by significant changes in performance (Tapping Accuracy and Tapping Force), occurred the latest. Fatigue time as determined by a significant change in tapping occurred last or second to last in seven of the eight conditions.

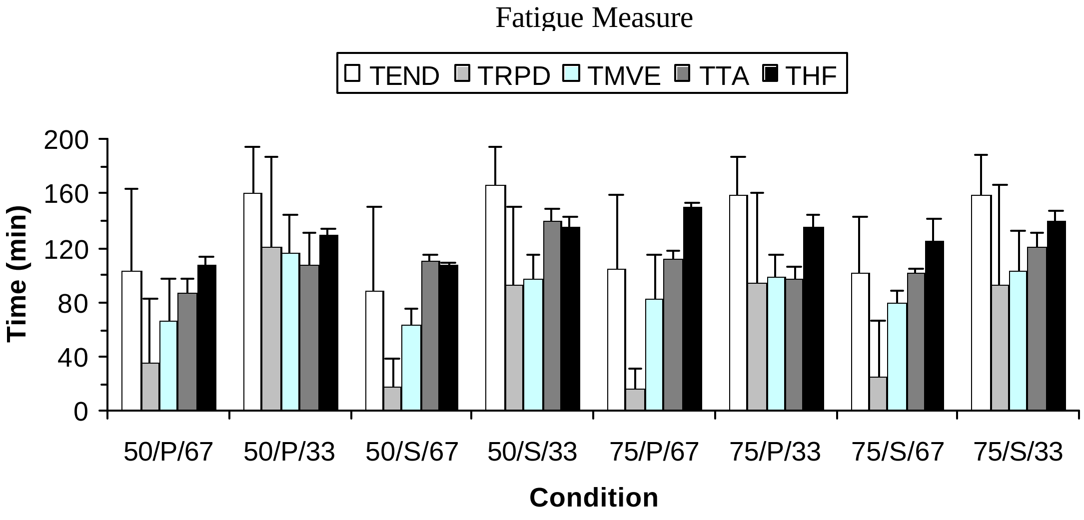


Figure 5.15. Average time to fatigue for all dependent measures shown with respect to condition. X-axis labels show % of arm elevation, hand orientation, and % duty cycle.

5.8 Correlation Matrices

Tables 9 – 11 shows the r^2 values for change per minute (b1), time to fatigue values, and values by rank (order of fatigue times) respectively. Data were grouped across participants for each condition. Most relationships showed only weak correlations (r^2<0.5). The only interactions that showed strong (r^2>0.5) correlations were among each category of measurement (e.g. TMVE – Mid, Trap, Ant Delt, Infra). Significant relationships include the correlations between hand force values. The strongest correlations (0.66< r^2 <0.90) are between the change/minute values. T_{RPD} and T_{END} also had strong correlations (r^2>0.66). The rates of change of the TMVE among all three muscles were moderately related to the rate of change of the Mid Deltoid (0.50< r^2 <0.71).

Table 9. Correlation matrix showing relationships among slopes of measures (Δ/min). Values with $r^2 > 0.5$ are bolded.

Variable	Mid	Trap	Ant	Infra	HF(AVG)	HF(SDV)	HF(MAX)	TA(AVG)
Trap	**0.5536**	-						
Ant	**0.7128**	**0.6471**	-					
Infra	**0.4968**	0.3552	0.3975	-				
HF(AVG)	-0.0503	0.091	0.1216	-0.0871	-			
HF(SDV)	-0.3254	-0.0801	-0.1038	-0.1894	**0.6649**	-		
HF(MAX)	-0.2084	-0.0793	-0.0057	-0.0468	**0.6834**	**0.9046**	-	
TA(AVG)	-0.1285	0.0569	-0.0831	-0.0938	-0.0685	-0.1207	-0.1858	-
TA(MAX)	-0.0403	0.0863	-0.0641	-0.0908	0.0424	0.1428	0.089	**0.6008**

Table 10. Correlation matrix showing relationships among Times to Fatigue. Values with $r^2 > 0.5$ are bolded.

