Localized Muscle Fatigue during Isotonic and Nonisotonic Isometric Efforts

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Abstract

Work-related musculoskeletal disorders (WMSDs) are prevalent in the workplace, and epidemiology studies show that these problems do not tend to diminish. While the use of new and advanced technology has substantially reduced the amount of physical workload, repetitive manual activities are still typically observed in various work settings. Despite their fairly low workload intensity, prolonged repetitive tasks have been associated with the development of musculoskeletal complaints and problems. Research on localized muscle fatigue (LMF) has been viewed as a viable endeavor toward understanding the processes and mechanisms associated with WMSDs. A mounting of evidence on local fatigue during sustained static work has been presented, but much less is known with respect to muscle fatigue during more complex activities.

A study was conducted with the primary objectives of determining the repeatability of several commonly used fatigue measures, and to evaluate the presence of long-lasting effects of fatigue from different recovery periods. Based on low-level intermittent arm abductions, findings from this study demonstrated that the use of perceptions of muscular discomfort and muscle strength as fatigue measures was satisfactory. In contrast, electromyography (EMG)-based measures were characterized by a fairly low repeatability. The study also suggested that, whenever practical, two days of recovery should be allotted in studies involving multiple exposures to fatiguing protocols. Long lasting effects of fatigue could be present when shorter amounts of recovery period were assigned.

A second study was also carried out to investigate the effects of work parameters (force-level, work-rest ratio, and work cycle) on muscular fatigue during intermittent static efforts. It was suggested that work conditions with muscular contraction level less than 12% MVE was non-fatiguing, irrespective of the values of the work parameters selected. Intermittent work with higher levels of muscle contraction might be acceptable, but it was dependent upon interactions of the other two parameters.

The effects of dynamic work conditions on muscle fatigue were investigated in another study. Findings from this third study suggested that muscles responded differently under dynamic conditions and the use of typical EMG measures (dynamic EMG) could be less sensitive. This study further demonstrated that fatigue evaluations during such conditions were difficult, and only a limited number of EMG-based measures could be potentially employed.

Dedication

Praise be to Allah – only with His blessings was this endeavor possible.

To my wife, Dewi, you are the most incredible person in my life. This work is dedicated to years, and years of your relentless patience and caring support.

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CHAPTER I

INTRODUCTION

1.1 RATIONALE FOR THE STUDY

Physical fatigue is a common phenomenon that people experience in their daily activities, and it can be generally indicated by a reduced ability to perform muscular work. Strenuous exercise or physical work, such as manual material handling (MMH) tasks, performed for an 8-hour work period can often lead to fatigue. Signs of fatigue are usually evident in an individual engaged in prolonged physical work requiring more than 30% to 40% of the individual's maximal aerobic capacity (Åstrand and Rodahl, 1986). Symptoms of fatigue may include subjective feelings of tiredness, which sometimes is accompanied by a decline in alertness, motivation, or willingness to perform the work. Fatigue is also often accompanied by substantial increases in physiological measures, such as heart rate, minute ventilation, body temperature, or oxygen uptake. For dynamic work requiring more than 50% of maximal aerobic capacity, it has been suggested that metabolite accumulation and a disturbed homeostasis result in fatigue and reduced endurance (Rodahl, 1989; Kilbom, 1995). In designing jobs involving physical exertions, the primary concern is usually to minimize fatigue, by creating tasks with metabolic demands that do not exceed the capacity of the cardiovascular system.

More recent technology has dramatically reduced the amount of heavy physical work required in performing industrial jobs. Advanced material handling equipment used in automobile manufacturing facilities, for instance, has eliminated most of the lifting, pushing, or pulling activities associated with assembling cars. In addition, guidelines for designing physical work, such as the NIOSH Lifting Equation (Waters et al., 1994), have been prescribed widely in order to reduce the likelihood of symptoms and injuries attributed to lifting activities. A number of similar guidelines have also been proposed that address other MMH activities such as pulling, pushing, and carrying. Administrative and engineering approaches to job design guidelines have also been reported (e.g., Sommerich et al., 1993). Though compliance is not necessarily implied, standards on prevention of musculoskeletal disorders have also been proposed (Dainoff, 1998). It is intended that the use of these guidelines and standards could result in work exposures (job demands) that are within workers' physical limitation and capacity, which ultimately reduces the risks of musculoskeletal symptoms and problems in industry.

While advances in production technology have typically eased workers from heavy physical activities, the occurrence of work-related musculoskeletal disorders (WMSDs) seems to persist in many industrial settings. The prevalence of WMSDs has been indicated in different reports (Magnusson and Pope, 1997; Evanoff and Rempel, 1998; Fathallah et al., 1998), and a high prevalence of such disorders has been noted in the United States and other developed countries (Gatchel and Mayer, 2000). Musculoskeletal symptoms and problems have been associated with various types of job, including office work (Maeda, 1977; Sommerich et al., 1993), manufacturing activities (Herberts and Kadefors, 1976; Maeda, 1977; Jonsson et al., 1988; Veiersted, 1994), service industry (Sommerich et al., 1993; Vasseljen et al., 2001), and construction sectors (Malmqvist et al., 1981).

The etiology of musculoskeletal injuries can be complex and multi-factorial (Jonsson et al., 1988; Westgaard, 1988; Visser et al., 2000; Forde et al., 2002), but a body of evidence suggests that several work factors (such as force, repetition, non-neutral posture, and vibration) are associated with the development of WMSDs (Evanoff and Rempel, 1998; Melhorn, 2000). In light manual jobs, static load and working with elevated arms have been shown to be related to disorders of the upper extremity (Sommerich et al., 1993; Björkstén et al., 2001). Individual and non work-related factors have also been cited as possible risk factors (Aptel et al., 2002), and more recently, studies have noted possible links between psychosocial factors (such as high mental load and remuneration) and the development of the disorders (Kumar and Fagarasanu, 2003).

Injury models and mechanisms have been proposed (Hagberg, 1982, Hagberg, 1984; Lieber and Friden, 1994; Kumar, 2001), and it has been shown that adverse effects to the human connective tissues can be cumulative. Prolonged and repetitive work tasks, in particular, could result in chemical disturbances that in the long run may result in injury and pain. Note that higher force is not necessarily a prerequisite for injuries to the muscle fibers. Indeed, musculoskeletal symptoms and complaints have often been reported in jobs requiring fairly low muscular workload. Known as the Cinderella effect (Sjøgaard and Søgaard, 1998), the hypothesis in such a condition is that the same group of muscle fibers is continuously recruited that results in impaired local metabolism, and the consequences become more deleterious when the same recruitment pattern is repeated over a long period of time.

In the past decade, efforts have been devoted toward understanding localized muscle fatigue, partly due to the possible connections between muscle fatigue and WMSDs (Baidya and Stevenson, 1988). Though the contributory effects of muscle fatigue on the development of disorders is not presently clear, it has been suggested that repetitive exposure to fatigue may result in impaired muscle functions. Muscle fatigue does not necessarily imply disorder (Mathiassen and Winkel, 1992), and no causal relationship between muscle fatigue and disorder development has yet been presented (Hansson et al., 1992). However, several studies suggest that factors closely related to fatigue, such as sustained muscle tension, work posture, and repetitive work, can contribute to the development of shoulder problems (Sommerich et al., 1993; Veiersted, 1994; Björkstén et al., 2001), which also imply that fatigue can be used as a surrogate measure of the risk (Nussbaum et al., 2001). It is generally accepted, though, that with an inadequate amount of recovery, cumulative fatigue may ultimately lead to adverse health effects (De Vries, 1968; Hagberg, 1982; Hagberg, 1984; Sundelin and Hagberg, 1992; Sommerich et al., 1993; Byström and Fransson-Hall, 1994; Kumar, 2001).

Studies on localized muscular fatigue may elucidate processes and mechanisms leading to the development of WMSDs, and provide information on task parameters associated with these disorders. With respect to designing industrial jobs, results from these studies could be used to establish guidelines and limits, with the purpose of minimizing the occurrence of musculoskeletal problems and symptoms in the workplace. A substantial amount of evidence has been presented that describes muscle fatigue from sustained static work, but only little information is available with regard to fatigue characteristics during more complex efforts.

1.2 THEORETICAL BACKGROUND

In contrast to fatigue involving the whole body, the concept of muscle fatigue has been used to indicate the effects of work (exercise) on a specific group of muscles. Although the phenomena of muscle fatigue can be traced back to reports in the early 1900s (e.g., Cobb and Forbes, 1923), Chaffin (1973) is probably the first author who coined the term “localized muscle fatigue” (LMF). Several definitions of LMF have been offered in the literature. LMF is most commonly described as occurring when there is a decrement in the amount of tension a muscle can generate, or when the muscle can no longer maintain the required force level due to exercise (Clarke and Stull, 1969; Komi and Tesch, 1979; Hagberg, 1981; Hainaut and Duchateau, 1989).

A slightly different definition has been offered (Fitts, 1996; Vøllestad, 1997) that defines local muscle fatigue as a reduction in muscle strength. The former definitions often imply that fatigue occurs at a specific point in time when the muscle is exhausted (i.e. failure point), while the latter suggest that fatigue (as assessed by declines in muscle strength) may have already occurred even before the muscle fails to perform the required contraction. The second definition, therefore, views LMF as a progressive event that can be indicated by a number of time-dependent changes. The concept of fatigue as a gradual process is also more preferable (De Luca, 1984; Bonato et al., 1996; Vøllestad, 1997), and allows investigators to observe mechanical, physiological, and biochemical changes that exist prior to exhaustion. More valuable information can thus be obtained by examining the fatigue process than merely noting the failure point.

LMF is often associated with certain types of work characteristics, such as prolonged dynamic and/or repetitive tasks. A decrease in muscle performance (strength) resulting from sustained static contractions has also been frequently cited. Presently, no well-established muscle fatigue mechanism has been reported, although based on some studies a number of possible factors have been suggested. Two primary processes – central and peripheral – are involved in muscle fatigue (Fitts, 1996). Central fatigue involves initial stimulation at the level of central nervous system and the transmission of action potentials along the motor neurons, while peripheral fatigue is related to the processes occurring at the neuro-muscular junction and the contractile elements. Central fatigue, such as impaired neuromuscular function, has been suggested as a critical factor contributing to LMF (Clarke et al., 1958; Avela et al., 2001)

Peripheral processes have been thought to play a more important role in LMF (Lieber and Friden, 1994), and more extensive descriptions of peripheral fatigue mechanisms have been offered in the literature. For instance, an imbalance of Na^+ and K^+ ions impairs the propagation of action potentials along the sarcolemma (Sjøgaard et al., 1988; Sejersted and Vøllestad, 1993; Fitts, 1996; Vøllestad, 1997). These action potentials are needed to facilitate the release of calcium ions, which in turn promotes the contracting mechanism of myosin and actin filaments. A number of factors may also degrade the process of Ca^{2+} release (and reuptake) from the sarcoplasmic reticulum, which consequently results in reduced number of cross-bridges (i.e. lower force or power produced). It is believed that accumulation of metabolic products, such as phosphate ions, is one of the main factors that reduces the affinity of the Ca^{2+}.

Muscle fatigue has also been associated with a decline in oxygen availability (Murthy et al., 2001) due, for example, to ischemia, which results in impaired metabolite removal. Additional evidence based on the use of near infra-red spectroscopy (NIRS) has also shown that the endurance of lower-back muscles was closely linked to the availability of oxygen (Yoshitake et al., 2001), although oxygen decreases due to elevated intra-muscular pressure were demonstrated only at moderate to higher levels of muscle contraction. An opposing argument suggested, however, that although muscle ischemia might induce LMF, lack of oxygen was not the responsible factor; rather, failure of the excitation-contraction coupling mechanism was the result of an accumulation of potassium (Kahn and Monod, 1989).

In summary, muscle contraction involves a series of long and complicated processes (see Westerblad et al., 2000 for a review). LMF may occur due to degraded processes at various sites, and multiple factors have been thought to contribute to this impairment. Muscle fatigue can also occur during both high and low levels of muscle contraction, particularly during prolonged static or dynamic work. It is generally difficult to specify a single factor responsible for the development of muscle fatigue, and the exact muscle fatigue mechanism is currently debatable.

Several different methods have been used to characterize manifestations of muscle fatigue. A number of subjective and objective signs can be observed, and have been utilized to indicate the development of LMF from repetitive or sustained efforts. One of the commonly used subjective measures is Borg's CR-10 scale (Borg, 1990). Using the scale, an individual's perception of muscle fatigue or discomfort resulting from an exercise can be expressed by assigning a number between 0 and 10, although pain or other muscular discomfort may not necessarily correlate with the development of LMF (Sejersted and Vøllestad, 1993). A widely used objective fatigue criterion, which is often considered as a gold standard, is the time-dependent decline of an individual's maximum voluntary exertion (MVE). Reduced work output, such as production rate, and a decline in work accuracy may also indicate local fatigue. Indirect but objective assessment of muscle fatigue can also be performed by measuring biochemical changes in the muscle. Additionally, NIRS has been increasingly used for determining the association between lack of oxygen and fatigue development.

Electromyography (EMG) has often been used to study muscle functions, and changes in EMG measures may indirectly indicate the development of muscle fatigue. The literature has generally shown that muscle fatigue from static contractions can be indicated by increases in EMG signal amplitude (Lindström et al., 1977; Kadefors, 1978; Duchene and Goubel, 1993) and/or spectral shifts toward lower frequencies (Chaffin, 1973; Kadefors, 1978; Marras, 1990; Duchene and Goubel, 1993; De Luca, 1997). The root-mean-square (RMS) of the signal has been commonly used to represent the magnitude of the signal, whereas the mean power frequency (MnPF) or median frequency (MdPF) has often been used to indicate shifts of the power spectrum. Significance of signal changes has been suggested in some studies (e.g., Öberg et al., 1990; Hagberg, 1981a) to indicate the onset of fatigue. The latter author has suggested that a decrease in MnPF accompanied by an increase in amplitude is a strong evidence for fatigue.

Different studies conducted in controlled settings have also confirmed the typical EMG changes during fatiguing isometric contractions. Petrofsky et al. (1982), for example, investigated changes in myoelectric amplitude and center frequency during fatiguing isometric contractions involving the handgrip, adductor policis muscles, quadriceps muscles, and biceps muscles. The exercise was sustained at 25, 40, or 70% of the subject's maximal voluntary contraction (MVC), and changes in EMG amplitude and center frequency were recorded throughout the duration of the exercise. The results showed that the EMG amplitudes increased throughout the duration of the exercise for all of the muscles, in all three levels of contractions. Except for the biceps muscles, the increases in EMG amplitude were linear in all contraction levels. This study also reported a linear decrease in center frequency of the spectra at any muscle tension in all muscle groups. Hagberg (1981b) investigated EMG signals during sustained and intermittent isometric contractions performed by the elbow flexors. The sustained contractions were performed at 15 – 50% MVC, while the intermittent exercises (50% duty cycle) were performed at mean contraction levels of 25 – 40% MVC. The study showed that fatigue development was well correlated with changes in amplitude and MnPF. Similar results have also been indicated in a number of other studies examining sustained contractions of finger flexors, elbow flexors and extensors, and knee extensors (Jørgensen et al., 1988), the deltoid and trapezius muscles (Hermans et al., 1999), the tibialis anterior muscles (Merletti et al., 1990), the trunk extensor muscles (Dieën et al., 1998), and the rectus femoris muscle (Viitasalo and Komi, 1977).

The mechanism underlying changes in EMG signals associated with fatiguing isometric contractions is still debated. Three possible explanations have been discussed in the literature, including motor unit recruitment, motor unit synchronization (grouping), and changes in muscle fiber conduction velocity (MFCV). Vøllestad (1997) has suggested that to maintain constant force output, additional recruitment of muscle fiber is performed, which is reflected in the increase in amplitude. De Luca (1984), however, has suggested that the first mechanism, although plausible, may not necessarily be true since at high muscle contraction (with minimal changes in recruitment) an increase in amplitude can still be observed. The second mechanism has been proposed by Chaffin (1973) as one of the primary mechanism causing EMG changes. Several researchers, however, have argued that the mechanism is not supported by the available evidence and mathematical modeling (e.g., Lindström et al., 1977; De Luca, 1984; De Luca, 1997). The last mechanism is probably the one most commonly cited in the literature. De Luca (1997) argued that the occlusion of blood flow (which can occur even at low contraction level) may cause accumulation of metabolic products, causing a decrease in pH of intra-muscular fluids, resulting in a decrease in conduction velocity, and finally causing spectral shifts. Since the phenomena are associated with fatigue development, this may explain the relationship between fatigue and changes in EMG signals (Dieën et al., 1998). Note that reductions in muscle fiber conduction velocity have an impact mainly on type II fibers (Gerdle and Fugl-Meyer, 1992), and fatigue from exercise involving type I fibers may not be associated with EMG power spectrum shifts. The decline in conduction velocity may also have a small effect on spectral changes (Krogh-Lund and Jørgensen, 1992), and the trend of the decline may even differ from that of EMG changes (Caffier et al., 1993). Evidence is obviously mixed (Vøllestad, 1997), and the relationship between fatigue and shifts in EMG spectrum needs to be examined further.

1.3 RESEARCH OBJECTIVES AND FRAMEWORK

Investigators generally agree that LMF is a complex process, and a large number of studies have thus been conducted to better understand this process, and to offer some insights on the relationships between various work factors and the development of muscular fatigue. Extensive reports examining fatigue from pure static effort are generally available in the literature. Much less information, however, is available for intermittent and/or dynamic work, typical in many industrial tasks. A very limited number of guidelines and limits derived from fatigue studies are available for jobs involving shoulder/arm activities, yet many industrial tasks are characterized by activities of the upper extremities in elevated postures. Although considered critical for ergonomic application, little information on design parameters, such as work pace and recovery, has been reported in the literature. Additional issues not sufficiently addressed are evaluations of fatigue measures during low-intensity intermittent static work. Some difficulties have also been noted, particularly with regard to characterizing muscular fatigue from dynamic efforts. Acceptable measures have not been well established, and the effects of different dynamic task parameters remain unclear.

The present work was aimed at addressing research issues noted above. Three separate studies were conducted as listed below:

Study 1

This study was conducted with the primary objectives of evaluating the repeatability of different commonly used fatigue measures, and the adequacy of several different recovery periods. Fatigue measures were obtained from activities of the shoulder (middle deltoid) muscle during one hour of intermittent low-intensity static efforts.

Study 2

This investigation examined the effects of several work parameters (force level, work-rest regimen, and work cycle) on the development of local muscle fatigue. It was intended that the resulting information be used for establishing design guidelines for static intermittent work. The experimental protocol involved repetitive and intermittent arm abductions, maintained until exhaustion or up to one hour. Similar to the first study, several commonly used measures were employed to study fatigue in response to the different work conditions.

Study 3

This last study investigated local fatigue during (dynamic) isometric non-isotonic work. Three work parameters were manipulated, and the effects on muscle fatigue were examined accordingly. A few different data processing methods were utilized, and potential fatigue measures were proposed. Fatigue response was based on continuous arm abductions, but the experimental protocol involved time-varying changes of muscle contractions.

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CHAPTER II

REPEATABILITY AND RECOVERY OF MUSCLE FATIGUE MEASURES DURING INTERMITTENT STATIC WORK

2.1 INTRODUCTION

Though sound evidence indicating a direct relationship has not yet been established, the development of localized muscle fatigue (LMF) is believed to be associated with an increased risk of musculoskeletal problems, and several different approaches to muscle fatigue assessments have been reported in the literature. In addition to evaluations of recovery processes and muscular endurance, changes in muscle performance and subjective measures during fatiguing efforts have often been employed. Moreover, myoelectrical-based measures, such as amplitude, mean (MnPF) or median (MdPF) power frequency, have been extensively used for determining the development of muscle fatigue.

Inferences from fatigue investigations utilizing such measures, however, can be hampered by the fact that several confounding factors could contribute to changes of fatigue measures. Electromyography (EMG) signals, for example, are dependent on a number of factors, including changes in muscle temperature (Duchene and Goubel, 1993; Dieën et al., 1993; Madigan and Pidcoe, 2002), differences in muscle length and/or velocity (Rosenburg and Seidel, 1989), or differences in the muscle fiber compositions (Duchene and Goubel, 1993; De Luca, 1997). There are also additional factors to consider when one employs surface EMG, such as electrode sites and distance (Marras, 1990; De Luca, 1997; Hogrel et al., 1998), the location of the pre-amplifier (Marras, 1990), or electrode-skin impedance (Marras, 1990). Lack of attention to these factors, could result in higher EMG variability, which makes data interpretation more difficult.