Variable	T_{End}	T_{RPD}	$TMVE_{Mid}$	TME_{Trap}	$TMVE_{Ant}$	$TMVE_{Infra}$	THF_{AVG}	THF_{SDV}	THF_{MAX}	TTA_{AVG}
TTF_{RPD}	**0.6581**	-								
$TMVE_{Mid}$	0.3377	0.3068	-							
TME_{Trap}	0.2463	0.1706	0.4113	-						
$TMVE_{Ant}$	0.3263	0.2207	**0.5064**	0.4713	-					
$TMVE_{Infra}$	0.3521	0.3195	0.2874	0.2613	0.2871	-				
THF_{AVG}	0.1373	0.0267	0.0357	0.1109	0.0408	0.0873	-			
THF_{SDV}	0.1262	0.1419	0.2046	0.2576	0.1741	0.0823	**0.5901**	-		
THF_{MAX}	0.1373	0.0012	0.0576	0.1190	0.0060	0.0383	**0.8151**	**0.6976**	-	
TTA_{AVG}	0.0345	-0.0744	0.0563	0.0658	0.1311	-0.0009	-0.1081	-0.0685	-0.1087	-
TTA_{MAX}	0.0783	0.0474	0.0551	-0.0445	0.1239	0.2256	-0.0676	-0.1305	-0.1338	**0.6456**

Table 11. Correlation matrix showing relationship among the ranked values of Time to Fatigue. Values with $r^2 > 0.5$ are bolded.

Variable	End	RPD	Mid	Trap	Ant	Infra	HF(AVG)	HF(SDV)	HF(MAX)	TA(AVG)
RPD	**0.7268**	-								
Mid	0.4934	0.4206	-							
Trap	0.2916	0.2548	0.4244	-						
Ant	0.3746	0.3284	**0.5632**	0.4718	-					
Infra	0.4323	0.399	0.3171	0.2364	0.2433	-				
HF(AVG)	0.1061	-0.009	0.0299	0.0924	0.0296	0.0808	-			
HF(SDV)	0.0831	0.0569	0.1192	0.1976	**0.571**	0.0538	**0.5242**	-		
HF(MAX)	0.1425	0.0281	0.0331	0.1018	-0.0366	0.0598	**0.8398**	**0.5838**	-	
TA(AVG)	0.2066	0.1326	0.0358	0.1423	0.2425	0.12113	-0.01	-0.004	-0.0202	-
TA(MAX)	0.1362	0.0269	0.0037	0.012	0.1754	0.2096	-0.119	-0.1945	-0.1286	**0.6714**

Chapter 6. Discussion

6.1 Overview

A primary objective of this study was to examine the relationship between performance changes and overhead work demands. An experimental work task was designed to mimic typical overhead working conditions found in automotive assembly plants. Sixteen different participants participated in the experiment. Two levels of work to rest ratio, work height, and hand position variables combined for a total of eight different experimental task conditions. Four independent measures based on subjective, objective, and physiological fatigue were used to quantify shoulder fatigue. For the purposes of this study, muscle fatigue was viewed as a surrogate measure for risk of injury. While little is known of the direct relationship between the two, existing evidence supports at least a correlation between fatigue development and an increased risk of injury. The current experiment was designed to identify acceptable exposure levels to overhead working conditions that will minimize fatigue development and in return pose the least risk for injury. Data collected in this experiment was also intended to provide design guidelines that will help maximize efficiency and quality of overhead work tasks while reducing the likelihood of developing shoulder fatigue.

Multiple measures of fatigue, including subjective, objective, and physiological changes, were used to evaluate the onset of fatigue. The accuracy and amount of force-applied characteristics of task performance were measured concurrently with fatigue onset to determine the relationship between fatigue and task performance. Times to fatigue that were calculated per condition were highly dependent on the measure of fatigue that was chosen. Time to fatigue was calculated based on the new fatigue index discussed previously. The time to fatigue was determined as a finite event, but in actuality fatigue happens gradually over a period of time and given rest breaks a worker may fluctuate between a fatigued and a non-fatigued state for a period of time. In order to design safe work systems, designers must be able to predict when the initial fatigued point will occur based on task conditions. If task designers rely on the observance of fatigue symptoms (discomfort, reduced quality, and reduced physical capabilities) to set limits, they have lost their opportunity to reduce the risk of injury caused by the cumulative effects of fatigue. Creating design guidelines that allow recovery periods prior to fatigue effects are noticeable will likely be the most effective method of reducing the potential for injury.

6.2 Major Results

Across all task conditions, the results indicated that working with hands above the shoulder caused participants to experience some level of shoulder fatigue. The results that were summarized in Figure 5.15 may provide the most useful form of data for task designers. This graph, which has been recreated in tabular form below (Table 12), can allow task designers to choose the condition that most closely resembles their task conditions and to choose the fatigue measure that best fits their corporate objectives.

Table 12. Time to fatigue (min) across all dependant measures. All times are shown as a function of percent arm reach, hand orientation, and duty cycle.

	Maximum Endurance		**Subjective, Physiological Measure**				**Performance Changes**			
Condition	Task Duration	**STD DEV**	RPD=1	MVE *(min)	**Average**	**STD DEV**	Tapping Accuracy *(min)	Tapping Force *(min)	**Average**	**STD DEV**
50/P/40	102.50	61.05	35.31	29.70	32.51	3.97	105.28	78.29	91.78	19.09
50/P/20	160.00	33.67	121.25	83.46	102.36	26.72	119.42	90.09	104.76	20.74
50/S/40	88.75	61.85	18.13	51.21	34.67	23.40	102.61	106.89	104.75	3.03
50/S/20	166.25	27.78	92.50	75.12	83.81	12.29	129.48	133.45	131.47	2.81
75/P/40	105.00	54.04	15.94	41.16	28.55	17.83	149.14	109.08	129.11	28.33
75/P/20	159.38	28.39	94.69	77.71	86.20	12.00	136.11	90.06	113.09	32.57
75/S/40	101.88	41.51	25.63	68.72	47.17	30.47	102.22	99.16	100.69	2.17
75/S/20	159.38	29.09	93.44	76.48	84.96	11.99	130.39	114.07	122.23	11.54

*(min) indicates that the minimum fatigue time was taken when there were multiple measures used to describe that variable.

Fatigue Measures

During all four 20-second conditions, fatigue as measured by task endurance occurred last, after all other fatigue measures showed a significant change from the pre-fatigued state. During the conditions that had more rest time assigned to them, participants were more willing to continue working beyond the point where fatigue had begun to occur. During the 40-second duty cycle conditions, the extrapolated data for performance measurers were more likely to be the lagging indicator of fatigue. During this experiment task duration was defined as the maximum endurance time (how long a subject performed the task). This fatigue measure provides a very distinct determination of the finite event of “fatigue point”. Task duration was derived as an average of how long participants were willing to participate during a particular condition. Conditions were terminated due to one of the following three conditions: participants performed the task for the maximum task time of 180 minutes, participants felt they were too fatigued to continue, participants showed physiological signs of significant fatigue. If a subject was too fatigued to continue it is assumed they have already progressed through the early stages of fatigue where discomfort is avoidable. Task designers must consider that continuing work to the fatigued point (maximum endurance) will increase the risk of developing cumulative trauma disorders and also has the potential of resulting in an acute injury. Since the fatigue point can really be considered as a fatigue range, use of the other measures to show the onset of fatigue should be used to establish safe work limits.

6.3 Hypotheses Tests

Two main hypotheses were formulated based on the literature review and with the results of pilot studies. The conclusions to these hypotheses, with respect to the current experiment are discussed below.

Hypothesis One:

- Task factors (duty cycle, hand orientation and arm elevation) will affect fatigue times for one or more measures of fatigue.

It was expected that conditions including 66% duty cycle, 75% arm elevation, and supinated hand posture would reach time to fatigue earlier than conditions that have 33% duty cycle, 50% arm elevation, and pronated hand position. Duty cycle was the independent variable with the most occurrences of significant effects on the times to fatigue (Table 13). It was expected that the effect of residual fatigue between tapping tasks would accumulate quicker during the 66% duty cycle conditions because of the reduced recovery time thus causing fatigue to occur at an increased rate. The experimental results supported this hypothesis. When an effect was identified, time to fatigue occurred an average of 26 min quicker during the 66% duty cycle. Both T_{END} and T_{RPE} had the greatest effect and resulted in time to fatigue differences that exceeded one hour between the 33% and 66% duty cycle conditions. These results are fairly consistent with previous research (Rohmert, 1973; Price, 1990), which found that short frequent rest breaks provide a better recovery opportunity compared with longer less frequent breaks for tasks require heavy efforts.

Table 13. Summary of significant findings of effect between independent and dependent variables.

	Duty Cycle	Arm Elevation	Hand Position
T_{END}	P < 0.001	-	-
T_{RPD}	P<0.0001	P<0.05	P<0.05
$TMVE_{MID}$	P<0.05	-	-
$TMVE_{TRAP}$	P<0.05	-	-
$TMVE_{ANT}$	P<0.05	-	-
$TMVE_{INFRA}$	P<0.05	-	-
THF_{AVG}	-	-	-
THF_{SDV}	-	P<0.04	-
THF_{MAX}	P<0.10	P<0.05	-
TTA_{AVG}	-	-	P<0.07
TTA_{MAX}	-	-	-