It is also not uncommon during a fatigue study to have individuals participating in a series of experimental sessions. In such an investigation, a series of strength test and/or fatiguing protocols are presented, and exposures to these protocols might result in “training/practice effects”. Training involving moderate to high intensity level of isometric exertions improves not only strength but also muscular resistance to fatigue (Müller, 1965; Hainaut and Duchateau, 1989). Other studies have reported, however, that short periods of isometric training did not improve one’s ability to perform maximum exertions (Gabriel et al., 2001), and that this type of training might only help subjects become familiar with experimental protocols (Rutherford et al., 2001). Nonetheless, evaluations of muscle fatigue could become problematic if changes in muscular performance are in fact present, due to repeated exposures to the experimental protocol.

2.1.1 Research on Repeatability

The issues noted above raise a question if different fatigue measures are indeed repeatable (i.e., producing consistent and precise results). Investigators generally agree that a repeatable measurement is an important prerequisite, before appropriate and valid inferences can be drawn. Different researchers have often used the term “reliability”, “reproducibility”, or “repeatability” interchangeably. Throughout this manuscript, reliability of a measurement procedure (or a measure) will relate to the fact that such particular procedure results in consistent outcomes when repeated under the same experimental conditions. The precision of a measurement will indicate the magnitude of variability associated with the measurement. Repeatability, thus, concerns with evaluating the levels of reliability and variability of outcomes obtained from a series of experimental tests.

Two of the commonly reported reliability indices include the Pearson’s (r) and the intra-class correlation coefficients (ICC). Though often used to evaluate the performance of a measure, the Pearson’s (r) suffers from a major drawback that it does not discriminate systematic bias present in the data, and hence, is not recommended as a measure of repeatability (Bartko, 1976; Denegar and Ball, 1993). Bartko (1966) described notations used and different procedures involved in estimating inter-rater reliability. Using the correct analysis of variance model, the resulting reliability value can be interpreted as a correlation coefficient. ICC has been applied widely in social sciences (Bartko, 1966), and more recently, the use of this tool has been extended to evaluate the performance (and validity) of different measurement procedures (measures) in other research areas, including ergonomics and clinical rehabilitations. ICC values typically range from 0 to 1, though negative values can still be obtained in some cases (Shrout and Fleiss, 1979). A value of zero is assigned when these negative ICCs are present. An ICC value of unity denotes perfect agreement among experimental trials (or raters), while 1-ICC (for $ICC \geq 0$) represents the percentage of variance due to discrepancies among trials (raters) (Bartko, 1976). It should be noted that a fairly small within-subject variance (compared to that of between-subject) is a prerequisite for high intra-class correlation coefficients (Bartko, 1976). The use of ICC as a method in determining repeatability has also brought up an issue of what constitutes “a reliable measure”. It has been a subject of discussion whether certain ICC values, say 0.7, can be considered as “moderate”, “good”, or even “excellent”. Disagreement seems to exist among researchers, and labeling ICC values has been perceived as a semantics matter (Shrout, 1998). Though dependent upon the circumstances of the research conducted, two of the more commonly used ICC indices can be calculated as follows (Shrout and Fleiss, 1979; Denegar and Ball, 1993):

$$\text{ICC}(2,1) = \frac{\text{BMS} - \text{EMS}}{\text{BMS} + (k-1)\text{EMS} + k[(\text{TMS}-\text{EMS})/N]} \qquad (1)$$

$$\text{ICC}(3,1) = \frac{\text{BMS} - \text{EMS}}{\text{BMS} + (k-1)\text{EMS}} \qquad (2)$$

BMS: Between-subject mean square
EMS: Error mean square
TMS: Trial mean square
k: Number of trials
N: Number of subjects
Note: Equation (2) is applied when a composite measure is used

Two additional (complementary) measures when performing a repeatability investigation have also been more commonly reported, including “standard error of measurement (SEM)” and “coefficient of variation (CV)”. While ICC indicates reliability, thus often used to evaluate the utility of a measurement procedure, it does not provide information on the measurement levels of precision. SEM and CV, on the other hand, provide an estimate of measurement precision, which in some cases are critical. Denegar and Ball (1993), for example, described the importance of reporting SEM along with ICC that allows for better data interpretation in a clinical setting. Further (and more detailed) arguments for the use of SEM were provided by Keating and Matyas (1998). In their paper, a case was presented in which high repeatability of a measurement does not necessarily mean high measurement utility. In fact, the paper demonstrated that fairly low ICC might be of little concern, assuming that the magnitude of measurement error is small. It should be noted that what constitutes a small measurement error will highly depend on the type of the measurement involved, and how the results will be interpreted. Calculations of both SEM and CV are provided in the following equations (Sleivert and Wenger, 1994).

$$SEM = SD \sqrt{(1-ICC)} \qquad (3)$$

$$CV = (SEM/Mean)*100 \qquad (4)$$

SD: Standard deviation of a measure
Mean: Grand mean of a measure

Investigations on repeatability have been conducted in various research areas, with a typical goal of determining the utility of certain measurement procedures. Dabonneville et al. (2003), for example, demonstrated that a single protocol (5 min running test) was deemed satisfactory for the purpose of estimating one's physical fitness. This conclusion was drawn on the basis of fairly high test-retest ICC values, combined with the small measurement errors. In the area of physical rehabilitation, Fong and Ng (2000) investigated several wrist postures and the associated grip strength. Their study was motivated by the fact that conflicting evidence existed as to which wrist position resulted in higher grip strength. Their results revealed that grip strength measurements were indeed highly repeatable (ICC > 0.9), regardless of the wrist posture adopted during the tests. A slightly different type of study (Geurts et al., 1993) was conducted, which involved subjects standing on a force platform. In this study, CV values were utilized in determining the best platform stabilometry parameters out of several measures commonly used in standing-balance experiments. Valuable information obtained from repeatability investigations have been exhibited in studies evaluating different test protocols among patients vs. healthy individuals (Keller et al., 2001), new strength test protocol (Dvir and Keating, 2001), and isometric strength tests in the workplace (Essendrop et al., 2001).

Despite the wide use of EMG in various (experimental, clinical, and work) settings, the issue of its repeatability used to receive very little attention. The work of Komi and Buskirk (1970) was one of a few early investigations addressing the repeatability of EMG measures.

Their study involved registrations of surface and wire electrode EMG during various levels of short isometric contractions. Moderate to excellent within-day reliability for the surface EMG amplitude was reported, and high reliability for the same measure was found for maximal effort during both static and dynamic contractions. These researchers also suggested the suitability of surface EMG for the purpose of long-term investigations.

In the recent decade, more studies have been conducted that address the repeatability of EMG measures and protocols in clinical, experimental, and work settings. Various types of muscular efforts have been investigated, and the reliability and precisions of different EMG-based measures have been assessed. Fairly high reliability (ICC >0.7) has been typically reported for measures obtained during maximal efforts (Sleivert and Wenger, 1994; Larsson et al., 1999; Cramer et al., 2002; Larsson et al., 2003). High reliability was also reported in a study examining MdPF collected from workers performing repetitive tasks (Veiersted, 1996). Good results were demonstrated in a study examining within- and between-day reliability of a range of sub maximal tests (Viitasalo and Komi, 1975.

In contrast, a broad range of repeatability has been reported for the use of amplitude and spectral measures (MnPF or MdPF) to evaluate local muscle fatigue. Larivière et al. (2003) reported considerably high reliability and small SEM of MdPF and amplitude slopes, during three trials of brief (30s) isometric efforts. Satisfactory results were also reported in an investigation comparing low-back pain vs. healthy individuals (Larivière et al., 2002), and the study further suggested that composite fatigue measures might improve reliability. On the other hand, in a study involving brief isometric back exercise (Elfving et al., 1999), repeatability for MdPF was moderate for the initial values, but poor for its rates of change. The investigators reported ICC of 0.04 to 0.46 and SEM of 0.17% to 0.30%/s for the MdPF slope, and further concluded that the large variability might make this measure of limited use. Similar study was also conducted (Falla et al., 2002) that examined EMG fatigue measures during very short (15 s) static cervical flexions over three non-consecutive days, and reported considerable wide levels of repeatability for the amplitude and MnPF. Mixed results have been reported in several other studies (Linssen et al., 1993; Ng and Richardson, 1996; Rainoldi et al., 2001).

2.1.2 Recovery of Muscle Fatigue

Appropriate assessments of local muscle fatigue can also be influenced by the amount of rest period assigned, such as when an individual is involved in a series of (experimental) tests, typical in studies evaluating the effects of certain work or experimental conditions. Depending on the types of efforts involved, studies investigating muscle fatigue during isometric or dynamic exercises have typically assigned one day to a couple of weeks of recovery between sessions (Petrofsky, 1986; Ng and Richardson, 1996; Knight and Kamen, 2001; Sbriccoli et al., 2001), while other studies have suggested substantially shorter recovery periods in the order of minutes or hours (e.g., Byström and Fransson-Hall, 1994; Larivière et al., 2003). A short recovery period may not provide sufficient time for the exercising muscle to recover, which can potentially influence muscular performance in subsequent experimental tests.

While a few studies have indicated the inadequacy of short recovery (e.g., Kroon and Naeije, 1988; Sbriccoli et al., 2001), others have shown that fairly brief rest periods are generally sufficient for complete recovery of myoelectrical measures. Kourinka (1988) investigated the recovery of MnPF following low-to-moderate levels of static or dynamic efforts, and found progressive MnPF recovery during the first few minutes of rest. Similar results were obtained in this study when the tasks were repeated several days later. The work of Kadefors et al. (1968) also demonstrated similar phenomena, in which recovery of spectral measures was mostly achieved within 90s. This study, however, suggest that patterns of recovery were dependent on the type of muscles. Elfving et al. (2002) demonstrated that patterns of MdPF recovery followed an exponential model, in which rapid recovery occurred in the first few minutes after the cessation of the exercise. Larivière et al. (2003) and co-workers conducted a study examining muscle fatigue from high levels of isometric contractions, and evaluated both the initial and slope of EMG measures. Their results provided evidence that a short period (10 minutes) of recovery was in fact sufficient.

Complete recovery of EMG may occur within short period of rests, yet long term effects of fatigue on muscular physiology and performance may actually be present. In a fatigue protocol involving intermittent static contractions, Corcos et al. (2002) noted that 10 minutes was enough for the recovery of muscle fiber conduction velocity, but further argued that other fatigue effects might still exist. Funderburk et al. (1974) utilized strength and endurance in evaluating recovery processes following fatiguing static efforts. Results of their study demonstrated substantially longer recovery, about 10 and 40 minutes for the strength and endurance measures, respectively. Søgaard et al.

(2003) recently investigated the effects of low force (10% and 30% MVE) intermittent isometric contractions sustained for 30 minutes. Using 60% work - 40% rest duty cycle, these investigators found that fatigue effects were present for both force levels. Recordings of mechanomyogram and muscle strength further provided evidence that these fatigue effects were observed, even after 30 minutes of recovery. Relatively longer rest periods have also been suggested when one considers muscle strength in evaluating muscle recovery (Byström and Fransson-Hall, 1994; Sbriccoli et al., 2001).

Furthermore, the presence of fatigue carried over from a previous exercise session has been indicated in the literature, even though subjects have been given an ample amount of resting time (e.g. 24 hours) compared to the length of the exercise period. A phenomenon known as "low frequency fatigue (LFF)" has been addressed in a number of studies (Byström and Fransson-Hall, 1994; Vøllestad, 1997; Westerblad et al., 2000), a condition in which a decline in electrically induced maximal muscle force is observed after a period of recovery due to previous prolonged muscle activity. LFF may be present as a result of prolonged low-intensity exercise, although subjects are often not able to sense this type of fatigue (Westerblad et al., 2000).

Evaluating the sufficiency of a recovery process requires a close examination of the measures utilized, the type, intensity, and conditions of work (muscle contractions), as well as other factors potentially influencing muscle fatigue and endurance (e.g., gender, age, or learning). From an investigator's point of view, shorter recovery periods are usually preferred, yet several investigations have indicated the possible long-term residual effects of fatiguing efforts (Edwards et al., 1977; Corcos et al., 2002), which may ultimately influence muscular performance during a subsequent experimental session. A number of studies have addressed recovery of muscular functions from sustained static work, but little information is available with respect to intermittent efforts.

2.1.3 Purpose of the Study

With respect to the various common fatigue measures, repeatability has become a subject of interest since these measures could ultimately be used to determine if (increased) risks of musculoskeletal problems are present in the workplace. Incorrect interpretations derived from fatigue-related data could also mislead one when evaluating the acceptability of certain jobs. Studies examining muscle fatigue from moderate to high levels of sustained static work has been extensively reported in the literature, and the utility of EMG and other measures for the assessment of muscle fatigue have been generally well agreed upon. Little information, however, is available on the repeatability of fatigue measures obtained from intermittent, low-intensity isometric efforts. Mixed results have been reported, particularly with regard to the use of EMG for assessment of fatigue. Repeatability investigations in this area have focused on various muscle groups, yet results obtained from the shoulder muscle are very limited. Additionally, the allocations of certain amount of recovery in the order of hours or up to 24 hrs has been a common practice in fatigue studies involving multiple exposures to an experimental protocol. In such studies, however, the possible long-term effects of fatigue have often been neglected. Further investigation is thus warranted to determine if long-term fatigue effects are indeed present. Therefore, it was the intention of this present investigation to assess the repeatability of several common muscle fatigue measures, including amplitude and spectral measures of EMG, muscle strength, and a subjective measure, and further, to determine the adequacy of different recovery periods following prolonged low-level intermittent isometric efforts.

2.2 EXPERIMENTAL METHODS

2.2.1 Participants

Eight university students (four male, four female) participated. Only those who were right-handed, physically active (as determined by a questionnaire), and had no previous (within 12 months) and serious shoulder/neck problems were eligible. An initial session was used to collect participants' demographic and anthropometric data, and to obtain their informed consent. This session was also used for the participants to familiarize themselves with the experimental procedures. More detailed physical description of the participants is presented in Table 2-1. The experimental procedures were reviewed and approved by the Virginia Tech Institutional Review Board (IRB).

Table 2-1. Participants' descriptive data.

	Age (years)	Stature (cm)	Body Mass (kg)	Upper Arm Length (cm)[a]
Mean	21.8	171.5	68.0	29.7
Std. Dev.	2.3	7.7	10.9	1.0
Range	19 - 25	163.0 - 184.5	54.0 - 84.7	28.0 - 31.0

[a] Distance between the acromion and the lateral epicondyle while standing with arm abducted.

2.2.2 Experimental Procedures

Secured on a horizontal surface, each participant was instructed to lie in a supine posture with the right (dominant) arm abducted at 90^0 (Figure 2-1). This posture was selected to eliminate the effect of arm mass during contractions. A padded strap was placed adjacent (medially) to the elbow and connected to a fixed load cell (SM-500, Interface, Scottsdale, AZ, USA) via a thin steel cable. A specially designed platform with minimal friction was used to support the active arm. Four strength test trials were subsequently performed, consisting of maximal exertions (abductions) of the right arm. The largest value obtained during such a procedure was considered as the participant's maximum voluntary exertion (MVE) for this particular experimental session.

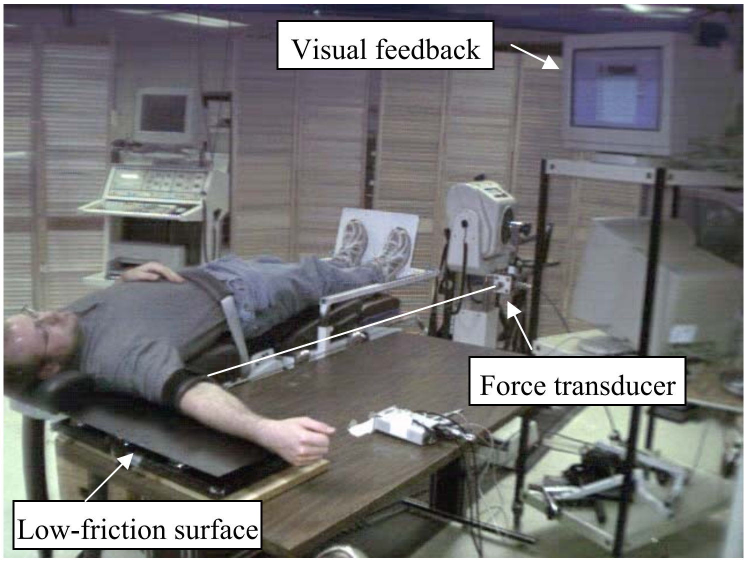


Figure 2-1. Experimental setup of the study.

Following a 10-minute rest, the participant performed the experimental task for an hour, consisting of intermittent arm abductions (10-second static contraction followed by 10-second relaxation) at 20% MVE. Computer-generated audio signals and visual force-feedback were given that indicated the amount of exertions to be maintained, and when to contract or to relax. MVE and ratings of perceived discomfort (RPD) were obtained every 10 minutes throughout the duration of the task, and immediately at the cessation of the task. Using the Borg's CR-10 scale (Borg, 1990), the latter measure represented participant's general perception of arm/shoulder discomfort associated with the task.

2.2.3 Recording and Processing of Surface EMG

Pre-gelled bipolar Ag/AgCl electrodes (1 cm diameter) with a 2.5 cm inter-electrode distance were used to obtain EMG signals. To ensure good skin-electrode contact, the skin was shaved, lightly abraded, and cleaned with 70% rubbing alcohol. An inter-electrode resistance of less than 10kΩ was considered acceptable. In a majority of cases, a resistance of less than 3-5kΩ was observed. Electrode placements over the middle deltoid muscles were performed according to Hermens et al. (1999). A measuring device and bony landmarks were used to maintain consistent electrode locations across experimental sessions (see below). A 20-minute period was provided in order to stabilize the electrodes on the skin. Additionally, each participant performed a light non-fatiguing muscle exercise (for about three minutes) to warm up the muscle.

An EMG amplifier (Measurement Systems Inc., Ann Arbor, MI, USA) was used to obtain myoelectrical signals. A preamplifier multiplied the signals by 100, and further amplification was done according to the gain setting of the amplifier. The signals were hardware filtered at 10 – 500 Hz; EMG raw and root-mean-square (110 ms time-constant) were subsequently sampled at 2048 Hz and 32 Hz, respectively. EMG signals were obtained only during the contraction period, and to minimize the effects of arm movement and/or changes in muscle tension at the beginning of muscle contraction, no recording was made during the first 2-seconds of the contraction period. Three evenly spaced 2-second EMG recordings were collected at the beginning, middle, and end of a contraction period (Figure 2-2).

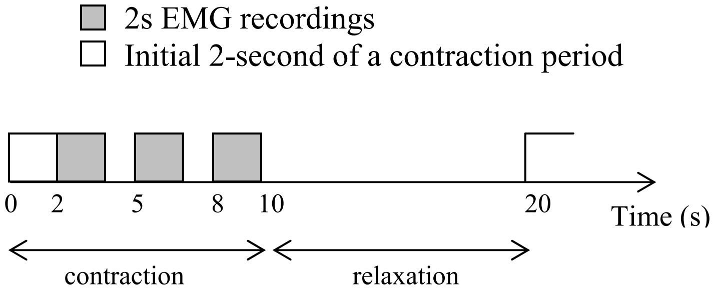


Figure 2-2. An illustration of EMG recordings during a contraction-relaxation cycle.

Each of the 2s raw EMG samples was separated into three overlapping 1s samples (Luttmann et al., 1996). Hanning window and Fourier Transform procedures were subsequently applied to each of the 1-second samples, and the resulting frequency spectra averaged to get a single power spectrum (Figure 2-3). Finally, spectral parameters (MnPF and MdPF) for the 2-second sample were determined (Merletti and Lo Conte, 1997) based on the averaged signal power spectrum. A program developed in LabView 5.1 (National Instruments) was utilized to collect and process the EMG signals.

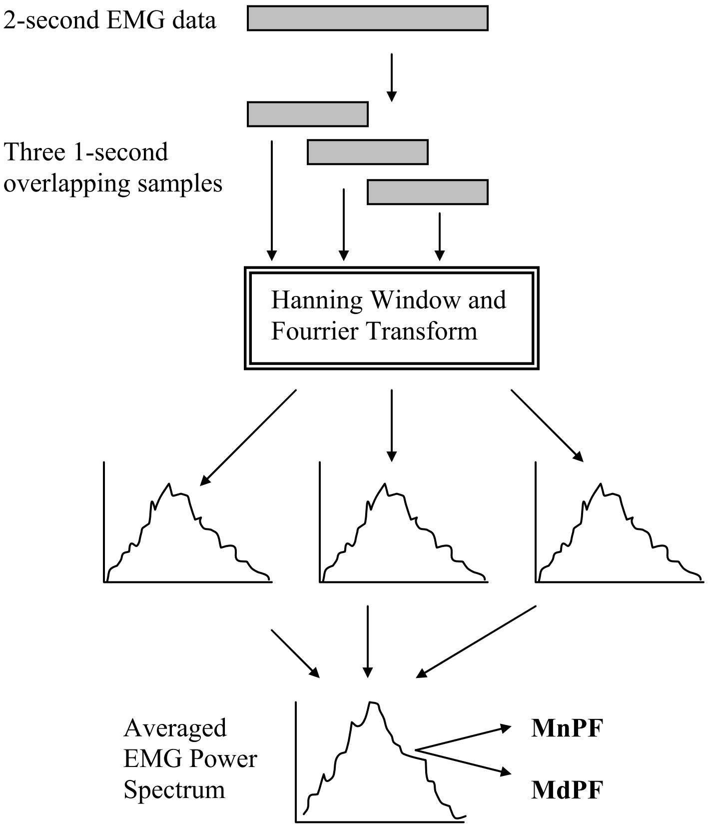


Figure 2-3. Schematic diagram of EMG processing procedure in the frequency domain.

2.2.4 Experimental Design

In order to assess the repeatability of the noted muscle fatigue measures, the exact same procedure was performed on five different experimental days (Day 1, 2, 6, 8, and 11). No counter balancing was done for this repeated-measures design, since the objective was to determine if order effects were present, and if these existed, to examine how they affected the repeatability of the fatigue measures. This design also resulted in four different recovery periods

(1, 2, 3, or 4 days) between two experimental sessions, with the expectations that inferences pertaining to the long lasting effects of fatigue could be implied. Therefore, the effects of recovery, if present, were confounded by the order of the experimental sessions. Dependent variables included initial (pre-fatigue) values and rates of change of muscle fatigue measures (i.e., MVE, RPD, RMS, MnPF, and MdPF). Intercepts and slopes of the fitted regression lines were used to estimate the initial values and rates of changes, respectively. Except for RPD, rates of change of the fatigue measures were normalized against the initial value. Analysis of variance (ANOVA) was employed to determine the significance ($P < 0.05$) of the main effect (experimental day) on the response variables. Repeatability of these variables was evaluated by intra-class correlation coefficients and the two measures of error (SEM and CV). ICC examines between-subject variability against within-subject variability, and unlike the commonly used correlation coefficient (r), is sensitive to systematic changes between experimental conditions (Denegar and Ball, 1993).

2.3 RESULTS

2.3.1 Maximum Voluntary Exertion (MVE)

Across experimental days and individuals, the range and mean (SD) of the initial (pre-fatigue) strength was 111.6-306.3 N and 186.6 (57.0) N, respectively. Within an individual, differences across days varied from 8% to about 24%, with an average of 14.2%. When initial MVEs on Day 1 were compared against those of Day 11, a tendency of increased muscular strength was observed in seven out of eight participants, and this effect was found to approach significance (P=0.09).

With respect to changes in muscle strength, a broad range of individual responses toward the experimental tasks was found. For example, a slight (4%) increase in strength was observed in one individual, while a decrease as large as (40%) was noted for another. Across days, the average MVE reduction (RedMVE) was 10% to 15%, with a maximum and minimum strength reduction observed on Day 2 and Day 8, respectively. Over all individuals, slopes of MVE (SMVE) reductions ranged from -0.11% to -0.18%/minute, and the results also demonstrated a similar phenomenon that the greatest effect on this measure was observed on the second experimental session (Day 2). In spite of these differences in MVE changes, the results were not significant for both the percent reduction ($P = 0.61$) and rates of decline ($P = 0.77$) measures.

2.3.2 Ratings of Perceived Discomfort (RPD)

When asked for their initial ratings, participants typically reported a rating of "zero" (no muscular discomfort) prior to performing the tasks. It is interesting to note that, on Day 1, half of the group gave clearly increasing ratings (Figure 2-4), while the rest gave relatively low values throughout the tasks. With minor variations, these patterns were generally similar across experimental days. Average final RPDs (FRPD) of about "3" were observed on Day 1 and 2, followed by considerable ($P = 0.08$) lower ratings for the remainder of the experimental sessions. Across days, slopes of RPD (SRPD) changes varied from 0.02 to 0.04/minute ($P = 0.18$), with the greatest slopes observed on Day 1 and Day 2.

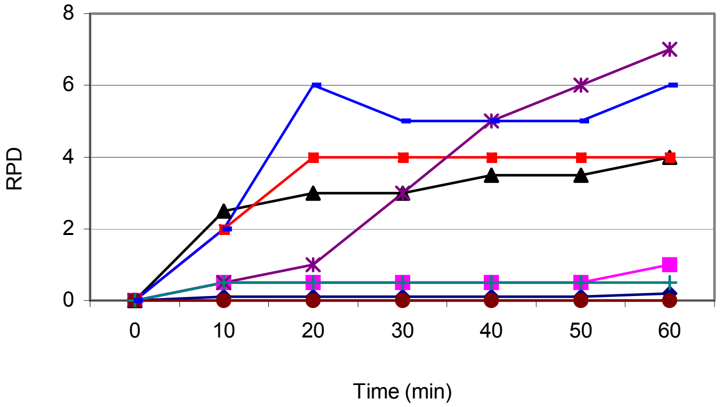


Figure 2-4. Individual RPDs obtained throughout the duration of the tasks on Day 1 (n=8).

2.3.3 Myoelectrical (EMG) Fatigue Measures

Root-Mean-Square (RMS)

Across individuals, initial RMS (IRMS) varied from 18.7% to 20.9% MVE (Figure 2-5). Within an experimental day, the highest intercepts were associated with the first data window, and vice versa. Inspections of the data suggested lower initial values on the first experimental day and considerably higher values for the remaining of the sessions. These day-to-day variations, however, were not significant ($P = 0.94 – 0.99$).

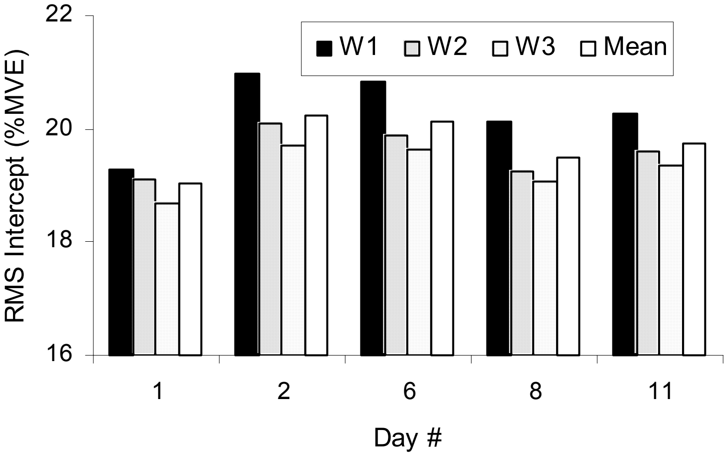


Figure 2-5. Intercepts of RMS data. W1, 2,and 3 represent the data window.

Though exceptions were present in a small number of sessions, declines in myoelectrical amplitudes were generally evident throughout an experimental task. Examining the first sampling windows only, for example, a total of 33 out of 40 experimental sessions were associated with negative RMS slopes (SRMS). Figure 2-6 demonstrates this observation, in which RMS data obtained from a participant showed a negative rate of RMS change. Note that, in several sessions, progressive declines were found during the first few minutes of the tasks, followed by more gradual slopes of the changes. Table 2-2 presents the magnitude of SRMS across individuals on each of the experimental days, which ranged from -0.0143 to -0.0638 %MVE/min. The greatest rate of changes was noted on Day 2, while the smallest was observed on the last experimental day (Day 11). Excluding results obtained on Day 1, the rates of RMS changes tended to decrease as individuals repeated the same tasks throughout the remainder of the experimental days. The *P* values, however, did not suggest significant differences for this measure.

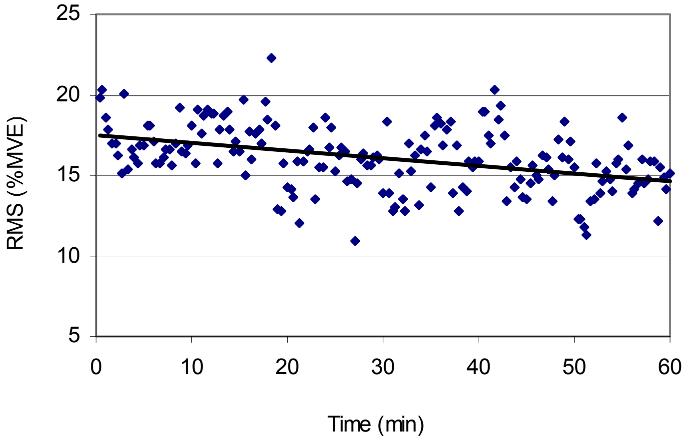


Figure 2-6. A sample of RMS data obtained from a participant on Day 2.

Table 2-2. Means of rates of RMS changes (%MVE/minute) across participants.

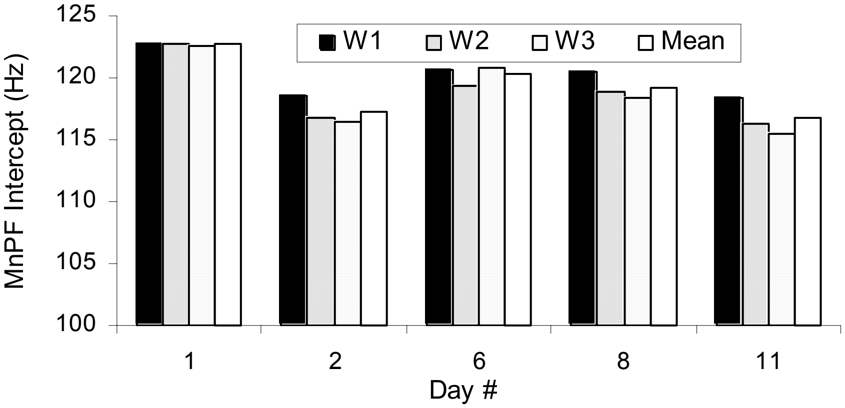
Data Window	Day # 1	2	6	8	11	*P*
1	-0.0550	-0.0638	-0.0346	-0.0349	-0.0273	0.4327
2	-0.0325	-0.0513	-0.0323	-0.0268	-0.0204	0.7726
3	-0.0325	-0.0325	-0.0244	-0.0224	-0.0143	0.9447
Mean	-0.0400	-0.0492	-0.0304	-0.0280	-0.0206	0.7547

Mean (MnPF) and Median (MdPF) Power Frequency

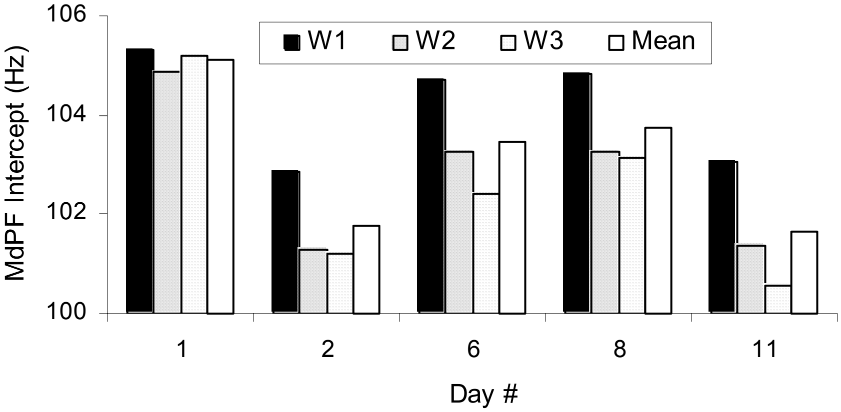
Depending on the experimental day involved, initial values of MnPF (IMnPF) taken from individual data varied from 101 to about 137 Hz (mean (SD) = 119.2 (7.6) Hz). Within an experimental day, the first sampling window tended to result in the greatest intercept value, followed by the second, and finally the third window (Figure 2-7). Marked differences in these intercept values were observed when comparing results between Day 1 and those of Day 2. Further statistical tests, however, did not indicate that experimental day affected these initial values of MnPF ($P = 0.103 – 0.312$).

Mean and standard deviation of the MdPF intercepts (IMdPF) were 103.2 Hz and 6.9 Hz, respectively, with similar range (35 Hz) of intercept values as that of MnPF. Similar to the observation of the MnPF intercepts, the first sampling windows seemed to be associated with higher MdPF intercepts. No particular pattern could be observed with respect to the experimental day, though substantially lower intercepts were noted on both Day 2 and 11.

Despite these apparent differences, the effect of day on this measure was not significant (*P* = 0.309 – 0.700).



(a)



(b)

Figure 2-7. Initial (a) MnPF and (b) MdPF values across participants. W1, 2, and 3 represent the EMG data window.

Changes in MnPF (SMnPF) were typically characterized by patterns of gradual declines, with a few exceptions noted in data obtained from several trials. An example of the data (second data window) collected from an individual is presented in Figure 2-8. For this particular set of data, a gradual decrease in MnPF throughout an experimental task was exhibited. A regression line fit to the data demonstrated a negative (-0.092 Hz/min) slope ($P < 0.01$). With respect to the data of the second sampling windows, for example, about 82% of the linear slopes were negatives. Opposite slopes were noted in data from four individuals, but these positive values were present only in one of the five experimental days. Additionally, there were data from one participant whose rates of changes exhibited positive values in three experimental days. These normalized slopes had a fairly broad range of values ranging from -0.219 to +0.080 Hz/min, with a grand mean (SD) of -0.058 (0.057) Hz/min. Within an experimental day, the average magnitude of MnPF rates of changes ranged from -0.043 to -0.078 Hz/min (Table 2-3). From this particular set of data, no particular pattern was exhibited with respect to experimental day factor. The average slopes somewhat varied from one experimental day to another. Day 2 was associated with the greatest rate of MnPF changes, while the lowest value was observed on Day 8, but the difference in these changes due to this experimental day factor was not significant (*P* = 0.630 – 0.936).

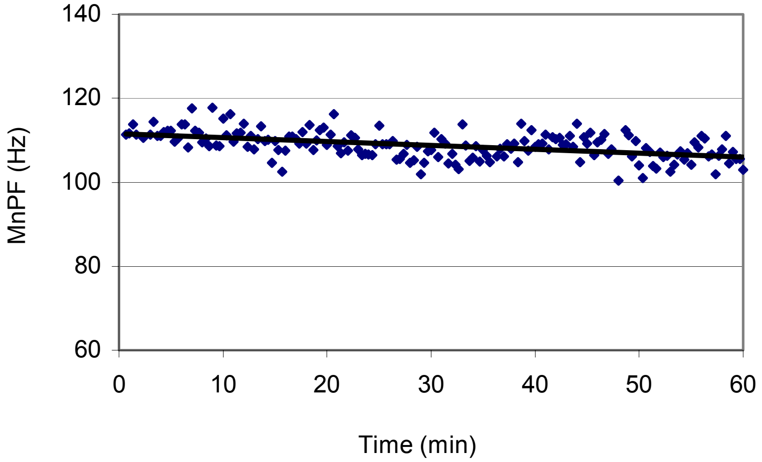


Figure 2-8. A sample of MnPF data obtained from a participant on Day 2.

Table 2-3. Mean slopes of MnPF changes.

Data Window	Day # 1	2	6	8	11	*P*
1	-0.044	-0.078	-0.060	-0.043	-0.063	0.630
2	-0.050	-0.069	-0.056	-0.047	-0.062	0.936
3	-0.058	-0.070	-0.056	-0.047	-0.060	0.932
Mean	-0.051	-0.072	-0.057	-0.046	-0.062	0.869

Similar evidence was noted when evaluating the other (MdPF) power frequency measure. Though negative slopes of MdPF (SMdPF) were typical descriptions of the data, a small percentage (10%) of the data showed non-negative trends. Examinations of individual data revealed a relatively wide range of rates of MdPF changes (-0.242 to +0.051 Hz/min). Grand mean and standard deviation for this normalized slope were -0.071 and 0.054 Hz/min, respectively. Figure 2-9 illustrates a sample data exhibiting changes of this spectral parameter throughout an experimental task. In this example, a declining (and linear) time series was evident, resulting in a rate of -0.100 Hz/min ($P < 0.01$). Averaged across participants, a day-to-day variation existed, with a magnitude of -0.051 to -0.094 Hz/min (Table 2-4). The largest and the smallest rates of changes were associated with spectral measure data obtained on Day 2 and Day 8, respectively. The *P* values, however, indicated that none of these variations was the result of the experimental day factor.

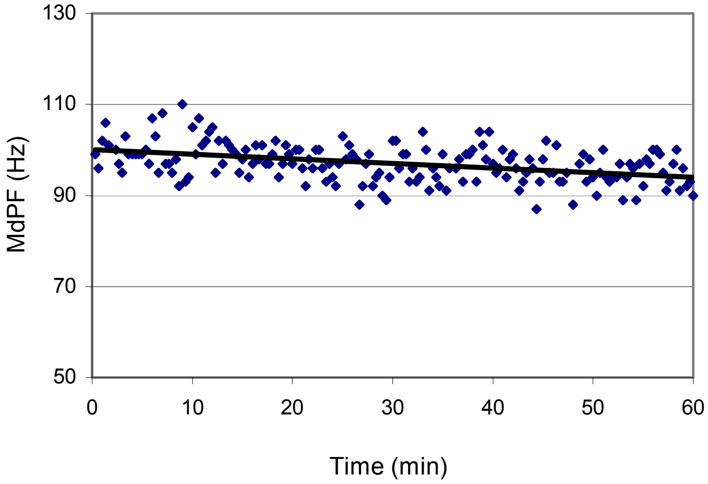


Figure 2-9. A sample of MdPF data obtained from a participant on Day 2.

Table 2-4. Mean slopes of MdPF changes.

Data Window	Day # 1	2	6	8	11	*P*
1	-0.070	-0.094	-0.071	-0.059	-0.072	0.684
2	-0.073	-0.082	-0.060	-0.051	-0.072	0.695
3	-0.083	-0.086	-0.063	-0.059	-0.067	0.711
Mean	-0.075	-0.088	-0.065	-0.056	-0.070	0.718

2.3.4 Repeatability of Fatigue Measures

Table 2-5 presents the reliability estimates (ICC 2,1) of the different measures employed in this study. The table also provides two additional complementary estimates, including the standard error of measurements (SEMs) and coefficient of variations (CVs). Initial MVE was characterized by a very high (0.96) ICC value and a reasonably small coefficient of variation (about 6%). Repeatability for changes in MVE and RPD during an experimental task was fairly good (ICC = 0.62 – 0.81), though the associated SEM (relative to the mean values) for these measures were somewhat large (CV = 46 – 83%).

Table 2-5. Intraclass correlation coefficients and precision estimates of the different measures employed (I:Initial; S: Slope; Red: % Reduction; F: Final).

Measures[a,b]	ICC	SEM	CV
IMVE	0.96	11.18	5.99
SMVE	0.62	0.12	83.90
RedMVE	0.72	7.17	55.15
FRPD	0.81	1.08	46.85
SRPD	0.81	0.02	50.58
IRMS1	0.28	4.08	20.12
IRMS2	0.28	4.02	20.53
IRMS3	0.35	3.84	19.91
IRMS-Mean	0.28	4.00	20.27
IMnPF1	0.57	4.43	3.68
IMnPF2	0.53	5.10	4.29
IMnPF3	0.48	6.22	5.24
IMnPF-Mean	0.57	4.84	4.06
MdPF-Int1	0.64	4.03	3.87
IMdPF2	0.62	4.20	4.09
IMdPF3	0.60	4.49	4.38
IMdPF-Mean	0.62	4.20	4.08
SRMS1	0.06	0.04	102.04
SRMS2	0.00	0.05	145.41
SRMS3	0.00	0.05	193.90
SRMS-Mean	0.00	0.04	132.48
SMnPF1	0.34	0.05	84.75
SMnPF2	0.17	0.05	92.29
SMnPF3	0.25	0.05	83.39
SMnPF-Mean	0.24	0.05	86.22
SMdPF1	0.39	0.05	62.96
SMdPF2	0.20	0.04	65.74
SMdPF3	0.25	0.05	64.12
SMdPF-Mean	0.29	0.04	62.57

[a] 1,2, and 3 represent the EMG data window

[b] ICC (3,1) was used for mean values

Repeatability values for initial EMG measures varied from fair to good. The initial values for EMG amplitude were substantially lower than those of the power spectral measures. The initial MdPF exhibited high ICC values (mean ICC = 0.62 over three data windows), coupled by considerably small SEMs. Slopes of these EMG measures were associated with fairly poor repeatability values. RMS rates of changes, in particular, tended to vary greatly (i.e., characterized by large CV values). Averaged over the three data windows, the ICCs for the normalized slope of MnPF and MdPF were 0.24 and 0.29, respectively. The highest ICC (0.39) was noted for the slope of MdPF data obtained from the first data window. For the power spectral measures, the magnitude of the changes only slightly exceeded the corresponding SEMs, which consequently resulted in fairly high CVs (62 – 92%).