Sigholm et al. (1984) found that degree of arm elevation was the most important factor affecting the rate of fatigue. It is clear that the results of the present experiment did not support this idea. While THF_{AVG} had no effect, it can be said that THF was slightly affected by arm elevation. Both THF_{SDV} and THF_{MAX} showed significant difference between the 50% and 75% arm elevation conditions. Performance metrics in particular were expected to show significant differences between the two arm elevation conditions. As discussed earlier, Wicker (1989) stated that task performance decreased as arm elevation increased. It was expected that applied force would vary more during the higher condition (75% arm elevation). THF_{MAX} and THF_{SDV} occurred an average of almost 23 minutes earlier during the 50% arm elevation condition. Contradicting the theory, conditions performed at the higher arm elevation setup were performed with more consistent applied hand forces throughout the condition. One possible explanation is that tapping forces were so variable throughout all conditions that no conclusions can be drawn. T_{RPD} was the only fatigue measure that showed significant effects among all three independent variables but arm elevation and hand position were only slight compared to duty cycle.

Studies, such as Herberts et al. (1984), have shown that along with pain and discomfort, the onset of fatigue causes a loss of fine motor control. It was expected that this loss of control would result in an increased number of errors in the experimental task. Chaffin (1973) also provided evidence that fatiguing exercises cause participants to increase the amount of time they take to perform the task and caused participants to overestimate the force required to produce light efforts. Since the experimental conditions did not allow for a self-paced task, it was expected that these fatigue characteristics would manifest in the form of increased hand force applied at the targets with the onset of fatigue. Previous experiments (Wickers et al, 1989) had found that performance accuracy decreased as the degree of arm elevation increased. This relationship was also examined with the performance data during the current experiment. It was expected to see that the 75% arm elevation conditions would produce increased amounts of errors with respect to the 50% arm elevation conditions.

The experimental conditions produced only weak relationships between performance changes with the onset of fatigue. All conditions showed an increase in errors with an increase in time, at a rate of 9-10% per hour. Errors increased, but not at a considerable rate. Previous experiments in this topic have compared working at elevated heights to working at elbow or table height. Wicker (1989) found that performance decrements happen immediately when hands are placed above the shoulder and that performance can decrease by almost 20%. In Wicker's experiment the performance decrements increased with the amount of hand elevation. Even though the present experiment did not have a work below shoulder height as a control it was still expected that performance decrements would be found across the two hand height variables. In contradiction to Wicker's results, the present study did not find a significant difference ($P>0.5$) in target accuracy. The effects of arm height x duty cycle did show some significant results with respect to $THF_{AVG,\ SDV,\ Max}$ (Figure 6.1).

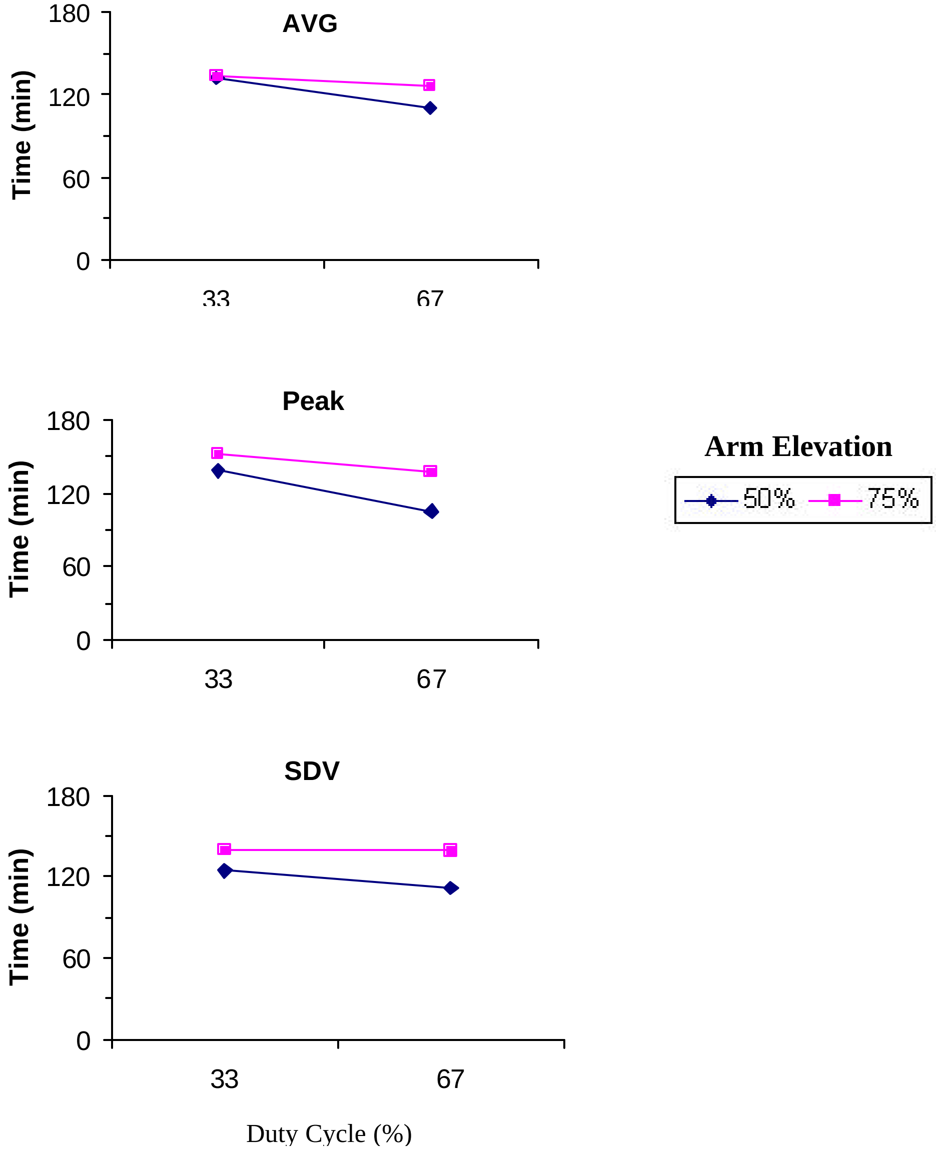


Figure 6.1. Arm height x duty cycle interaction for THF$_{AVG, SDV, Peak}$. X-axis label shows % duty cycle.

The lack of findings may be attributed to a lack of task difficulty. Previous researchers have pointed out that performance accuracy is highly dependent of the task's difficulty. The results of the current study were similar to the task performance results found by Sundelin (1992). In Sundelin's previous experiment, participants performed a table height, fatiguing task that required participants to repetitively grasp small cylinders and place them through a hole. In one condition, participants performed the task uninterrupted and in a second condition participants were provided with rest breaks. Sundelin measured the work output over the two conditions, and while the results showed a significant increase in fatigue for the interrupted work condition, there was no measurable effect on the change in work output. Sundelin indicated that this effect was most likely "due to the fact that the repetitive duty cycle was rather mechanistic and did not require high mental skills". While the present experiment was created to mimic a typical workstation in an automotive assembly plant, the element requiring precision (hitting the target), may have been too easy for participants, and led to the lack of difference in performance between conditions.

The target hand force did increase over time for a majority of the conditions (average rate is 4%-11% per hour). In Wicker (1989), participants were required to move between plates and place a stylus in holes in plates. Wicker found that, as fatigue developed, the participants could not perform the movements between the holes as quickly and there was also an increase in dwell time. Once the participants placed the stylus in the hole in a fatigued state, participants stayed on the target longer than in a non-fatigued state. Wicker's experiment was a self-paced task. During the current experiment there were no significant changes over the conditions with respect to hand force. While the present experiment did not measure dwell time or evaluate the changes in movement it was expected that when participants started to fatigue they would feel rushed and would need to work to increase movement velocity thus when they hit the target it would produce a greater force. As discussed earlier the $THF_{Avg, STD, Max}$ increased at a faster rate during the 50% reach conditions. On the whole, target-tapping forces did not show significant changes with time. One possible explanation may be that the fatigue onset was not linear with respect to time. Once participants were determined to be substantially fatigued, the experiment was stopped to prevent risk of injury. However this limited the amount of data collected in a fatigued state.

Hypothesis Two:

- Changes in task performance will correspond with changes in fatigue measures.

It was expected that there would be a direct relationship, showing that once physiological and subjective signs of fatigue began to appear there would also be marked change in the performance. No such relationships were found. Table 14 shows the summary of the correlation tables highlighting the performance variables. Table 15 shows the correlation values for the fatigue time rank order per condition. There were no strong correlations based on the standard time to fatigue calculations. However there were strong correlations for a few variables (T_{End}) with respect to TTA_{Avg}. This hypothesis was developed based on previous research. It was expected that as time passed it would required more muscular effort to perform the given task. If the subject had determined their task performance needed additional precision the decision to perform with increased precision would require an increase in muscle activity (Laursen et al, 1998). Laursen et al (1998) also found that increased precision demands lends to adopting a more stiff posture. They suggest that by increasing the muscle tension in the shoulder, the shoulder system becomes more rigid and thus provides more controllable movements. Thus, it was believed that there would be a relationship between muscle fatigue and task performance decrements.