2.4 DISCUSSION

This investigation was conducted with the objectives of evaluating the repeatability of several fatigue measures, obtained over five different experimental days, and to determine whether several recovery periods have different effects on the measures. The latter objective thus implied if certain durations of rest would be sufficient for full recovery of muscle function. Across experimental days, each individual in this study was able to maintain the exercise for the entire duration of the experiment (i.e., one hour). Work on fatigue involving intermittent contractions with similar work-rest regimen and load level has reported that people in general will have no difficulties in sustaining this level of effort for one hour (e.g., Mundale, 1970). For prolonged efforts, several reports have in fact suggested the acceptability of intermittent work examined in this study (Byström and Kilbom, 1990; Byström and Fransson-Hall, 1994).

Studies examining localized fatigue are of importance, particularly since fatigue could play an essential part in a series of complex processes leading to the occurrence of musculoskeletal symptoms and disorders in the workplace (Hagberg, 1984; Kumar, 2001). Muscular fatigue is also a limiting factor in the production of work, and is closely related to factors contributing to injuries of the musculature. Appropriate assessments of muscle fatigue, hence, are valuable, especially when the results are to be used for the purpose of designing jobs, or in determining if certain job conditions pose an increased risk of disorders.

2.4.1 Muscle Strength

Pre-fatigue muscle strength was used in this study to estimate the adequacy of different recovery periods. Based on this measure, the results provided no indication of long lasting effects of fatigue on any subsequent experimental days, implying that a 24-hr rest period might be adequate. Recovery of muscle performance is clearly a function of intensity and types of work performed. Research has shown, however, that progressive recovery of muscle strength could be achieved within a short period of rest (e.g., 10 minutes), though the process may require substantially longer duration to complete (Lind, 1959; Clarke, 1962; Funderburk et al., 1974; Søgaard et al., 2003). While no fatigue effects seemed to be carried over to the subsequent sessions, it is interesting to note that there was an increasing pattern of IMVE across sessions. Indeed, comparisons of mean strength data between Day 1 and Day 11 revealed a 7% increase. Though not significant, the trend suggests that participants were able to exert more forces during the subsequent sessions. This trend could probably be best explained by the fact that participants had likely become more familiar with the test protocol that allowed for better and more efficient muscle performance. Familiarization with the strength test protocol was also given to all participants several days before Day 1, but repeated tests throughout the study apparently provided some sort of continuous learning. This effect was found in seven out of eight individuals, demonstrating that adaptations to the strength test protocols were indeed present. Engelhorn (1987) in fact suggested that through repeated trials, participants might acquire several types of feedback that eventually improves movement efficiency. This improvement is also more pronounced in younger persons (Knight and Kamen, 2001), which was the subject pool involved in this study. Another explanation for this phenomenon is probably due to the strengthening effect resulting from repetitive tasks. Resistance training has been shown to increase MVE (Knight and Kamen, 2001), but it is not known if low intensity static exercise could be the cause of the changes. A study by Rutherford et al. (2001) investigated whether strength test protocol improved force generation. The investigator suggested that the protocol might provide a learning effect (neural adaptation), but no muscle hypertrophy.

Muscle strength at the start of an experimental session obviously showed excellent repeatability, as evidenced from very high ICC accompanied by considerably small values of SEM and CV. This finding also implies consistencies of the measurement protocol, as well as other factors possibly influencing strength outcomes. Apparently, standardized procedures (e.g., instructions, and time of the day) and tight experimental requirements (e.g., exclusions of heavy physical activities while involved in the experiment) helped in preserving this consistency. Though slightly lower reliability and higher SEM were reported (Dvir and Keating, 2001) compared to those of this study, muscle strength determined at the beginning of an experimental session has been generally repeatable (Komi and Buskirk, 1970; Clarke and Gentry, 1971; Rainoldi et al., 2001).

Muscle fatigue was obvious at the end of an experimental session, as indicated by reductions (10-15%) in muscular performance. Muscle strength declines of up to 25% have been reported in a study involving continuous static contractions of low intensity (Seghers et al., 2003), while the corresponding figure was about 12% for very low continuous contractions (Sjøgaard et al., 1986). For intermittent static efforts, substantial MVE declines (20%) due to brief moderate intensity work have been reported (Corcos et al., 2002). Comparable results were also found in an investigation similar to the current study (Søgaard et al., 2003). MVE data from this study clearly showed the presence of muscle fatigue induced by the low-level intermittent work done for 60 minutes. With respect to MVE changes, no particular pattern over days could be observed, though the greatest changes were observed on Day 2. One might speculate that the 24 hr rest between Day 1 and Day 2 might not be enough, but further evidence will be needed before such a conclusion can be drawn.

Across the experimental days, variability of MVE-based measures (SMVE and RedMVE) was apparent. Nevertheless, these measures of fatigue demonstrated adequate repeatability. Though markedly lower than that of IMVE, the associated ICCs could be considered acceptable. Of the two measures, however, RedMVE seemed to be more consistent and was associated with lower variability. Recall that RedMVEs were based on only a pair of strength data obtained immediately prior and after an exercise. For the majority of individuals, muscle strength at the end of an exercise was typically lower than the pre-fatigue strength, and thus, resulted in consistent strength differences. In contrast, rates of MVE changes (SMVE) were determined from a series of strength test data obtained throughout an experimental task. It was possible, for example, that maximal effort performed during the initial stages of the exercise resulted in similar (or even increased) MVE, which consequently lead to higher data variability. Regardless of these differences, strength-related fatigue measures (RedMVE in particular) could probably be claimed as satisfactory.

2.4.2 Subjective Ratings

Across experimental days, all of the participants reported zero values for RPD obtained at the commencement of a task, suggesting no left over fatigue from previous sessions. However, changes in RPD revealed a contrasting finding, in which both FRPD and SRPD showed greatest values on Day 1 and Day 2, and considerably lower values for the rest of the experimental days. Higher RPD changes on the first day could indicate that participants used this session to familiarize themselves with the task regimen, regardless of the practice session provided earlier. The musculoskeletal system and the associated feedback mechanisms apparently were in the process of adapting to the new environment, which likely resulted in higher subjective ratings. Higher ratings on the second day demand a different explanation, since the first session could have served as a "practice session". The only possible reason was that participants have not been completely recovered from the task performed on Day 1, demonstrating inadequacy of the 24 hr rest periods.

Good agreement between FRPD and SRPD was obtained, and both of these subjective measures of fatigue were associated with fairly high ICCs and moderate level of error estimates. This finding suggests that perceptions of muscular discomfort are somewhat repeatable, despite the relatively low work intensity employed in this study. Consistencies in RPD could be inadvertently influenced by participants who might try to deliberately memorize their (previous) ratings. This confounding effect had been expected, and was minimized by instructing the participants to be honest and to focus their ratings based only on the task currently performed.

2.4.3 Myoelectrical Amplitude and Spectral Parameters

Observed initial EMG RMS was around 20% MVE, closely reflecting the work load intensity during the contraction periods. Averaged over individuals, initial EMG amplitudes did not appear to show any particular trend, and it was difficult to show if different rest durations were related to the variability of this measure. Within an experimental session, the three data windows were associated with a declining pattern of intercept values, demonstrating lower motor unit activities as time progresses. This finding was also in agreement with negative rates of RMS changes, typically observed across individuals and sessions. Similar to findings on subjective ratings, higher initial RMS values were observed on Day 1 and Day 2, while lower values were found on the rest of the sessions. It was possible that muscle functions responded strongly when the task was presented the first time, but became more efficient throughout the rest of the experimental days. The fact that amplitude declined as the task progressed raised an interesting issue, since the development of muscle fatigue during static work was typically associated with an increase in EMG amplitudes (Petrofsky, 1979; Habes et al., 1985; Petrofsky, 1986; Krogh-Lund and Jørgensen, 1991; Krogh-Lund and Jørgensen, 1992; Sundelin, 1993; Seghers et al., 2003). Low work intensity has been commonly cited as the primary reason for small or non-increasing amplitude changes (Hagberg, 1981; Baidya and Stevenson, 1988; Öberg et al., 1994). It was also possible that different motor unit recruitment strategies were present, as a mechanism to minimize muscle fatigue. EMG amplitudes obtained in this experiment apparently did not provide enough information, which hampered further evaluations of muscle fatigue development associated with the task.

The difficulties in utilizing the information from EMG amplitude for the assessments of muscle fatigue were also associated with the poor repeatability of the amplitude measures. Though the corresponding error estimates might be acceptable, the reliability of IRMS was somewhat poor. Much worse repeatability was found with respect to rates of RMS changes, in which very poor reliability values were accompanied by incredibly large error measures. This finding demonstrated that the utility of EMG amplitude for the assessments of fatigue from low-level isometric contractions was questionable. Although formal analysis was not carried out, comparisons between genders might provide some insights to data variability. Qualitative examinations of individual SRMS showed greater data variability associated with female participants, but this was found only for the first data window. Large variability for this measure could also be due to the fact that efficiency of muscle functions considerably improved, particularly during the last few experimental days. Coupled with low-intensity contractions, this lead to inconsistencies in the recruitment of motor units involved. Repeatability of this measure has been reported in a number of studies. EMG amplitudes associated with maximal efforts typically showed good to excellent reliability and/or fairly small standard error (Sleivert and Wenger, 1994; Larsson et al., 1999; Cramer et al., 2002). During isometric efforts, fair to excellent reliability has been reported for the rates of amplitude changes (Dieën and Heijblom, 1996; Larivière et al., 2003). These two studies involved sustained exercise and much higher work intensity that likely resulted in (typical) recruitment of additional motor units as fatigue develops. This process might also lead to more consistent amplitude changes, yielding higher reliability coefficients. In contrast, the present study employed intermittent effort performed at substantially lower intensities. The nature of these factors may not necessarily result in consistent recruitments of more motor units. In fact, the increasing pattern of RMS was observed only in a small number of sessions. Furthermore, a totally conflicting result was found when examining the pattern across days within a few individuals. These inconsistencies were believed to result in higher data variability.

EMG changes in the frequency domain were also used in the present study for the purpose of muscle fatigue evaluations. Despite the small magnitude of spectral parameter declines, this study demonstrated that, in the majority of sessions, static intermittent work of fairly low intensities were adequate in inducing local muscle fatigue. Accumulation of byproducts have been cited as one of the factors associated with the slowing down of the muscle fiber conduction velocity, that eventually leads to the downward shifts of the EMG spectra (Eberstein and Beattie, 1985). It is likely that the magnitude of spectral shifts were dependent upon the experimental protocol employed in a particular study. Very high intensity continuous static work has shown to result in about 10 Hz decreases in MnPF (Elfving et al., 2002), which was about two to three times as that in this investigation. Data from a few sessions, however, showed the non-decreasing patterns of spectral changes. Similar results have been reported in the literature (Hagberg, 1981), suggesting the low contraction levels and an increase in muscle temperature as possible factors masking the typical changes. It was also possible that the resting phases (during the intermittent work) allowed for metabolite eliminations (Byström and Kilbom, 1990), thus providing the contracting muscle a chance to recover. Furthermore, individuals in the present study received visual feedback (as opposed to proprioceptive feedback), which was probably also associated with the relatively smaller EMG changes (Sjøgaard et al., 2000; Madeleine et al., 2002).

Comparisons of the data from the three data windows revealed the time-dependent reductions in spectral measures. Such a finding implied that the progressions of muscle fatigue were in fact present during the 10-second contraction periods. Across experimental days, neither significant differences nor specific patterns of initial spectral parameters were observed. It was possible that complete recovery was achieved within as little as 24hr rest period. Indeed, other investigations have reported that recovery of initial spectral measures followed exponential pattern (Elfving et al., 2002), and rapid and/or complete recovery was typically obtained within a brief period of time (Kadefors et al., 1968; Kourinka, 1988; Larivière et al., 2003). The only study suggesting long-term effects of fatigue as measured by the initial values of spectral measures is probably found in the work of Sbriccoli et al. (2001). Interesting, and somewhat conflicting, results were found when rates of MnPF and MdPF changes were examined more closely. Though no particular trends were observed over the five experimental days, Day 2 was associated with the largest declines in both of the spectral measures. Since no significant differences found, it is possible that this phenomenon was only part of the natural variability of the spectral measures. It is also possible, however, that the 24 hr rest period assigned following the end of Day 1 was not adequate for the complete recovery of spectral measures. If this was the case, finding from this study demonstrated the existence of long-lasting fatigue effects induced by prolonged low-level intermittent efforts. Very limited information, however, is available that could support this argument, particularly since the majority of reports in the literature do not examine slopes of spectral measure for evaluating the process of recovery. The work of Kroon and Naeije (1988) reported shifts in MnPF, and demonstrated that fatigue was not recovered after 25 hrs. Even though their work involved exhausting dynamic exercises, the finding suggested that long lasting effects were possible.

Initial values for MnPF were characterized by fair reliability and relatively small error estimates, while better repeatability was found for the initial MdPF. This result implied that long lasting effects of fatigue, if existed, might not be captured by these measures, and on each experimental day, the muscle always started from similar initial non-fatigued phases. The literature generally reported satisfactory repeatability of the initial values of the spectral parameters (Ng and Richardson, 1996; Elfving et al., 1999). In contrast, poor reliability was found for shifts in spectral parameters, raising an issue of utility of such measures, particularly during low-level muscle contractions. The varying patterns of EMG changes were observed for a few individuals (i.e. conflicting results within an individual, across sessions). It was of interest if the data from certain individuals were more consistent than those from others. Female individuals in this study were characterized by about 40% less muscle strength compared to their male counterparts. Compared to the stronger population, several studies have indicated that weaker individuals are less fatigable, that fatigue measures obtained from the latter group could possibly be less consistent. In this investigation, data on standard deviations of normalized SMnPF and SMdPF did not indicate such a tendency, i.e., similar magnitude of data variability was found in both genders. It was also possible that the low contraction intensity employed and the intermittent nature of the protocol in the present study did not yield great fatigue effects, and hence, were associated with less consistent results. Additionally, an increase in muscle temperature could potentially confound the changes. However, with standardized procedure in place (e.g., light exercise to warm up the active muscle prior to the actual tests), the likelihood of this factor causing the inconsistencies was probably negligible. The work of Ng and Richardson (1996) was conducted with the main objective of determining the repeatability of MdPF. Unlike the present study, their investigations involved continuous and high intensity work (unsupported pronated trunk holding), which presumably could result in considerable fatigue effects and repeatable spectral changes. The investigators, however, only found poor to moderate level of MdPF repeatability. Similar results with respect to the repeatability of spectral measures have also been reported in the literature (Elfving et al., 1999; Rainoldi et al., 2001). It should be noted that poor results have been demonstrated in a number of repeatability studies examining fatigue effects during moderate to high intensity continuous static efforts. Therefore, it would not come as a surprise that the present study, regardless of the workload used, provided evidence for poor repeatability for EMG spectral measures.

2.4.4 Study Limitations

A few limitations of this study are worth noting. Counter balancing was not done for the experimental design, thus the order of the experimental sessions could confound the effects of recovery periods. For example, this study assigned 24 hrs of recovery between the first two sessions, and different results could be present if this recovery period had been allotted between the last two experimental sessions. Therefore, the presence of long lasting effects of fatigue, as suggested in this study, was implied instead of determined from the experimental results.

There were five experimental sessions examined in this study, but only a fairly small number of participants (compared to the number of sessions) were involved in this study. In fact, across the different response variables, the statistical power of the study was relatively low (less than 0.56), and having more participants could likely yield more precise results (i.e., less within-subject compared to between-subject variability). For practical reasons, however, this option was not adopted in this study.

Though not known, higher contraction levels could also result in different findings. Indeed, some investigators have reported more consistent (EMG) results when the effort levels were around or higher than 30% MVE. This study was originally designed to involve relatively low contraction levels, with the objective of representing the typical workload during repetitive arm elevations in a number of manual jobs. For this study, therefore, higher effort levels may not be the appropriate choice.

Several factors inherent in the experimental procedures could also potentially confound the resulting data. Increased muscle temperature, for instance, could be present that masked the actual changes in myoelectrical activities. Reapplications of electrodes might also affect consistency of EMG signals. Additionally, strength test procedures might be influenced by an individual's physical activities and circumstances prior to coming for the session. Standardized procedures and instructions, however, were employed to ensure that these effects were negligible.

Finally, the different measures examined in the present work were analyzed in an aggregate basis. Between-day repeatability was evaluated using means of fatigue measures, and inferences were drawn on the basis of these averages. Consequently, findings from this study are only applicable to a group of individuals.

2.5 CONCLUSION

Several fatigue measures were employed in this investigation, and based on muscle strength and subjective measures, intermittent and low-intensity isometric efforts sustained for 60 minutes were generally sufficient to induce local muscle fatigue. Typical EMG amplitude increases were not demonstrated in the majority of experimental sessions. Though relatively small in magnitude, shifts of the EMG spectra to the lower frequencies were found. The present study also sought to determine the adequacy of several recovery periods, and none of the measures used demonstrated substantial long-term effects of muscle fatigue (i.e., recovery could be complete within 24 hr). Data from a few measures, however, seemed to indicate the inadequacy of the 24 hr rest period; thus, whenever practical, a minimum of two-days of recovery should be allotted to individuals engaged in a series of prolonged static efforts. For the purpose of muscle fatigue evaluations, the repeatability of both strength and subjective measures are deemed to be satisfactory. In contrast, rates of EMG change in both temporal and frequency domains do not seem to be repeatable, and information with respect to these measures might be of limited use. Though these findings are probably specific to the experimental protocols utilized in this study, caution should be used when drawing inferences solely based on EMG measures. Inaccurate conclusions may indeed occur (Dimitrova and Dimitrov, 2003), resulting in misleading results when addressing muscle fatigue in the workplace.

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CHAPTER III

MUSCLE ENDURANCE AND LOCALIZED FATIGUE DURING INTERMITTENT STATIC WORK

3.1 INTRODUCTION

3.1.1 Rationale

Critical in designing industrial tasks involving physical activities is the determination of how long an individual worker can perform the tasks without undue fatigue. In the area of manufacturing, such endurance information enables production engineers to determine the work output or productivity rate of a facility, and to perform production forecasts over certain time periods. This information may also help management schedule rest periods, and provide a basis for designing job rotations/enlargements. Also important are the workload levels workers can maintain during regular 8-hr work periods. Early work by Frederick W. Taylor (in Niebel and Freivalds, 1999) exemplifies the concept of optimal workloads associated with prolonged tasks, which result in maximum work output. From a physiological point of view, information on muscular workload can be useful in determining when workers should stop working and how much rest should be assigned to them. The main objective is, therefore, to maximize the rate of work while at the same time keeping the workers from unnecessary fatigue resulting from prolonged physical work activities.

A body of knowledge describing the relationship between workloads and endurance or whole-body fatigue has been generally established. Based on physiological responses, researchers are usually able to crudely classify the severity of workloads associated with the physical activities of a job. A criterion to minimize fatigue has been commonly proposed: for most people, work should not exceed 30 – 40% of their maximum work capacity (Åstrand and Rodahl, 1986; Rodahl, 1989). Other limits and criteria based on different physiological measures have also been suggested (Grandjean, 1988), with the main purpose of ensuring that metabolic demands associated with work activities do not exceed the capacity of the cardiovascular system. The mechanisms of general fatigue have also been described in the literature, with disturbed homeostasis and accumulation of metabolites as some of the main causal factors.

As opposed to the vast knowledge on whole body fatigue associated with dynamic work, less is known on the phenomena exhibited by smaller muscle groups engaged in static activities. Although early research (Tutle et al., 1950; Clarke et al., 1958; Rohmert, 1960) as well as more recent studies (e.g., Björkstén and Jonsson, 1977; Sato et al., 1984; Kahn and Monod, 1989; Garg and Hegmann, 2000) has demonstrated the specific relationship between muscle force and endurance during static work, a number of issues have not been sufficiently addressed in the literature. These issues include localized muscle fatigue and endurance during prolonged static work on the order of hours instead of minutes, and how intermittent tasks and the corresponding task parameters including cycle time and work-rest regimen affect the development of muscle fatigue. In addition, the effects of several critical factors such as types of muscle, age, and gender on muscle endurance have not been investigated extensively. Studies in this area will contribute to a better understanding of muscle responses and capacity during prolonged static work, thus allow for improved work evaluation and design.

3.1.2 Force-Endurance Relationship during Isometric Work

Endurance can be defined as the maximum amount of time a muscle or muscle group can sustain a particular level of exertion. In laboratory studies, endurance is usually determined after participants fail to maintain a required force level despite feedback and verbal encouragements given by the experimenter. Research investigating the relationship between muscle force and endurance has shown that the duration of isometric contractions is a function of relative contraction levels. An intense muscular exertion will typically last for less than a minute, while a relatively low contraction level can generally be sustained for a much longer duration. The work of Rohmert (1960) is a classic example illustrating such a relationship. The relationship, as depicted in Figure 3-1, indicates how long a particular level (% maximum voluntary exertion or MVE) of continuous isometric contraction can be maintained. The curve shows, for example, that an isometric contraction level of 50% MVE can be sustained continuously for only about one minute, while those less than 25% MVE can be maintained for approximately four minutes or more.