Table 14. Correlation Matrix (r^2 values) - Average Times To Fatigue.

		T_{RPD}			TMVE				
		1	2	3	MID	TRAP	ANT	INFRA	T_{END}
TTA	AVG	0.0074	0.0159	0.0669	0.0886	0.0727	0.0867	0.0041	0.0805
	Peak	0.2676	0.2855	0.3760	0.2068	0.4016	0.2256	0.2370	0.3813
THF	AVG	0.1602	0.1770	0.2483	0.0466	0.3292	0.0464	0.4661	0.3008
	SDV	0.0079	0.0064	0.0376	0.0322	0.1793	0.0200	0.1869	0.0938
	MAX	0.2707	0.2622	0.3619	0.3910	0.5329	0.3284	0.3900	0.4844

Table 15. Correlation Matrix (r^2 values) - Rank Times To Fatigue Subject Averaged Data. Values with $r^2 > 0.5$ are bolded.

		T_{RPD}			TMVE				T_{END}
		1	2	3	MID	TRAP	ANT	INFRA	
TTA	AVG	0.4133	**0.7299**	**0.6944**	0.1451	0.2268	0.2079	0.3832	**0.5925**
	Peak	0.0459	0.1589	0.3265	0.4444	0.2500	0.0645	0.1451	0.4193
THF	AVG	0.0204	0.0468	0.2500	0.1111	0.1837	0.0759	0.2744	0.3298
	SDV	0.0006	0.0012	0.0686	0.0686	0.2046	0.0503	0.2268	0.1435
	MAX	0.0958	0.0572	0.2268	0.2744	0.2999	0.1310	0.2744	0.2760

During the present experiment particular importance was paid to the Middle Deltoid, Trapezius, and Anterior Deltoid because of their antagonistic duties. Wicker et al. (1989) had found the strongest, but still only moderate, relationship between movement performance and antagonistic muscles. With hands in an elevated posture, limb stabilization movements are created by the antagonistic muscles in the shoulder girdle (Dempster, 1965). Wicker's results supported that there were no relationships caused by local fatigue and the moderate relationships were found with regional discomfort values. In the present experiment, no relationship was seen with the localized MVE values.

6.4 Study Limitations and Future Research

The results of the current experiment were affected by several limiting factors. The experimental design made use of a Latin Square to determine the treatment condition order. There were only moderate effects of treatment order for strength, hand force, and endurance time. These order effects were most likely due to a learning effect. Once exposed to both a 20-second duty cycle condition and a 40 second condition participants developed expectations of their own abilities. If participants lasted the entire time during a 40 second duty cycle condition then they perceived a 20 second duty cycle as easy regardless of the additional variables. The effect of the order treatment was viewed as having minimal effects on the outcome of the study. There were also additional aspects of the study, discussed below, that do warrant further investigation and may have acted as study limitations and provided more significant study results.

Limited study results may be a function of the task difficulty level. Both Sundelin (1992) and Wicker et al. (1989) have suggested that the effects of performance decrements are only slight in tasks that are very cyclic and mundane. Perhaps a slightly more strenuous task would have provided more significant results. The current experimental task was monotonous, required very little cognitive work, and did not require the participants to react to the situation around them. Participants were given little feedback on their task performance during the experiment. Prior to beginning the experiment, they were encouraged to hit the center of the target and apply a consistent amount of force. The performance data (THF, TTA) collected during the experiment was highly variable and produced few relationships. Perhaps more detailed, more frequent performance instructions could have decreased data variability. It is also important that future research should attempt to find links between fatigued task performance and decrements in quality. While no substantial correlations were found during this study it is believed that this relationship does exist. Future research should focus on increasing the task difficulty and increasing the amount of dependent variables measured.

The rigidity of the task demands may have also provided study limitations. Previous research has suggested that the most significant effect of performance decrements during overhead work is increased movement times as fatigue accrues (Lance et. al., 1971; Wicker et. al., 1989). This variable was not measured during the current experiment and effects were ignored since the task was paced. The paced aspect could be removed from the experiment by making participants tap the targets for the total of the duty cycle. Data could be collected on the difference in the frequency of strikes during the conditions. This would also provide a more realistic work situation. At assembly plants, workers know how much work must be completed for each cycle and they know how long the cycle time is. They are free to change their work pace as they see fit. In future work, analysis should be performed on the movement times between the targets. In addition to increased performance measures participants were also asked to perform the task with very little movement. Unlike most manufacturing situations where operators are required to walk and move with the assembly line, participants were required to stand in one place. Often participants complained of back pain and were seen stretching their lower trunk during the provided rest periods. Participants preformed the experiment while standing on a forceplate (3ft. x 2 ft.) to allow for balance data to be collected and analyzed in future work. With limited movement area participants were not able to freely change their stance. Operators in automotive assembly plants are often required to walk with the product as it travels overhead perhaps adding to task difficulty.