Based on handgrip tasks, reports have indicated that muscle endurance associated with moderate levels of static exertion (20 – 30% MVE) varies between 3 – 16 minutes (Clarke et al., 1958; Funderburk et al., 1974; Petrofsky, 1986; Byström et al., 1991). At the same contraction levels, research examining other muscle groups such as knee extensors, elbow flexors/extensors, or arm abductors has revealed slightly lower endurance times, ranging from about 2.5 to 10 minutes (Caldwell, 1963; Müller, 1965; Stulen and De Luca, 1978; Viitasalo and Komi, 1978; Krogh-Lund and Jørgensen, 1991; Krogh-Lund and Jørgensen, 1992; Krogh-Lund and Jørgensen, 1993; Hansson et al., 1992; Krogh-Lund, 1993; Hermans et al., 1999).

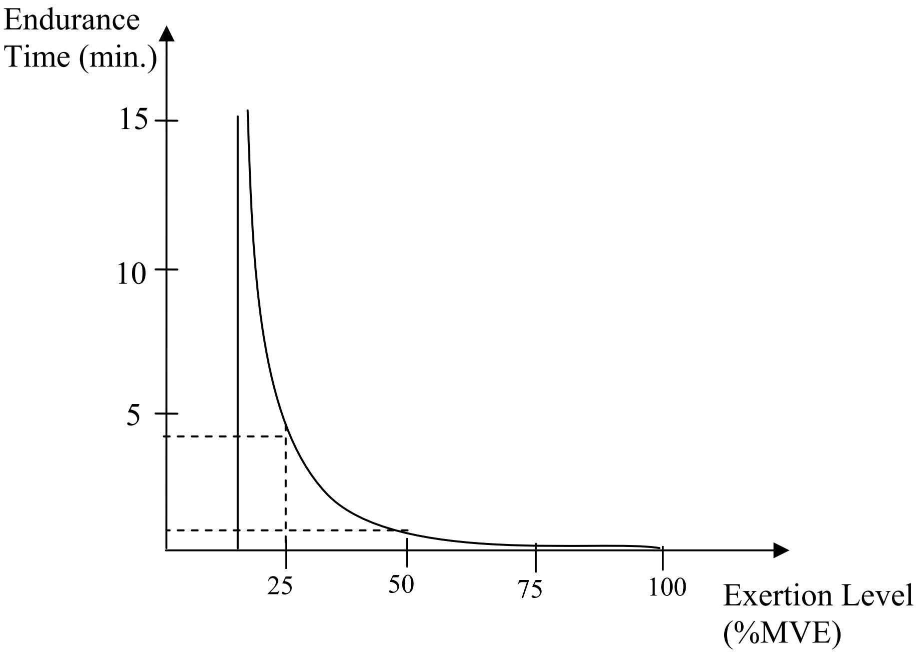


Figure 3-1. Typical force vs. endurance relationship. The asymptote indicates that continuous static contraction of about 15% MVE or less can be sustained for an "indefinite" amount of time (Adapted from Rohmert, 1960)

The shape of the force-endurance curve is hyperbolic (Kahn and Monod, 1989), and the asymptote represents a specific contraction level below which static muscular contraction can be sustained for a relatively long period of time. This particular contraction level has been referred to as the "critical force" (Monod and Scherrer, 1965), and substantial increases in endurance time are commonly observed during continuous isometric contractions performed below this critical force. Rohmert (1960) studied force-endurance relationships in several muscle groups including the arm, trunk, and leg muscles, and based on workloads of 20% to 100% MVE it was indicated that static work of less than 15% MVE can be maintained for a "long period" of time without fatigue. Similar results based on five male subjects were also reported by Pottier et al. (1969), noting that a critical force of about 17% MVC was applicable for continuous isometric contraction. Several other studies have also indicated that a long duration of static work can be sustained, provided that the contraction level is less than 15 – 20% MVE (Monod and Scherrer, 1965; Müller, 1965; Bonde-Petersen et al., 1975). A progressive decline in muscle endurance associated with static work above 15% MVE has been explained by the fact that blood supply is compromised (Barcroft and Millen, 1939; Müller, 1965) due to an increasing intra-muscle pressure. This muscle ischemia in turn leads to muscle energy imbalance (Sjøgaard et al., 1988) and impaired muscle functions (Hagberg, 1984). Higher contraction levels are also associated with anaerobic metabolism of the muscle cells (Koerhuis et al., 2003), which further results in accumulation of lactic acid or other chemical substances inducing myalgia.

For longer work durations, a force level of about 10% MVE can be maintained for one hour, while a lower level of muscle exertion (4-5% MVE) may be sustained for up to eight hours (Ulmer et al., 1989). These critical forces are also in line with those reported by Björkstén and Jonsson (1977). These latter investigators examined elbow flexors and showed that isometric exercise at about 8% MVE could be sustained for one hour, although they further suggested that only a low level of muscle contraction could be performed continuously for 4 - 8 hours. Examination of the literature suggests that the critical force for 1-hour isometric exercise typically ranges from about 8% to 20% MVE (Monod and Scherrer, 1965; Bonde-Petersen et al., 1975; Björkstén and Jonsson, 1977; Hagberg, 1981; Jørgensen et al., 1988; Caffier et al., 1993). Results, however, may vary considerably and these threshold values may not apply across all studies. Very low critical force values (2 – 5% MVE) have been indicated in some studies (Mundale, 1970; Sato et al., 1984; Sjøgaard, 1986). In fact, at 10% MVE the associated endurance time for the elbow flexors was less than 1 hr (Krogh-Lund, 1993), and in static elbow extension tasks this level could only be performed for about 18 minutes (Fallentin and Jørgensen, 1992). Nevertheless, in work design an exertion level of less than about 15% - 20% MVC has been recommended, which would allow an individual to perform prolonged static activities (e.g., Niebel and Freivalds, 1999). The adoption of the 15% MVC as a work criterion is probably due to the experimental results reported in a number of early studies.

Studies examining isometric contractions have been extended to address intermittent static contractions, a condition that often characterizes light industrial jobs such as assembly operations. Workers doing such jobs, for example, generally perform a static activity for a short period of time followed by a period of rest or muscle inactivity. The activity is usually repetitive during a workday, and follows a specific work-rest regimen for each work cycle. Experimental tasks simulating intermittent work conditions have been usually conducted by having subjects perform a series of contraction-relaxation efforts maintained until exhaustion. Cycle times determine the time duration for one complete task, and duty cycles characterize the proportion of contraction to relaxation periods. A series of 10-second intermittent tasks with 0.4 duty cycle, for example, indicates sustained muscle contraction for 4 seconds, followed by a 6-second relaxation period.

Force-endurance relationships during intermittent static exercise appear to be similar to that of continuous exercise (Monod and Scherrer, 1965; Björkstén and Jonsson, 1977; Hagberg, 1981; Kahn and Monod, 1989). Compared to continuous exercise, however, the same contraction level can be performed much longer, depending on the work-rest regimen involved in the exercise. During intermittent exercise, the static exertion level that can be sustained for a long time (i.e. critical force) is consequently higher than that obtained from continuous static exercise. Note that for the purpose of comparisons with sustained isometric exercise, the critical force values from intermittent exercise should be expressed as "mean critical force", which is the product of duty cycle and critical force. It is believed that the relaxation periods increase endurance time by allowing for blood flow restoration (Kahn and Monod, 1989) and elimination of accumulated metabolites (Byström and Kilbom, 1990). In addition to physiological benefits, relaxation periods may also provide a motivational factor that contributes to longer muscle endurance (Byström et al., 1991).

Based on maximum exercise durations of 30 minutes, Pottier et al. (1969) showed that at duty cycles of 0.2, 0.5, 0.8, the critical forces were around 62%, 37%, and 22% MVE respectively. Monod and Scherrer (1965) demonstrated that subjects were able to sustain a mean critical force of 20% MVE for a long time during intermittent work with a 0.5 duty cycle. Kahn and Monod (1989) further suggested that this particular work-rest schedule would result in maximum work output. Based on the same duty cycle, Hagberg (1981) indicated 25% MVE to be the mean critical force, which is considerably higher than the 12% to about 16% MVE reported by Björkstén and Jonsson (1977). The latter authors also indicated that the largest mean critical force value was obtained when the proportion of the contraction period was 70% of the cycle time. Ulmer et al. (1989) attempted to extrapolate endurance data from three studies, and their results indicated that critical forces associated with intermittent tasks for 1-hour were around 9 – 11% MVE, while the values for 8-hour intermittent work were 3.9 – 5.4% MVE. Mundale (1970) proposed that, regardless of the proportion of contraction to relaxation periods, static intermittent tasks could be carried out for a long time, if the muscle contraction level did not exceed 20% MVE. Despite the discrepancies found among studies, the literature generally indicates that tasks involving contraction and relaxation can result in longer muscle endurance and higher mean critical force values. Assuming that the amount of "work" during static intermittent exercise is the product of muscle forces and the actual exercise durations, more work can be generated due to the intermittent nature of the tasks.

Differences in muscle behavior as represented by endurance time during isometric exercise have stirred debates over whether muscle characteristics affect muscle endurance. Rohmert (1960) and Caldwell (1963) have noted that no inter-individual differences are observed when endurance is expressed as a function of normalized force levels (i.e. % MVE). In the experiment done by the latter author, for example, no significant differences in endurance time were found between male and female subjects. Differences, whenever present, were attributed to other factors including motivation and physical conditioning, but not due to differences in subject's physical strength. Since the force-endurance relationship is based on relative force level or percent of MVE, no muscle endurance differences would be observed among individuals with different muscle strength (Müller, 1965). Kahn and Monod (1989) further noted that the relationship between endurance time and force level was the same across subjects, irrelevant of the types of muscle fibers involved.

In contrast, Björkstén and Jonsson (1977) have indicated possible differences in muscle endurance between weak and strong subjects. Although not significant, results of their study showed that females (weak subjects) tended to have higher critical forces compared to their male counterparts (strong subjects). Female subjects were also shown to have significantly longer endurance than their male counterparts during isometric handgrip tasks (Petrofsky, 1986). Such differences have also been observed when comparing subjects of different ages (Larsson and Karlsson, 1978), and between marathon and short-distance runners (Ulmer et al., 1989). Both studies have suggested that differences in endurance time are, at least partly, attributable to different types of muscle fibers involved in the exercise. A similar finding was also reported by Hultén et al. (1975), who noted that different leg muscle types contributed to differences in endurance time. Large endurance time discrepancies between muscles were also reported by Bigland-Ritchie et al. (1986a) and Fallentin and Jørgensen (1992). Substantial differences in endurance time were indicated by Fallentin and Jørgensen (1992) in which the endurance of elbow extensor muscles was much shorter (18.1 minutes) than that of the elbow flexor muscles (111.3 minutes) during sustained static work. Using a duty cycle of 0.6, Bigland-Ritchie et al. (1986a) reported that endurance of the quadriceps muscle was much lower compared to that of the soleus muscle. Muscle endurance can apparently be influenced by a number of factors, including maximum force capabilities of a muscle, types of muscle fibers, and gender (Dieën and Oude Vrielink, 1994).

3.1.3 Acceptable Contraction Level for Prolonged Activities

Endurance data may be used as design guidelines, such as when estimating the maximum work duration for certain occupational activities. Although different muscles may exhibit different endurance, moderate levels of static work (20-30% MVE) can usually be maintained for up to 10-15 minutes (e.g., Funderburk et al., 1974; Byström et al., 1991). For prolonged static efforts, such as those performed for one hr or more, the interest is generally in determining workloads that can be maintained throughout the duration of the task (i.e., critical force). It is assumed that the majority of people will be able to maintain static work for hours, as long as the workloads are less than the critical force. A workload of about 10 - 15% MVE, for example, can generally be sustained for one hr or more (Jørgensen et al., 1988; Ulmer et al., 1989; Caffier et al., 1993). It is noteworthy that, although they are of academic interest, studies examining prolonged continuous static efforts may have little practical applications.

Although critical forces may indicate the maximum level of exertion that can be sustained for a long time, it does not necessarily imply that they are acceptable. Monod and Scherrer (in Kahn and Monod, 1989) proposed the term “maximum tolerance time”, indicating that the acceptable duration of a continuous task was only a fraction of the actual muscle endurance, especially for workloads higher than 15% MVE. Their suggestion was based on limitations of the cardiovascular system working at higher muscle contraction levels. In addition, the use of endurance data as a basis in determining an acceptable workload may not be "safe", particularly since the development of muscle fatigue often precedes exhaustion. At the end of an exercise period fatigue may have accumulated that, in the long run and without sufficient recovery, may lead to impairment or even injurious effects to muscle functions (Hagberg and Kvarnström, 1984; Sommerich et al., 1993; Byström and Fransson-Hall, 1994; Kumar, 2001). Therefore, instead of using muscle endurance data, investigators have proposed the use of various fatigue measures (e.g., blood flow, muscle electrical activity, strength tests, and subjective responses) to assess acceptability of workloads.

Based on these fatigue measures, reports in the literature indicate that the acceptable contraction level for continuous isometric work is in fact less than what has been previously suggested, and the 15% - 20% MVE criterion as a guideline in designing work of long duration may not be applicable. Jørgensen et al. (1988), for instance, evaluated fatigue of finger flexors, elbow flexors and extensors, and knee extensors, and indicated that some of their subjects were not able to sustain an isometric contraction level of 10% MVE for one hour. Although all of the subjects could maintain a 5% MVE force for one hour, these investigators also showed a substantial reduction in muscle strength at the end of exercise period. In their study, considerable changes in electromyography (EMG) parameters, such as a decline in mean spectral frequency and an increase in EMG amplitude, were also observed during the exercise at 5% MVE. These authors, therefore, concluded that the 15 – 20% MVE limit for prolonged static effort was not appropriate.

An assessment of acceptability of contraction levels was also conducted in a study investigating fatigue from handgrip tasks Byström and Kilbom (1990). Based on measures of blood flow and EMG, the authors suggested that fatigue might develop at a low contraction level of 10% MVE. Similar tasks were also investigated by Byström and Fransson-Hall (1994), and several fatigue measures were simultaneously evaluated during and after the exercise. Their study indicated that continuous handgrip contractions exceeding 10% MVE were indeed unacceptable. Other investigators have argued that only a very low level of static muscular contraction can be maintained for 4-8 hours (Björkstén and Jonsson, 1977). According to Sjøgaard (1986), this level of isometric contraction is probably about 5% MVE, though in some muscles even this low level is sufficient to cause muscle exhaustion within an hour. In Ulmer et al. (1989), it was reported that one subject could not maintain a prolonged static task at 8%

MVE, and EMG signs of fatigue were found in one subject performing static contractions of about 3% MVE. It appears that an acceptable muscle contraction level for continuous static work is probably less than 5% MVE (Mundale, 1970), although long-duration static activities involving even low muscle contraction should be minimized or eliminated (Björkstén and Jonsson, 1977; Sjøgaard et al., 1986; Caffier et al., 1993).

Much less information on acceptable contraction levels during intermittent exercise is available in the literature. Nevertheless, a few reports have indicated that the acceptable level of contraction during static intermittent exercise is also lower than that obtained from muscle endurance data. Monod and Scherrer (1965), for example, reported that the mean critical force for static intermittent work is around 20% MVE (duty cycle = 0.5), while based on physiological measures Byström and Kilbom (1990) showed that the mean acceptable contraction level was 16.75% MVE (duty cycle = 0.67). A study (Jørgensen et al., 1988) incorporating physiological measures of fatigue was also conducted to determine the mean acceptable level associated with intermittent static exercise performed for a long period of time (7 hours). EMG data indicated that 20% MVE at a duty cycle of 0.67 could be maintained for 2 – 3 hours, and no signs of fatigue were observed during the entire task period at a contraction level of 15% MVE (duty cycle = 0.67). A similar value was indicated in a study by Byström and Fransson-Hall (1994), who reported that a 10% mean contraction level was acceptable for prolonged handgrip exercise. Their conclusion was based on various physiological measures, such as EMG, metabolite levels, blood pressure, and analysis of the recovery periods. Results of these various studies generally suggest that the mean acceptable level for prolonged static intermittent effort is in the order of 10% - 14% MVE, and the provision of relaxation period results in higher acceptable workloads.

3.1.4 Purpose of the Study

Experimental research investigating muscle fatigue and endurance associated with static work provides useful information that can be used as guidelines for job design. Studies on intermittent effort, in particular, suggest acceptability of certain workloads during prolonged static activities. Moreover, experimental results have indicated which work-rest schedules are suitable to both minimize fatigue and maximize work outputs. Results from studies investigating handgrip tasks, for instance, may be used to design occupational activities requiring hand-finger exertions. Design criteria that allow the exertions to be performed for a relatively long time have been reported in the literature (e.g., Byström and Kilbom, 1990; Byström and Fransson-Hall, 1994). A very low level of continuous hand-finger activities may be acceptable, while a much higher mean level (10% - 15% MVE) may be employed when the activities are intermittent. An acceptable rest period determined psychophysically as a function of exertion level and work period has also been reported in the literature (Abu-Ali et al., 1996).

While tasks involving shoulder muscles are prevalent in a number of occupational activities, very little research has addressed shoulder muscles engaged in prolonged static work. It is not known whether shoulder muscles will exhibit similar behaviors compared to other muscles during prolonged static work. In addition to handgrip exercise, studies have only examined tasks involving elbow flexors/extensors, knee extensors, or back muscles. Of those studies examining shoulder muscles, most have focused on continuous exercise (e.g., Sato et al., 1984; Hagberg and Kvarnström, 1984; Garg and Hegmann, 2000), and very few have evaluated shoulder muscle endurance and fatigue during isometric intermittent exercise (e.g., Jørgensen et al., 1988). Design guidelines have been suggested in a number studies, but the results generally apply only to specific task conditions. This limitation stems from the fact that intermittent work is characterized by a number of task parameters such the cycle-time, the ratio of work to rest periods, and the levels of effort involved. Despite possible interactions among parameters, very little information is available in the literature that describes how these work parameters, as a whole, affect muscle fatigue and endurance. Information on shoulder muscle endurance and fatigue can provide substantial contributions to an effort to minimize the likelihood of musculoskeletal symptoms of the shoulder-neck area, particularly since muscle fatigue during repetitive tasks has been identified as a possible risk factor to muscular discomfort (Sundelin and Hagberg, 1992) and discomfort in the shoulder-neck area has been commonly reported among industrial workers (Jonsson, 1982).

The objective of this investigation was to provide a general description of fatigue and endurance of the shoulder muscle engaged in various conditions of low-to-moderate levels of intermittent static work. The effects of task parameters (force level, work-rest ratio, and cycle time) and their possible interactions were examined in this study. Higher order models relating work factors with fatigue measures were established, and associations among the fatigue measures were determined. Finally, design guidelines and acceptability of the different work conditions were offered.

3.2 METHODS

3.2.1 Participants

A total of 90 university students (45 male, 45 female) were included in the study, with mean (SD) age, stature, and body mass of 21.8 (2.0) years old, 165.3 (18.2) cm, 68.8 (19.0) kg, respectively. Participation in the study was limited to right–handed subjects due to the complexity of hardware setup, and only to those with moderate daily physical activities and no reported previous (12 months) history of shoulder/neck problems. A brief interview was conducted to determine eligibility of those willing to participate. Informed written consent (using procedures approved by the Virginia Tech Institutional Review Board), anthropometry, and demographic data were obtained prior to the start of an experimental session.

3.2.2 Work Tasks

Each participant did three minutes of light, non-fatiguing, shoulder exercise prior to performing a series of strength tests. Following a 5-10 minute rest, the participants performed an experimental exercise comprised of intermittent isometric-isotonic contractions, according to a predetermined cycle time, duty cycle, and exertion level (Figure 3-2). Each individual performed the exercise while lying down in a supine posture, with the right arm abducted at 90^0 (cf. Figure 2-1, p.II-9, Chapter II). Both visual and audio feedback was provided that allowed the individual to determine when to perform the contractions, and to control the amount of muscular exertion. Muscle endurance was determined at the point of exhaustion, or the exercise was terminated when the exercise duration had reached 60 minutes. Subjective perceptions of muscular discomfort (based on the Borg CR-10 scale, Borg (1990)) and muscle strength were collected approximately every 10 minutes, and immediately after the cessation of the exercise.

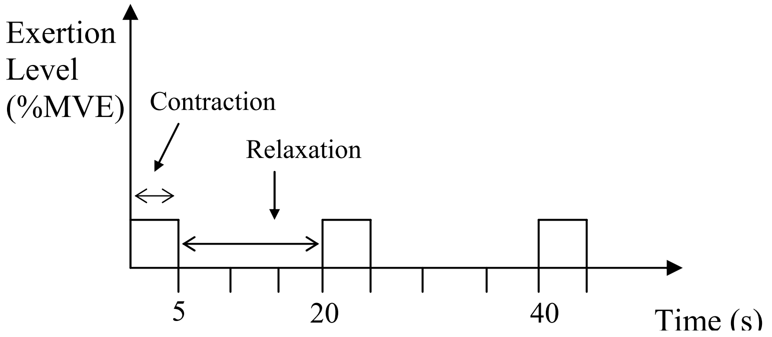


Figure 3-2. An example of intermittent exercise with a cycle time of 20 seconds and a duty cycle of 0.25.

3.2.3 Recording and Processing of Surface EMG

Pre-gelled bipolar Ag/AgCl electrodes (1 cm diameter) with a 2.5 cm inter-electrode distance were used to obtain EMG signals from the middle deltoid muscle. To ensure good skin-electrode contact, the skin was shaved, lightly abraded, and cleaned with 70% rubbing alcohol. An inter-electrode resistance of less than 10kΩ was considered acceptable. Electrode placements over the middle deltoid muscles were performed according to Hermens et al. (1999). A 20-minute period was provided in order to stabilize the electrodes on the skin.

An EMG amplifier (Measurement Systems Inc., Ann Arbor, MI, USA) was used to obtain myoelectrical signals. A preamplifier strengthened the signal by 100, and further amplification was done according to the gain setting of the amplifier. The signals were hardware-filtered at 10 – 500 Hz, and both raw and root-mean-square (110 ms time-constant) signals were digitally sampled at 2048 Hz and 32 Hz, respectively. EMG RMS signals were finally low-pass filtered (Butterworth, 4th order, 6Hz cut-off frequency).

EMG data were obtained only during the contraction period, and to minimize the effects of arm movement and/or changes in muscle tension that could be present during the beginning of muscle contractions, no recordings were made during the first 2-second of the contraction periods. Three evenly spaced 2-second EMG recordings were collected throughout the remainder of the contraction periods. Myoelectrical activity for each contraction period was based on the average of the three 2s data epochs.

Further signal processing in the frequency domain included decomposing each of the 2-second raw EMG samples into three overlapping 1-second samples (Luttmann et al., 1996). Hanning window and Fourier Transform procedures were subsequently applied to each of the 1-second samples, and the resulting frequency spectra averaged to get a single power spectrum. Spectral measures (MnPF and MdPF) for the 2s epoch were determined (Merletti and Lo Conte, 1997) based on the averaged signal power spectrum. The associated spectral measures for a particular contraction period were determined from the average of the three MnPFs or MdPFs. A program developed in LabView 5.1 (National Instruments) was used to collect and process the EMG signals.

3.2.4 Experimental Design and Analysis

An orthogonal central composite design with three factors (contraction level (%MVE), duty cycle, and cycle time (s)) was employed in this experiment (Figure 3-3). The basis of this design (Figure 2-3) was a 2^3 full factorial design with additional treatment combinations at one "center" and six "star" or "axial" points (Neter et al., 1996). An α value (axial distance) of 1.216 was chosen to achieve an orthogonality of the resulting polynomial regression parameters, and a total of five factor levels could be examined for each factor. For factor levels equaled to 3, this design resulted in substantially reduced number (15) of experimental conditions when compared to 27 associated with the regular 3^3 full factorial design. The resulting design with "coded" values is shown in Table 3-1.

The second step in designing this experiment was to determine the corresponding "real" values to be investigated. This study aimed at investigating low-intensity workloads and, therefore, only muscle efforts between 10% - 30% MVE were examined. This range of muscle contraction levels is consistent with a task requiring arm abductions with (or without) the hand holding a light hand-tool. To address a relatively wide range of work-rest regimens, a duty cycle between 0.25 – 0.75 was selected. Many studies have examined static efforts with short work-cycles (less than 10 s); this experiment, hence, was designed to examine considerably longer cycle-times (20 - 180 seconds). Table 3-1 presents the different experimental conditions in real values. It was the intention of this study that these experimental conditions would represent a range of actual light, repetitive manual jobs in industry.

Six participants (replications) were assigned to each experimental condition, and for a between-subject design, a total of 90 individuals were involved in this experiment. Response variables included endurance time (ET) and rates of changes (linear slopes) of the following measures: muscle strength (MVE), subjective ratings of perceived muscular discomfort (RPD), EMG amplitude (RMS) and frequency spectral measures (MnPF and MdPF). Except for RPD, slopes of these measures were normalized to their initial (intercept) values. Initial analysis involved analysis of variance (ANOVA) of the first eight conditions (2^3 full-factorial), with the purpose of finding significant main and interaction effects. Subsequent analyses included the use of response surface methodology to determine higher order models. Contour plots of the response variables were also used to evaluate the effects of different combinations of factor levels. Lastly, linear regression was employed to establish associations between response variables. A $P < 0.05$ criterion was used to determine significance of statistical tests.

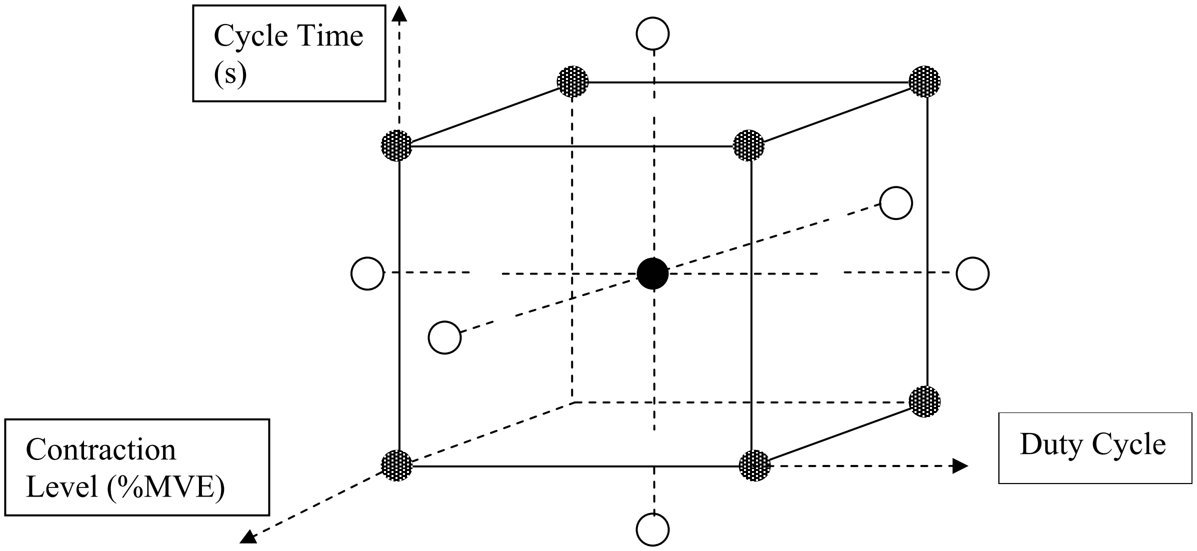


Figure 3-3. An illustration of the experimental design. The three axes of the cube represent three experimental factors. The center point (filled circle) denotes a condition in which all the factor levels are set at the middle value, while the corner points are the conditions of the 2^3 design. The star points (white circles) represent conditions with two factor levels set at the middle value and the third factor at an extreme value. Six replications (participants) were assigned to each condition.

Table 3-1. Factors and factor levels used in the experiment. The factor levels have been chosen to represent a relatively broad range of work conditions.

Experimental Conditions	Levels (Coded Values)		
	Contraction Level (%MVE)	Duty Cycle	Cycle Time (s)
1	+1	+1	+1
2	+1	+1	-1
3	+1	-1	+1
4	+1	-1	-1
5	-1	+1	+1
6	-1	+1	-1
7	-1	-1	+1
8	-1	-1	-1
9	+1.216	0	0
10	-1.1216	0	0
11	0	+1.216	0
12	0	-1.1216	0
13	0	0	+1.216
14	0	0	-1.1216
15	0	0	0

Experimental Conditions	Levels (Real Values)		
	Contraction Level (%MVE)	Duty Cycle	Cycle Time (s)
1	28	0.75	166
2	28	0.75	34
3	28	0.25	166
4	28	0.25	34
5	12	0.75	166
6	12	0.75	34
7	12	0.25	166
8	12	0.25	34
9	30	0.5	100
10	10	0.5	100
11	20	0.8	100
12	20	0.2	100
13	20	0.5	180
14	20	0.5	20
15	20	0.5	100

3.3 RESULTS

3.3.1 Endurance Time

The majority of the work conditions investigated were associated with exercise durations of roughly 60 minutes. As shown in Figure 3-4, three conditions (Condition 1, 2, and 11) yielded substantially shorter endurance times (about 30 minutes or less), and these conditions were characterized by an exercise mean contraction level (MCL) of greater than or equal to 16% MVE (Table 3-2). A fairly broad range of inter-individual endurance data was noted for conditions with short endurance times. Within a condition, for example, it was not uncommon to observe a few individuals whose endurance times were less than 10 minutes, while others were able to maintain the exercise much longer (e.g., greater than 30 minutes). For these conditions, standard deviations for the data were as high as 22 minutes. In the longer-duration conditions (i.e., those with mean endurance times of close to 60 minutes), slightly shorter endurance (in the order of 50 minutes) in one individual was sometimes found. The effects of contraction level, duty cycle, and their interaction were significant ($P<0.01$). Differences in work cycle seemed to affect endurance time, particularly for the higher (28% MVE) contraction level, and the effects were more pronounced for the first two shorter-duration conditions. These effects, however, were not significant ($P = 0.19$).

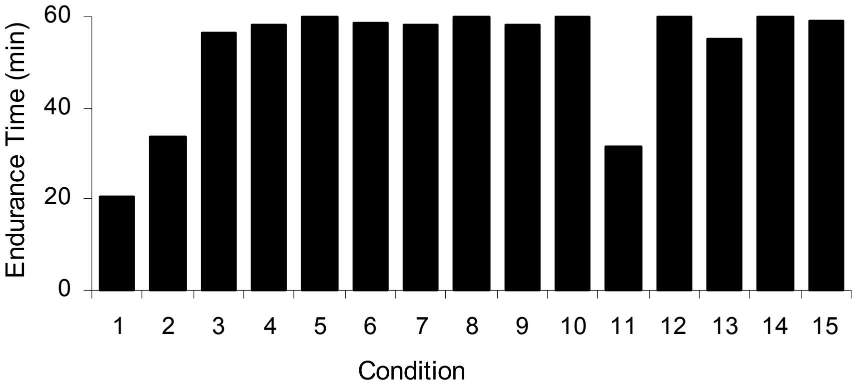


Figure 3-4. Mean endurance times across conditions. Refer to Table 3-2 for values of the work parameters associated with each condition.

Table 3-2. Summary of fatigue measures data (means).

Condition #	Contr. Level (%MVE)	Duty Cycle	Cycle Time (s)	MCL[a] (%MVE)	End.Time (min)	SMVE (%/min)	SRPD (unit/min)	SRMS (%MVE/min)	SMnPF (Hz/min)	SMdPF (Hz/min)
1	28	0.75	166	21	20.7	-0.87	0.43	0.60	-1.88	-1.84
2	28	0.75	34	21	33.7	-0.87	0.25	0.34	-0.72	-0.65
3	28	0.25	166	7	56.7	-0.33	0.10	0.00	-0.03	-0.03
4	28	0.25	34	7	58.3	-0.40	0.11	0.00	-0.03	-0.01
5	12	0.75	166	9	60.0	-0.14	0.08	-0.04	-0.21	-0.18
6	12	0.75	34	9	60.0	-0.21	0.07	-0.02	-0.02	-0.03
7	12	0.25	166	3	60.0	-0.14	0.05	-0.02	-0.02	-0.05
8	12	0.25	34	3	60.0	-0.06	0.05	0.01	0.08	0.05
9	30	0.5	100	15	58.3	-0.36	0.12	0.09	-0.21	-0.26
10	10	0.5	100	5	60.0	-0.16	0.05	-0.06	0.02	0.00
11	20	0.8	100	16	31.3	-0.47	0.31	0.05	-0.28	-0.30
12	20	0.2	100	4	60.0	-0.13	0.05	-0.05	0.04	0.00
13	20	0.5	180	10	60.0	-0.25	0.10	-0.13	-0.25	-0.14
14	20	0.5	20	10	60.0	-0.15	0.07	-0.05	-0.06	-0.06
15	20	0.5	100	10	60.0	-0.18	0.08	-0.06	-0.07	-0.06

[a] Mean contraction level (MCL) = Contraction Level x Duty Cycle

3.3.2 Muscular Strength

The average (SD) of muscular strength (MVE) obtained at the beginning of an experimental session was 160.1 (57.0) N. The maximum and minimum of the pre-fatigue MVEs were 348.3 and 64.7 N, respectively. Across all conditions, no significant difference in initial strength was found (*P*=0.72 – 0.85). As shown in Figure 3-5, reductions in muscle strength across individuals had slopes of MVE (SMVE) that varied from 0.06% to 0.87%/min. Shorter-duration conditions were typically associated with more marked reductions of muscle strength. Conditions 1 and 2 (MCL = 21% MVE), in particular, were associated with rates of MVE changes of roughly 0.9%/min, a figure that was at least twice greater than those in other conditions. A much smaller rate (an average of around 0.12%) was observed for conditions with MCL of less than or equal to 5%MVE. Contraction level and duty cycle contributed to differences in changes in muscle strength (*P*<0.01). Cycle time, however, did not affect rates of muscle strength changes (*P* = 0.86).

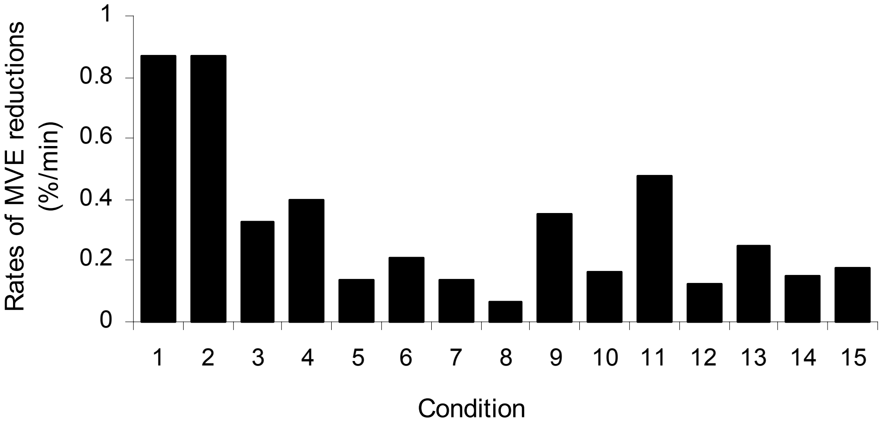


Figure 3-5. Mean rates of strength reduction. Work parameters associated with each condition were shown in Table 3-2.

3.3.3 Subjective Measure of Muscle Discomfort

All of the participants reported a rating of "0 (no discomfort at all)" for perceptions of muscular discomfort (RPD) at the commencement of the exercise. For shorter-duration conditions, an RPD of around 9 was typically reported before the exercise was ceased. The first two conditions, with MCL of 21% MVE, were characterized by fairly high RPD rates of changes (0.34/minute). A similar rate was also observed in one experimental condition (CL = 20% MVE, DC = 0.8, CT = 100s). These rates were three times (or more) greater than those observed in the remaining of the experimental conditions. Rates of RPD changes were significantly influenced by levels of muscle contraction, the duty cycle used, and their interaction ($P<0.01$). In a few conditions, longer cycle time resulted in higher RPD slopes, as indicated by the P value that approached significance ($P = 0.073$).

3.3.4 Myoelectrical Measures

Within each condition, initial values (intercepts) of EMG RMS were typically very close to the muscular contraction level specified in this study; a difference of less than 4% MVE was normally observed. A discrepancy of nearly 9% MVE, however, was observed in one experimental condition (CL = 30% MVE, DC = 0.5, CT = 100s). Substantial increases in EMG amplitude, roughly 0.6% and 0.3% MVE/minute, were observed in the first and second experimental conditions, respectively. These conditions were characterized by higher contraction levels (28% MVE), longer duty cycles (0.75), and considerably shorter exercise durations. Positive slopes (about 0.07% MVE/minute) of EMG amplitude were also observed in two other conditions in which the MCL was 15% or 16% MVE. The remaining experimental conditions were associated with relatively inconsistent results. An experimental condition with low MCL (3% MVE), for example, yielded positive rates of change, while those with much higher MCL corresponded to negative slopes. For this fatigue measure, significant effects were found for contraction level ($P<0.01$) and duty cycle ($P<0.05$).

Mean intercept (SD) values for the MnPF and MdPF were 115.4 (11.7) Hz and 100.8 (10.8) Hz, respectively. Shorter-duration conditions were associated with clear spectral measure declines, ranging from -0.2 Hz to -1.9 Hz/minute. Conditions with exercise durations of 60 minutes were characterized by much smaller slopes. Non-negative slopes were found in a few experimental conditions where MCL was less than or equal to 5% MVE. Similar to the results for previous measures, differences in slopes of spectral measures were significantly affected by CL and DC ($P<0.01$) and their interactions ($P<0.05$). The effects of cycle time on slopes of MnPF and MdPF were obvious in a few experimental conditions, with shorter cycle time resulting in smaller rates of changes. This phenomenon, however, was not found consistently across conditions ($P = 0.103$ and 0.055 for MnPF and MdPF, respectively).

3.3.5 Models for Different Fatigue Measures

Based on the response surface methodology, higher-order models were determined for each of the fatigue measures. Table 3-3 provides the parameters associated with each of the models. Except for ET and SRPD data, lack of fit tests did not show significance, indicating the adequacy of the models. Note that the models require coded values as the input, and that to use a model, each of the input (real) values have to be transformed according to the following equations:

$CL_{coded} = (CL_{real} - 20)/8$

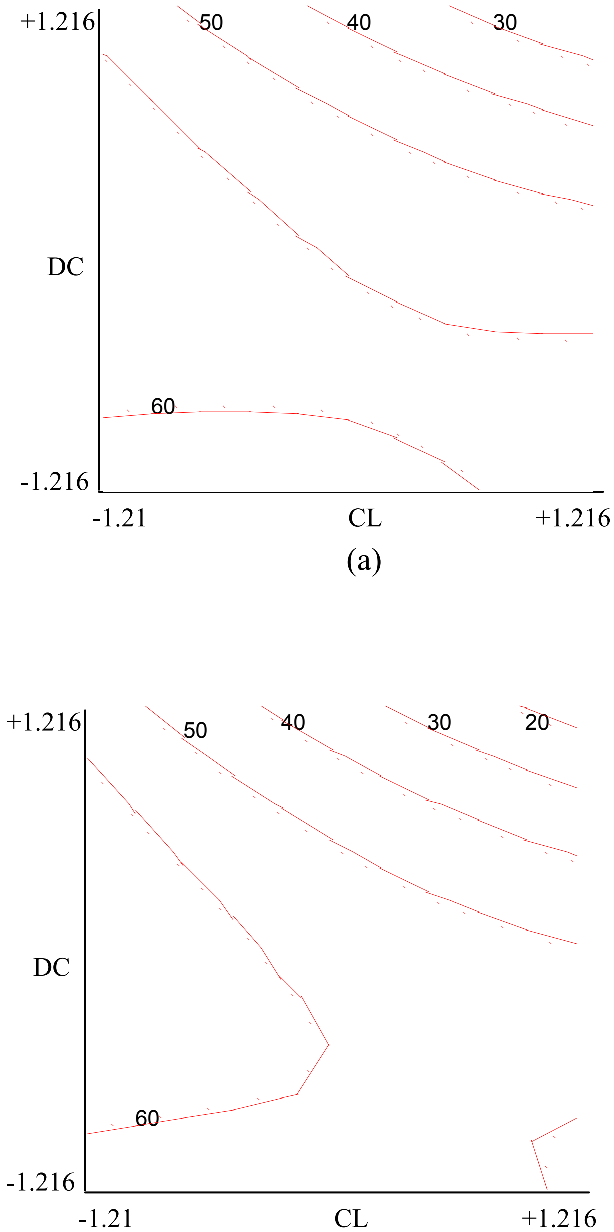
$DC_{coded} = (DC_{real} - 0.5)/0.25$

$CT_{coded} = (CT_{real} - 100)/66$

These prediction models could be used to determine the magnitude of the (fatigue measure) changes, assuming values for the work parameters are known. For example, using Table 3-3 and the transformation equations above, a condition characterized by a contraction intensity, duty-cycle, and cycle-time of 20% MVE, 0.75, and 100s, would result in predicted muscle endurance of 41.2 minutes. Additionally, several contour plots for this fatigue measure could be derived, showing the combinations of factor levels that would yield the same magnitude of response. An example is presented (Figure 3-6) that shows a two-dimensional plot of ET. These plots show the interaction effects of CL and DC on endurance time, when the CT is set at 60s or 120s. A shorter ET is shown at the upper right-hand corner of the plots, and this value becomes greater toward the center of the chart. Though the two plots are somewhat similar, the second (lower) figure with longer CT shows shifts of the plots toward the lower-left corner. Using a similar procedure, plots of SMVE (Figure 3-7) and those of other measures can also be produced. Since the plots are two-dimensional, only interactions of two work parameters can be shown at a time. Recall, however, that significant interaction effects (for several measures) were found for CL and DC that it is more valuable to show this relationship in the contour plots.