Perhaps the most critical limitation to this study is the operational definition of fatigue. The results of the study are dependent upon the existence of a direct relationship between fatigue development and injury potential. While fatigue is a commonly used as a surrogate measure of injury it is still a major assumption. With the exception of RPD and endurance time, the remaining independent variable's fatigue times were determined with the use of a fatigue index. Many of the results in this experiment were based on using predictive equations for determining the fatigue point. Fatigue times were calculated when a significant change in the rate of change was identified. The rate of change function is less reliable for variable data, which was prevalent among the performance metrics. In addition to variable data, the experimental conditions also created by a ceiling effect for TRPD and TEND. Since the task was stopped at three hours even if no criteria for stopping had been met, this placed an artificial limit on the endurance times. The other variables (TMVE, TTA, THF) used data extrapolation to determine fatigue times beyond 180 min. This experimental design aspect was justified by typical industrial work patterns. Due to break schedules industrial workers rarely exceed a work period that is longer than three hours but nonetheless still affected the TRPD and TEND results. A primary strength of the present experiment was the use of multiple measures of fatigue. While no one measure of fatigue stood out as the best predictor, with the use of multiple measures practitioners can choose the measure that best fit's their need.

Future research in this area should be focused at increasing the power of the study. The power of the study was relatively low considering there were only 16 participants that were used during this initial phase. It is also important to note that the participants in the current study were not work hardened like workers typical to assembly plants. Repeating the experimental design with an increased number of independent variables will also help to increase the power of the study. Particularly increasing the number of duty cycle conditions will help to determine if the effects determined from this initial study are true. As noted earlier female participants had longer endurance time, reached TRPD later, and had MVEs decline at a slower rate than male participants. While the current study decided to ignore this gender effect due to industrial applications it would be interesting to further investigate the gender differences in fatigue development during overhead work. The results, while limited due to sample size, tend to suggest that females develop shoulder fatigue at a slower rate than males during overhead work.

Chapter 7. Conclusions

The two main objectives of the current study were to first examine human capabilities during overhead work, and second evaluate the effects of fatigue on task performance. With a better definition of human capabilities during overhead working conditions industrial task designers can use the results to design work cycles that minimize the effects of muscle fatigue and in turn reduce shoulder injuries. Current industrial standard for preferred working posture is to design work that can be performed with the arms close to the trunk, at the waist, and elbows at the side (Konz, 1990). Past research has proven links between increased degree of arm elevation and an increased rate of fatigue (Chaffin 1973, Herberts 1984). However it is unrealistic to expect all industrial tasks to be performed in the preferred working posture. The question then is if work is performed outside of preferred posture, how long can that posture and work be maintained? Table 11 describes the fatigue times by independent variable for each condition. Task designers should choose the condition that most closely mimics their work situation and then choose the fatigue measure that matches their main design objectives (e.g. Optimizing injury reduction would require use of TMVE or TRPD variables compared to choosing TTA or THF for performance optimization).

The data collected during this study would support that a worker would experience physical fatigue prior to showing performance decrements. However, it is important to note that at any degree of elevation there will be performance decrements compared to work at elbow height. Most likely the performance decrements appear in the form of increased time to perform the task and increased efforts to perform the task. These movement related decrements occur almost immediately when the hands are placed overhead. Therefore, efforts should be made to avoid working postures above the shoulder. The time to fatigue data (Table 11) serves as guidelines to task designers. These guidelines can be used to determine work rotation schedules and develop overhead working tasks that will reduce the potential for injury development and optimize task performance.

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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 sixteen participants 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 which 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 : 1. Male 2. Female
(please circle one)
Address :
____

Phone # and email :
____

Date of Birth : _______________

What is your present work? : _______________

How long have you been doing it? : _______________

Handedness : 1. Right 2. Left
(please circle one)

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 RPD SCALE INSTRUCTIONS

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

6 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

7 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 (<10K?) ?
12.0 Warmup exercises (~2 minutes + 2 minutes rest) ?
13.0 Lumbar *RAMP* MVEs ?
  13.1 Shallow breaths during rest trials
  13.2 Fold arms during torso extension, measure moment arm
14.0 Shoulder *RAMP* MVEs ?
  14.1 Rest after trapezius trial
15.0 Practice Trials ?
16.0 Redo Shoulder RAMP MVEs 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 __ __ __ __ __ __ __ __