Table 3-3. Parameter estimates and the adjusted R^2 for each of the models.

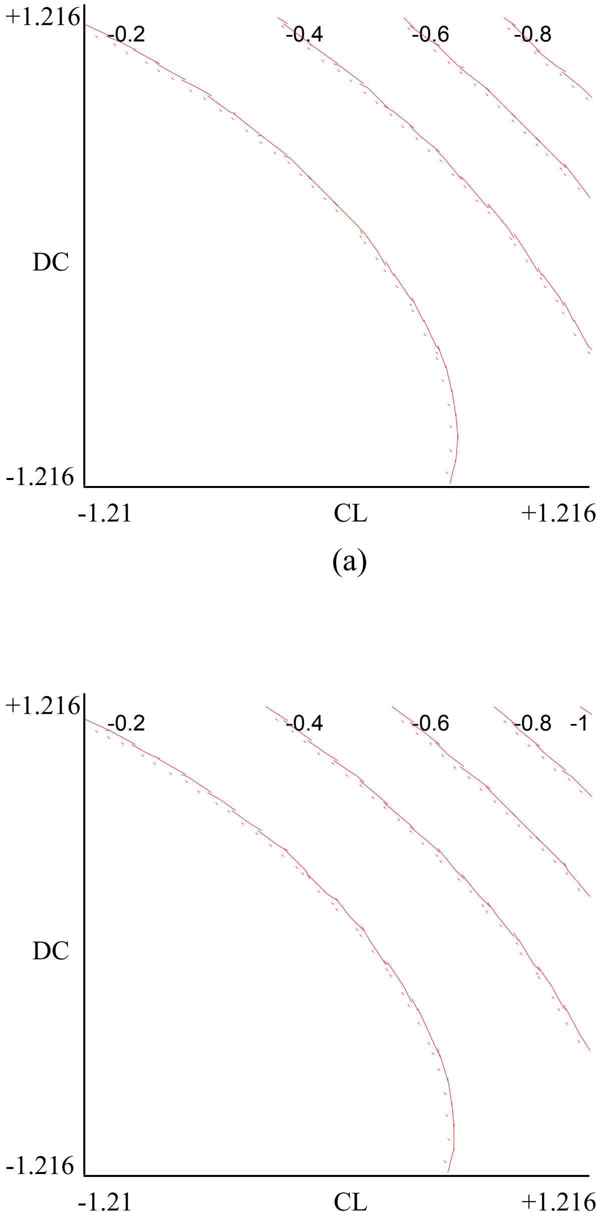
Fatigue Measure	Parameter Estimates Intercept	CL	DC	CT	CL*DC	CL*CT	DC*CT	CL*CL	DC*DC	CT*CT	Adj R^2
Endurance Time (Min)	58.136	-6.337	-8.694	-1.903	-7.593	-1.805	-1.013	0.926	-8.204	-0.201	0.56
SMVE (%/min)	-0.152	-0.196	-0.144	-0.004	-0.107	0.008	0.009	-0.080	-0.106	-0.038	0.33
SRPD (unit/min)	0.083	0.065	0.075	0.020	0.052	0.021	0.024	-0.002	0.064	0.000	0.60
SRMS (%MVE/min)	-0.115	0.108	0.092	0.010	0.125	0.039	0.033	0.099	0.088	0.029	0.25
SMnPF (Hz/min)	0.025	-0.252	-0.293	-0.153	-0.280	-0.109	-0.157	-0.104	-0.119	-0.144	0.34
SMdPF (Hz/min)	0.020	-0.240	-0.277	-0.143	-0.280	-0.120	-0.152	-0.120	-0.133	-0.100	0.39



(a)

(b)

Figure 3-6. Contour plots for ET. The (a) upper and (b) lower figures were based on CT of 60 and 120 seconds, respectively.



(a)

(b)

Figure 3-7. Contour plots for SMVE. The (a) upper and (b) lower figures were based on CT of 60 and 120 seconds, respectively.

3.3.6 Relationships between Fatigue Measures

Using linear regression, several equations were derived that described relationships between a fatigue measure to another. Endurance time was chosen as a variable of interest, and a good linear fit was found for SRPD. The resulting equation is shown below:

$$ET = 65.55 - 104.25\ (SRPD) \qquad \text{Adj. } R^2 = 0.79$$

A poor relationship (Adj. $R^2 = 0.38$), however, was found for the association between ET and SMVE. Similar low-quality relationships (Adj. $R^2 < 0.30$) were also found between ET and EMG-based fatigue measures. Linear fits were determined between SMVE and the other measures, but the results indicated low association (Adj. $R^2 < 0.30$) among these measures as well.

3.4 DISCUSSION

The objective of the present work was to investigate the effects of work parameters on muscle endurance and fatigue during prolonged (one hour) intermittent static work. Unlike studies examining sustained static contractions, investigations on intermittent work have faced a number of challenges due to the number of work parameters involved. Investigations on sustained static contractions have often involved one task parameter (i.e., muscle contraction level). In contrast, at least two parameters characterize intermittent static work, including contraction intensity and the durations of the contraction and relaxation periods. The latter work parameter is determined based on two other parameters, which are the cycle time and the duty cycle of the tasks. Studies in this area normally address a range of values for each of the work parameters, which consequently lead to the relatively large number of experimental conditions to be investigated. The requirements for fairly large number of experimental conditions are probably the reason for lack of study data of muscle fatigue during intermittent static efforts.

3.4.1 Mean Critical Force

Research on static muscular work has often addressed the maximum workload (muscle contraction level) that can be maintained for a relatively long period of time (i.e., critical force), and a contraction level of ~15% MVE (for continuous tasks) was often suggested in early studies (e.g., Rohmert, 1960; Monod and Scherrer, 1965; Pottier et al., 1969). A similar research question also applies for intermittent effort, and based on endurance time data, Björkstén and

Jonsson, (1977) reported that mean critical force (critical force x duty cyle) was ~14% MVE, a figure that was considerably lower than those reported by Monod and Scherrer (1965) or Hagberg (1981). In the former investigation, a cycle time of 10 s was used, and across individuals, only negligible differences in mean critical force were present for a range of duty cycles of 0.3 to 0.7. The present work demonstrated that work conditions with mean contraction levels of less than 15% MVE could generally be sustained for 60 minutes; thus, the mean critical force was 15% MVE. It should be noted, however, that this measure of physical capability could be highly dependent upon the contraction level and the duty cycle employed. Indeed, this investigation found that, based on a cycle time of 100 s, a condition with similar mean contraction level (16% MVE) but different contraction level and duty cycle, resulted in substantially shorter (31 minute) endurance time. Though not systematically investigated, it was possible that combinations of values chosen for these two work parameters could affect endurance of skeletal muscle.

3.4.2 Evidence of Muscular Fatigue

Several commonly used measures of muscle fatigue were employed in this study, and based solely on endurance data, three work conditions were found to be very fatiguing (i.e., shorter exercise periods). Two of these conditions were characterized by a contraction level of 28% MVE and a duty-cycle of 0.75, or equivalent to a mean contraction level of 21% MVE. Regardless of the cycle-time used, both conditions were associated with fairly short muscular endurance times. The endurance data were in agreement with those reported by Byström et al. (1991) who investigated intermittent handgrip tasks of 25% MVE (180s work-10s rest). It was likely that during such contractions muscle ischemia was present (Barcroft and Millen, 1939) due to compromised muscle blood flows. Fairly short relaxation times might not have been adequate to restore this adverse effect. The other experimental condition with shorter endurance times were comprised of a contraction level, duty-cycle, and cycle-time of 20% MVE, 0.8, and 100s, respectively. These results suggest that work intensity with MCL greater than about 16% MVE could be very fatiguing. As noted previously, however, this critical value might vary depending on the actual contraction level and duty-cycle values selected. Data from a condition with similar MCL suggests that shorter contraction periods, coupled with higher workload, could extend muscle endurance.

In this study, muscular endurance could not be used to discriminate the remaining different work conditions, and further fatigue assessments needed to be based on other measures. Though with a varying degree, reductions of muscle strength indicated that the majority of the work conditions examined resulted in the development of muscle fatigue. Substantial degradations in muscle performance were found not only for MCLs of greater than 15% MVE, but also when the exertion levels were relatively high (28% MVE). A minimum reduction rate of 0.4%/minute was observed, and for the two most fatiguing conditions, an individual value of nearly 2%/minute was found, comparable to those reported by Bigland-Ritchie et al. (1986a). It could be argued that both central (neuromuscular transmission) and peripheral factors might be responsible for the development of local fatigue (Bigland-Ritchie et al., 1986a). Surely a conscious decision involving the central nervous system (CNS) determines muscular endurance (Kayser, 2003), but it is generally believed that impaired muscle contractile mechanisms are responsible for muscle failure to generate the required force (Bigland-Ritchie et al., 1986a; Bigland-Ritchie et al., 1986b).

Somewhat different interpretations can be drawn using perceptions of muscle discomfort as a measure of fatigue. It was shown that work conditions with MCLs of 5% MVE or less did not exhibit substantial increases in RPD. For those with MCLs between 5% - 10% MVE, changes in perceived discomfort could be considerably influenced by the choice of work parameters. Above 15% MVE, perceptions of fatigue could be fairly high, regardless of the values of work parameters chosen.

Changes in myoelectrical amplitude and spectral measures have often been associated with the developments of muscle fatigue. Several investigators have, indeed, suggested that an increase in EMG amplitude combined with downward shifts of spectral measures as strong evidence of muscle fatigue (e.g., Hagberg, 1981; Luttmann et al., 2000). In the present investigation, such a phenomenon was demonstrated in three experimental conditions whose workload was about 30% MVE. Conditions with lower contraction level, though considered fatiguing, did not yield these simultaneous EMG changes. Non-typical trends in EMG amplitude, commonly caused by low muscular contraction levels, have been noted in several reports (e.g., Baidya and Stevenson, 1988). This finding clearly shows that typical myoelectrical changes during fatiguing efforts could be observed consistently only when higher levels of muscle contraction (and higher MCL) were involved.

Both mean and median power frequency showed a similar behavior with respect to the different work conditions, and inferences on fatigue based on these two measures would generally result in similar outcomes. The first work condition (MCL=21% MVE, CT=166s) was obviously very fatiguing, as indicated by substantial shifts in spectral measures. This fatigue effect, however, was greatly reduced when the same condition was performed with much shorter cycle-time (34s). Fatigue effects were also apparent in other conditions with MCL of as low as 10% MVE. Jørgensen et al. (1988) reported that no fatigue effects were evident in a study involving a workload of 15% MVE and contraction and relaxation durations of 10 s and 5 s, respectively. Similar to results of their study, in this study, relatively small spectral shifts were observed in one condition with MCL of 10% MVE (DC=0.5, CT=20 s). This observation, however, did not apply to the same condition with different cycle-times. In fact, cycle-time tended to result in greater fatigue effects, and more pronounced spectral shifts were observed as the cycle-time became much longer (i.e., 180 s). Declining trends in spectral measures were also present for conditions with MCLs between 5% - 10% MVE, but the magnitude of the trends seemed to be influenced by the work parameters. Small or non-negative changes in Mn/MdPF were typically observed for work conditions with MCLs of 5% MVE or less, regardless of the values of the work parameters. These findings, hence, suggest that the different work parameters and their interactions could affect the magnitude of EMG-based fatigue measures.

3.4.3 Acceptability of Intermittent Static Effort

Individual preferences (e.g., psychophysical procedures) have been used for evaluating the acceptability of work parameters, and this approach was reported for determining acceptable handgrip tasks (Abu-Ali et al., 1996). More comprehensive approaches involving various measures of muscular fatigue have also been utilized, and such measures could be very valuable in determining the acceptability of certain work conditions or experimental protocols. An acceptable condition is, thus, one that satisfies the criteria based on both subjective and objective measures; acceptable and non-fatiguing work conditions could presumably result in lower risks of musculoskeletal injury.

Based on muscular endurance data, a number of studies have examined a variety of intermittent efforts, and erroneously reported the results as acceptable work conditions. Mundale (1970), for example, suggested that a contraction level of 20% MVE was acceptable for intermittent tasks, regardless of the work-rest ratio and cycle-time chosen. The present study also supported the fact that an exercise protocol of 20% MVE with different combinations of duty-cycle and cycle-time could be maintained for at least 60 minutes. As noted above, however, substantially greater changes in myoelectrical response were observed in the same exercise protocol with longer work cycle. Such a finding clearly demonstrates the importance of acceptability criteria that are based on a number of fatigue measures.

A few studies have been conducted that evaluated the acceptability of intermittent static efforts based on physiological and subjective responses. Byström and Kilbom (1990) utilized EMG, post-exercise blood flow, and subjective rating data to determine the acceptability of handgrip tasks. It was demonstrated that intermittent work of 10% MVE (regardless of the duty cycle selected) and 25% MVE (10s work-5s rest) was considered acceptable. In another investigation, acceptability was determined based on a number of physiological responses and changes in muscle strength, in addition to subjective ratings and the recovery process following an exercise (Byström and Fransson-Hall, 1994). These investigators suggested the acceptability of intermittent handgrip tasks at MCLs of 10% MVE, and further noted that fatigue was present for tasks with MCLs greater than or equal to 17% MVE.

Criteria for acceptability are difficult to determine, and no specific and commonly accepted criteria have been reported in the literature. Nevertheless, results here can be used to develop a set of criteria with respect to the different fatigue measures used. First, only work conditions associated with mean exercise durations of 60 minutes were considered. Second, a maximum subjective rating of “5 (strong)” and a decline in muscle strength of less than 10% were selected. These figures translated into rates of RPD and MVE changes of 0.08 and 0.17%/minute, respectively. Selection of these criteria was somewhat arbitrary. Assuming an actual work period of 60 minutes, an RPD of 5 could represent the limit that the majority of individuals might be willing to accept. As for changes in muscle strength, different studies have often used 10% difference as a measure of consistency during MVE test procedures, implying actual 10% strength reductions to be negligible. Finally, consistency in myoelectrical changes was also chosen for acceptability criteria. It should be noted that typical RMS increase was not always found across the fatiguing conditions, and hence, a criterion based on this measure was not considered further. Instead of relying on the average values, consistency of spectral measure changes was defined as negative slopes that were observed in at least five out of six (83%)

individual data, within an experimental condition. Using these measures, an acceptable condition was one that was characterized by inconsistent downward shifts in both MnPF and MdPF.

For comparison purposes, Table 3-5 was developed that lists all the different experimental conditions and the associated work parameters examined in this study. Conditions not shaded represented those which were acceptable according to all of the criteria described above. It is clearly demonstrated that a mean workload intensity as high as 10% MVE could be considered acceptable, but also that intermittent tasks with the same or lower MCL did not necessarily imply acceptability. Obviously, the magnitude of muscle contraction and work-rest regimen play a critical factor. Conditions 3, 4, and 13, for example, were comprised of MCL less than or equal to 10% MVE, yet local fatigue was present. It is probably safe to suggest that at muscle contraction intensity of 12% MVE, acceptability is not compromised by the different combinations of the other two work parameters.

Table 3-5. Acceptable experimental conditions (non-shaded areas).

Condition	CL (%MVE)	DC	MCL (%MVE)	CT (s)
1	28	0.75	21	166
2	28	0.75	21	34
3	28	0.25	7	166
4	28	0.25	7	34
5	12	0.75	9	166
6	12	0.75	9	34
7	12	0.25	3	166
8	12	0.25	3	34
9	30	0.5	15	100
10	10	0.5	5	100
11	20	0.8	16	100
12	20	0.2	4	100
13	20	0.5	10	180
14	20	0.5	10	20
15	20	0.5	10	100

3.4.4 Design Guidelines

Existing studies have generally indicated that intermittent work is more advantageous than sustained static work with comparable workload. For comparable muscle contraction intensity, intermittent tasks can typically be performed longer, resulting in more work output. Apparently, regular breaks during static efforts allow for restoration of blood supply and ion fluxes (Jørgensen et al., 1988). Rest periods may also provide a motivating factor to workers performing the job. Selection of acceptable work conditions, however, remains a challenging task. A large number of combinations can be derived for the three work parameters described in this study. Certain assumptions may have to be stated before design guidelines can be implemented in real work settings. A workload intensity of less than 30% MVE and a maximum work cycle of three minutes could probably be representative of what workers typically perform in the job. Additionally, a total work duration of one hour might seem reasonable, since regular breaks may have to be assigned for longer, repetitive jobs.

Findings from this investigation suggest that a workload intensity of up to 12% MVE is acceptable, regardless of the duty cycle and work cycle chosen. Moreover, this study also points out the benefits of shorter, but more frequent, rest periods. Caution should be taken, however, in that very short pauses (in the order of seconds) in combination with very long work cycles (e.g., greater than three minutes) might actually result in detrimental effects (Byström et al., 1991).

Relationships between different work parameters and fatigue measures have been established, and two formulae based on ET and SRPD could potentially be used as design guidelines. Using work duration as a criterion, a combination of work parameters could be determined, which ensures job demands that are within workers physical capacity. A similar approach can also be used based on the highest level of muscular discomfort that workers are willing to tolerate. Since both of these measures have a fairly high degree of relationship, a good agreement could be obtained when task parameters are derived based on any of these two measures.

3.4.5 Study Limitations

Findings from this present study could be implemented in work settings with similar conditions, but the following considerations should be taken into account. Individuals recruited in this investigation were all university students. Though they were physically fit and healthy, considerable differences in muscular performance could be expected when comparing against industrial workers. Physical traits, including muscle strength, anthropometry, and age, could be different, and the effects of subjective and motivational factors cannot be ruled out. Industrial workers could be older than college-age students, and age difference has been shown to influence subjective measures during fatiguing conditions (Allman and Rice, 2003).

Discrepancies may also be found in terms of physiological responses to repetitive tasks. In fact, differences in motor strategies between experienced workers vs. reference individuals have been reported in the literature (Madeleine et al., 2003). Muscle fatigue is also obviously task dependent (Bigland-Ritchie et al., 1995), and discrepancies in work characteristics might result in different fatigue responses. Postures adopted in this study, for example, were relatively restricted and may not resemble the actual work situations. Workers typically perform the jobs in standing positions, and arm movements are very seldom restricted to abductions in the frontal plane only.

Note that design guidelines offered in the present work only provided general direction, and thus should be applied with caution. Findings were based on groups of individuals that the applicability of such guidelines may vary from one person to another. Furthermore, work parameters chosen were constrained to specific values, and inferences beyond these values may not be appropriate. Both very short (less than 20 s) or very long (greater than 180 s) work cycles were not investigated in this study, and the effects of these extreme conditions were unclear. In fact, careful considerations should always be given when determining work parameters that are within the constraints examined in this study. Simultaneous use of several fatigue measures is definitely encouraged when evaluating the acceptability of certain work parameter values. Lastly, models developed in this study provide mean responses, and information pertaining to response distributions (e.g., estimating fatigue responses of weak or highly fit individuals) is not provided.

A few other limitations in this study should also be noted with regard to the experimental design and procedures. First, a between-subject design was used that a confounding effect (e.g., due to recruitment of non-homogeneous groups) could potentially be present. Differences in muscular strength have been shown to influence muscle fatigability, but the statistical test performed revealed that no such differences. Participants' demographic (age and anthropometric features) could also affect the results, but no (between-subject) differences pertaining to any of these factors were observed. Additionally, a screening interview was conducted prior to each experimental session to ensure more homogeneous pool of participants. Deviations from standard arm posture during the experiment might have occurred that affected the resulting EMG signals. This problem was minimized by continuous visual observation, and reminding the participants to strictly follow the instructions. Changes in muscle temperature throughout the duration of an experiment were also possible, which could mask the true behavior of myoelectrical signals. These changes were not monitored, but it was expected that the light warming-up session, together with a series of strength test trials prior to the actual experiment were sufficient to allow the exercising muscle to achieve a steady-state muscle temperature. Finally, it could be argued that strength test trial performed every 10 minutes could induce muscle fatigue, although using a similar test protocol (Bigland-Ritchie et al., 1986a) it was demonstrated that the effects were negligible.