22.0 Lab Preparation

22.1 Forms, trial lists, fees for subject, etc. ? ? ? **?** ? **?** ? **?** ?

22.2 Strain Gauge calibration ? ? ? **?** ? **?** ? **?** ?

22.3 Fixture setup and positioning ? ? ? **?** ? **?** ? **?** ?

22.4 Configure Labview programs ? ? ? **?** ? **?** ? **?**

22.5 Prepare buckets and weights ? ? ? **?** ? **?** ? **?** ?

23.0 Subject Preparation

23.1 Verify no soreness or abnormal activities ? ? ? **?** ? **?** ? **?** ?

23.2 Clothing ? ? ? **?** ? **?** ? **?** ?

23.3 Electrode placement *(see Diagram)* ? ? ? **?** ? **?** ? **?**

23.4 Check resistance ? ? ? **?** ? **?** ? **?**

24.0 Pre-testing

24.1 Subject bathroom break ? ? ? **?** ? **?** ? **?**

24.2 Verify interelectrode resistance (<10K?) ? ? ? **?** ? **?** ? **?**

24.3 Set EMG amplifier gains ? ? ? **?** ? **?** ? **?**

24.4 Rest (>5 min) ? ? ? **?** ? **?** ? **?**

25.0 Testing

25.1 Warmup exercises (~ 2 min) ? ? ? **?** ? **?** ? **?**

25.2 Baseline RPD values ? ? ? **?** ? **?** ? **?**

25.3 Baseline MPF values using test weights (x3) ? ? ? **?** ? **?** ? **?**

25.4 Lumbar rest &*RAMP* MVEs (Record force & RMS; x1) ? ? ? **?** ? **?** ? **?**

25.5 Shoulder rest &*RAMP* MVEs (Record force & RMS; x1) ? ? ? **?** ? **?** ? **?**

25.6 Run Task Configuration ? ? ? **?** ? **?** ? **?**

25.7 Stop when any of MVEs is <75% or RPD >6 ? ? ? **?** ? **?** ? **?**

25.8 Final Shoulder *RAMP* MVEs ? ? ? **?** ? **?** ? **?**

26.0 Post-Testing

26.1 Electrode marker instructions ? ? ? **?** ? **?** ? **?**

26.2 Avoid abnormal shoulder activity and rest ? ? ? **?** ? **?** ? **?**

26.3 Confirm next session and pay subject ? ? ? **?** ? **?** ? **?**

Kim Sherman

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VITA

Education

12/1997 – 12/ 2003 Virginia Tech, **Blacksburg VA**
M.S., Industrial and Systems Engineering - Human Factors Engineering and Ergonomics

09/1993 – 12/1997 Virginia Tech, **Blacksburg VA**
B.S., Industrial and Systems Engineering, Dec 1997
Minor: Psychology

Certifications & Associations

Engineer in Training (F.E., 1997)
Practitioner in MODAPTS Fundamentals
Alpha Pi Mu
Human Factors and Ergonomics Society

Experience

Sandalwood, Farmington Hills Michigan 2001 - present
Senior Project Engineer

- Overhead work measurement at automotive assembly plants
- Installed process verification system at Norfolk Assembly plant as part of the 2204, F-150 launch
- Conducted evaluation of current Ergonomics process and outcome metrics. Performed statistical analysis to determine correlation between process metrics and program results.
- Performed ergonomic risk analysis at automotive assembly plants, classifying root cause
- Co-Developed rotation program based on Ergonomic risks including process protocol and job assignment logarithms

Johnson Controls Incorporated, Holland Michigan1999-2001
Corporate Ergonomist

- Wholly responsible for the ergonomics of all door panel products, prototypes, manufacturing lines, and operators throughout the organization.
- Improved, created and maintained a successful global ergonomic program.
- Taught and created focused ergonomic training classes aimed at educating engineers, leadership, and operators.

- Taught plant ergonomic teams how to recognize, analyze, and resolve ergonomic risk factors. Facilitated classes on a monthly basis at regional and local facilities. Worked with these cross-functional teams to brainstorm solutions and follow through with implementation.

Publications and Presentations

- Maury A. Nussbaum, Laura Clark, Margeret Lanza, Kim Rice: Fatigue and Endurance Limits During Intermittent Overhead Work. AIHAJ. (62): 446-456 (2001)
- Presentation 46th Annual Human Factors & Ergonomic Society
  K. Rice, B. Joseph, H. Kilduff-Rich: The Ergonomics Process in a Large Industry: A Case Study. Proceedings HFES (2002)