3.5 CONCLUSIONS

Intermittent work has been shown to extend muscular endurance and result in more work output. Different combinations of work parameters with mean contraction levels of less than or equal to 15% MVE, could likely be maintained for at least 60 minutes. This limit, however, is sensitive to different work parameters, and does not necessarily imply acceptability of work conditions. Instead of relying on endurance data, assessment of acceptable conditions should be based on simultaneous evaluations of several measures of local muscle fatigue. Work conditions with muscular contraction level less than 12% MVE could probably be non-fatiguing, irrespective of the values of the work parameters selected. Not only is muscle fatigue highly sensitive to workload levels and duty-cycle, it is also influenced by the combinations of these two factors. Lastly, shorter work durations (more frequent) rest breaks seem to be beneficial in minimizing fatigue effects, but extreme work-rest ratios (e.g., relatively long work cycle combined with very short pause) should probably be avoided. The present work investigated muscle fatigue and endurance during intermittent efforts, and models for the assessments of muscle fatigue were established based on different work parameters.

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CHAPTER IV
MUSCULAR LOAD AND FATIGUE DURING ISOMETRIC-NONISOTONIC EFFORTS

4.1 INTRODUCTION

4.1.1 Rationale

Muscular endurance has been used widely as a measure of an individual's physical work capacity during static efforts. Guidelines for the design of occupational activities, aimed at reducing the risk of work-related musculoskeletal symptoms and disorders, have also been derived from endurance data. Early studies indicated that muscle endurance was inversely and roughly exponentially related to static workload (e.g., percent of maximum force), and that a static effort of about 15% – 20% of an individual's maximum voluntary exertion (MVE) could generally be sustained for "a long time" (Rohmert, 1960; Caldwell, 1963; Monod and Scherrer, 1965; Müller, 1965). In contrast, more recent reports suggest that only very low levels of static contraction can be maintained for an extended period of time (Björkstén and Jonsson, 1977; Sjøgaard, 1986; Ulmer et al., 1989). Relationships between muscle endurance and workload levels (% MVE) can further be used to evaluate postural workloads (Dieën and Oude Vrielink, 1994), rest allowances (Rohmert, 1973), or to select work-rest schedules (Dul et al., 1991; Douwes and Dul, 1993; Dul et al., 1994) that result in reduced fatigue. Based on endurance data, the ratio of contraction-period to task cycle-time that results in maximum work output can also be determined (e.g., Björkstén and Jonsson, 1977).

Although endurance data can be of practical value in designing occupational tasks, measures of localized muscle fatigue (LMF) are often suggested as a more comprehensive approach in evaluating work tasks, due to their (presumed) association with physiological and biochemical changes leading to tissue disorders (Vøllestad and Sejersted, 1988; Kumar et al., 2001). While specific mechanisms responsible for LMF are still debated, research has generally indicated that muscle fatigue during static efforts is characterized by changes in subjective and/or objective measures such as muscle strengths and myoelectrical activities. Accordingly, these measures have been used commonly to assess fatigue onset and development during static tasks. Other quantitative measures including intra-muscular pressure, muscle deoxygenation, or metabolite concentrations have also been utilized to evaluate the development and progression of muscle fatigue.

Despite extensive study of static work, pure static contractions are rarely found in real work settings. Work tasks are more often dynamic, characterized by time-varying changes in muscle length and/or tension. These changes can be the result of variations in the activities performed, amount of forces exerted, or postures adopted throughout the work. Pauses and micro-breaks, often inherent parts of a work task, also introduce variations in muscle activities. Task measures, including cycle time and duty cycle, may also vary considerably resulting in continuous changes in muscle activity. All these factors generally result in tasks that are not only dynamic but also more complex, and hence make ergonomic evaluations of such tasks more challenging.

Although quantitative evaluations of dynamic work can be done by calculating (or measuring) all forces/moments theoretically involved in a task, this approach is generally difficult and not practical for the majority of vocational studies. As an alternative, studies have commonly employed electromyography (EMG) to assess muscle workload and fatigue development during dynamic work. Several EMG-based methods have been suggested in the literature, but despite consensus reached on the use of EMG for the evaluation of dynamic work, disagreements still exist on details of the methods. Factors limiting the applicability of the methods are often the result of the immense EMG data involved, and/or the violations of underlying assumptions of EMG using standard processing techniques. Attempts have been made to address both the former (e.g., Jonsson, 1976; Ericson and Hagberg, 1978) and the latter issues (e.g., Potvin and Bent, 1997; Nussbaum, 2001), yet whether the available methods are applicable across a variety of dynamic task conditions remains an open question.

Regardless of these unresolved issues, (surface) EMG procedures are still an attractive and viable option for evaluating dynamic work, primarily because EMG signals closely represent muscle activity and can reflect physiological changes during an activity. Indeed, a considerable number of ergonomic evaluations of vocational workload have been based on EMG data. Results from EMG studies, therefore, may provide a better understanding of the characteristics of dynamic tasks along with task measures associated with muscular endurance and the development of fatigue.

4.1.2 Methods for Characterizing Muscular Load

Electromyographical assessments of muscular stress are often used in conditions where direct measurements of external stress (e.g., force or moment) during work tasks are difficult, if not impossible. Since quantitative relationships between EMG amplitude and force exerted can be established (Jonsson, 1976; Ericson and Hagberg, 1978; Petrofsky et al., 1982; Aarås, 1994; Grant et al., 1994), normalized EMG recordings can represent levels of muscle activities (Marras, 1990; De Luca, 1997), and thus muscular loads. EMG evaluations of muscular load may also provide useful information, such as the possible effects of various work conditions on the development of work-related musculoskeletal illnesses (e.g., Aarås, 1994; Ankrum, 2000).

Assessments of muscle loads based on EMG measures (e.g., root-mean-square EMG) during continuous static tasks are generally uncomplicated, and the amount of physical stress during the tasks can be sufficiently represented by, for example, mean and/or peak EMG values. In contrast, EMG assessments of muscle load during dynamic tasks with complex movements are more difficult, particularly when the force levels are intermittent (see previous section) or change continuously over time. In these conditions, mean or peak EMG values may no longer be a reliable measure of muscle contraction levels. During a prolonged dynamic task, for instance, a short burst of high-intensity muscle activity could be present that, across the duration of work, peak EMG value may not represent overall muscle activities. Similarly, mean EMG value may be of little value in describing muscle activity in conditions where muscle force levels and their durations vary greatly.

A possible option in describing muscle activities during prolonged dynamic work is to collect EMG continuously over the whole work task period. The resulting EMG data can thus be presented as levels of muscle activity over time throughout the work period. Although seemingly useful, this approach requires collecting a substantially larger amount of data, which may not be practical for prolonged EMG recordings. Additionally, the large amount of data makes detailed analysis of the data difficult, and a further data reduction process is thus warranted.

In vocational electromyography, an early approach towards reducing the data collected during prolonged dynamic tasks was to determine the distribution of EMG amplitudes over the course of a work period (Jonsson and Hagberg, 1974; Hagberg and Jonsson, 1975). This approach determined the percentage of time that muscle contraction levels exceeded certain predetermined limits (e.g., contraction level performed during a standardized posture). Using this approach, for example, Jonsson and Hagberg (1974) were able to show different EMG amplitude distributions associated with various task conditions, and subsequently determine the "optimal" task condition.

A similar but more refined method has been proposed that not only simplifies data handling, but also offers less complicated interpretations of the data. Erroneously referred to as Amplitude Probability Distribution Function or APDF (Jonsson, 1976; Jonsson, 1978), this method results in cumulative probability distributions of EMG (CPDE) throughout a work (recording) period. A CPDE thus describes the total time duration certain levels of myoelectrical activities occur. Since the interest is usually on levels of muscle force exerted, the CPDE can be easily transformed into a cumulative probability distribution of force (CPDF), assuming that a force-EMG relationship can be established (Jonsson, 1982). The CPDF then characterizes force exertions of specific muscle groups during prolonged work, and assessments of muscular workload can be performed accordingly. Figure 4-1 presents an overview of procedures for developing a CPDF function. Note that throughout the manuscript, CPDE and CPDF will refer to cumulative distributions of EMG and force data, respectively.

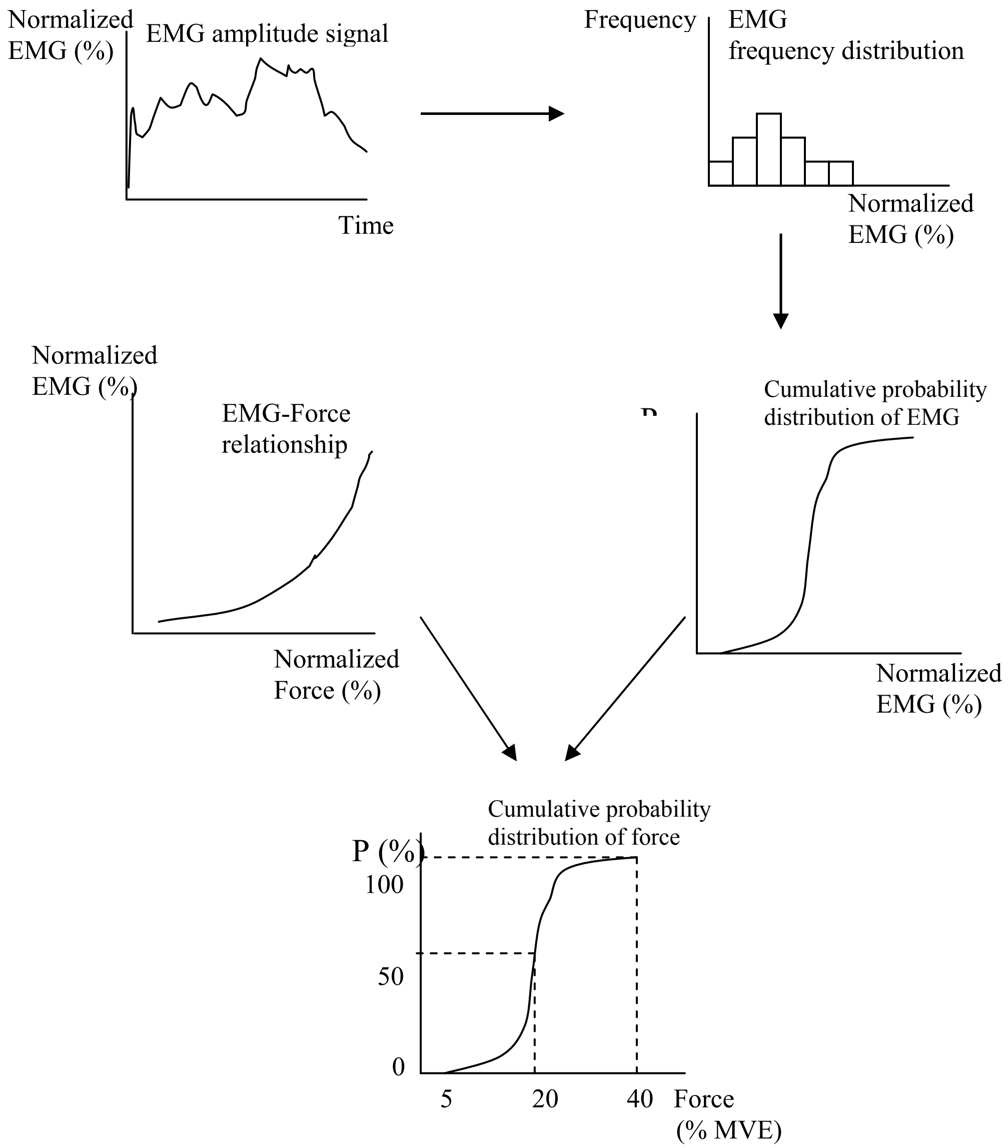

Figure 4-1. Overview of procedures used for developing a CPDF function. The normalized EMG-force relationship is used to transform the CPDE into CPDF.

A number of points along the CPDF function are of interest for describing muscular workload. The CPDF function in Figure 4-1 shows, for instance, that the lowest contraction level (P_0) is equal to about 5% MVE, indicating that during the work period the muscle always works at 5% MVE, or greater (i.e., the muscle is never completely at rest). It is also shown that during half of the recording period the muscular contraction levels are at or below 20% MVE

(P_{50} = 20% MVE), while the peak force exerted (P_{100}) is around 40% MVE. Different sets of percentile values such as P_{10}, P_{50}, and P_{90} have also been proposed to reflect internal muscle responses to external task conditions. Jonsson (1982) has defined P_{10} as the "static muscle contraction level", P_{50} as the "median level" which is close to the mean contraction level, and P_{90} to indicate peak muscle force during work. These three percentile values may also indicate sustained activation of muscle fibers, cumulative muscle load and fatigue, and muscle mechanical overloading, respectively (Visser et al., 2000). Regardless of the different ways to infer a CPDF, a CPDF function is useful for representing muscle load profiles quantitatively (Jonsson, 1976; Hagberg, 1979), and the associated percentile values can be used for the purpose of comparisons across various work task conditions, or for assessing the acceptability of the task (described in the following section),

Although potentially a useful data reduction technique, the CPDF (or likewise CPDE) method has received some criticisms, particularly since the method does not take into account the temporal characteristics of a work task (such as the duration or cycle time). Linderhed (1993) demonstrated that EMG signals obtained from tasks involving two considerably different duty cycles resulted in nearly indistinguishable CPDEs. Noting that the durations of relaxation (pause) periods are critical to muscular response, the author suggested adding a third dimension that considers the length of time a range of EMG activities occurs. Similar comments were also made that CPDF method could not reveal the effect of muscle contraction frequencies at different load levels during a work task (Winkel and Bendix, 1984).

More recent efforts have been presented (e.g., Mathiassen, 2003) that quantify workloads during dynamic/repetitive tasks, and that also take into account the variation of the workload intensity in the time domain. Based on EMG amplitude, for instance, a method was proposed that described variations in muscular loads (exertion frequency and duration) during dynamic activities (Mathiassen and Winkel, 1991). The method, called exposure variation analysis or EVA, involves categorizing muscle load levels (e.g. in force or EMG amplitude) over time into a number of classes of load levels and load level durations. These classes make up a matrix in which each cell represents the total duration a particular level of muscle contraction occurs. The classification scheme is somewhat arbitrary at present, although higher matrix resolution results in more difficult interpretations. Mathiassen and Winkel (1991) have claimed that, in contrast to CPDF, EVA is capable of capturing variations in task measures such as cycle time and duty cycle. These investigators have further noted that the method enables a more detailed analysis of muscle load characteristics, such as whether a particular muscular load during a task is made up of many short contractions or a few long ones. Based on EMG activities registered from the upper-trapezius muscle, their study demonstrated that a keyboard data entry job was characterized by long periods of low-level contraction, while crane coupling operations were represented by extended periods of very low muscle efforts combined with several brief moderate contractions. The EVA, in summary, is a simple data reduction technique for characterizing dynamic work, yet a relatively comprehensive method to identify muscular load variations during work.

4.1.3 Assessment of Fatigue during Dynamic Efforts

A number of subjective and objective measures can be used for the assessment of localized muscle fatigue (LMF). Several types of subjective rating scales have been used, such as Borg's CR-10 scale (Borg, 1990) or its variants. Exercise-induced reductions in muscle strength (MVE) has been viewed as an objective, direct, and reliable measure of muscle fatigue (Vøllestad, 1997). Additionally, several indirect assessment methods have been employed which are based on physiological responses accompanying muscle fatigue. Changes in myoelectrical activities (e.g., amplitude or frequency spectral measures), in particular, have been commonly used to indicate the development of fatigue during static efforts. This EMG-based method has the advantage of being objective and unobtrusive.

During dynamic tasks, however, EMG assessment of muscle fatigue can be more difficult, and interpretations of fatigue based on EMG data collected during these tasks have to be made with great care (Merletti and Lo Conte, 1997). This difficulty stems from the fact that EMG spectral analysis should be derived from signals that are stationary (Bonato et al., 1996; Duchene and Goubel, 1993; Roy et al., 1998), a condition that limits EMG recordings to muscle contractions that are isometric and isotonic (Bonato et al., 1996; De Luca, 1997). Dynamic tasks, in contrast, are often composed of complex movements and/or exertions resulting in time-varying changes in muscle length, velocity, or force. These changes result in non-stationary signals, causing variations in frequency content, such that the use of EMG spectral estimates to assess fatigue may not be appropriate.

Several approaches to the problem of EMG signal non-stationarity have been offered, such as collecting EMG signal during a series of submaximal isometric test contractions performed throughout a dynamic work condition (Kadefors, 1978). Examples of this approach were demonstrated in vocational studies investigating shoulder muscle fatigue during manual drilling activities (Christensen, 1986a, Christensen, 1986b), and lifting activities (Habes et al., 1985; Potvin and Norman, 1993). Several submaximal isometric test contractions (e.g., flexing the arm forward while holding a load) were carried out immediately prior and after each dynamic task, and subsequent spectral analysis was performed to assess shoulder muscle fatigue. The use of such an approach has received several criticisms. These criticisms include the possibility that motor units recruited during the test contractions may be different from those involved during dynamic activities (Dieën et al., 1996), that the introduction of the test contractions may actually induce fatigue (Roy et al., 1998), and that test contractions may interfere with the task being studied.

Despite arguments against EMG spectral analysis based on signal non-stationarity, some investigators believe that reliable spectral estimates can be derived from dynamic EMG, particularly during tasks involving repetitive and standardized movements. Potvin and Bent (1997) investigated the biceps brachii muscle during repetitive flexion-extension movements, and demonstrated that muscle fatigue was reflected by a decline in mean power frequency (MnPF) estimates derived from both isometric and dynamic contractions. The authors further suggested that MnPF recorded during dynamic contractions could be used to evaluate muscle fatigue. Other evidence advocating the use of dynamic EMG has been reported in a more recent study investigating shoulder muscles during prolonged overhead occupational tasks (Nussbaum, 2001). Although variability of spectral measures derived from dynamic contractions was moderately higher than those obtained during submaximal static test contractions, this study demonstrated that dynamic EMG measures may actually be more sensitive in indicating muscle fatigue. Despite reservations on the data processing techniques, dynamic EMG has been considered a viable approach in quantifying muscle fatigue (Christensen et al., 1995; Luttmann et al., 2000), with additional support provided in a variety of studies examining the shoulder muscles (Kadefors et al., 1976; Sundelin and Hagberg, 1992; Sundelin, 1993; Luttmann et al., 1996), the biceps brachii muscle (Hagberg, 1981), the trunk flexors (Morlock et al., 1997), and the erector spinae (Luttmann et al., 1996).

As noted previously, quantifications of muscular loads during dynamic efforts can be performed by utilizing the CPDF. The same method can be implemented to indicate if certain workloads are excessive, or to evaluate the development of localized muscle fatigue. Proponents of this method have claimed that CPDF functions are valuable in ergonomic evaluation of various work conditions (Jonsson and Hagberg, 1974; Jonsson, 1988; Aarås, 1994), and to avoid muscle fatigue and discomfort, it has been suggested that the muscular load levels at P_{10}, P_{50}, and P_{90}, during work should not exceed 5%, 14%, and 70% MVE respectively (Jonsson, 1978). When a cumulative probability distribution of EMG amplitude (CPDE) is derived from prolonged activities, a "right shift" (Figure 4-2) in the CPDE function will be observed toward the end of the activities. This can in turn be interpreted as a sign of fatigue (Hagberg and Jonsson, 1975; Hagberg, 1979; Ericson and Hagberg, 1978), and reflects the increase in EMG signal power, typical during fatiguing efforts.

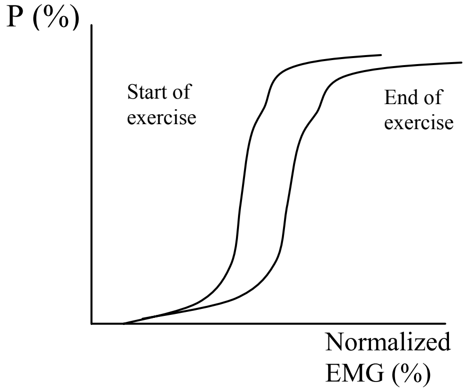

Figure 4-2. A shift in CPDE functions is depicted during prolonged exercise. Such as shift can be considered as indicating fatigue.

3.1.4 Purpose of the Study

Design guidelines pertaining to static work have been extensively addressed in the literature, yet the vast majority of occupational tasks are dynamic in nature. Investigators have been challenged to present efficient methods to quantify dynamic work, especially with the primary goal of characterizing muscular loads from performing occupational tasks. EMG-based assessments of muscle load are an attractive alternative to direct measurements of workload, although the nature of dynamic work (e.g., work duration and workload variability) necessitates collections of a substantial amount of data. The cumulative probability distribution of EMG (CPDE) has been proposed as an efficient data reduction procedure, and it is argued that the procedure reflects patterns of muscular loads during non-fatiguing dynamic efforts. Nonetheless, criticisms of the procedure suggest that it cannot describe temporal variations of workloads (e.g., differences in duty cycle and/or cycle time), presumably associated with risks of musculoskeletal discomforts or injuries. CPDE measures may also not be adequately sensitive across different task conditions (Visser et al., 2000). Exposure variation analysis (EVA) has been suggested as an alternative data reduction method that captures information on load variability, even though the adequacy of the method from ergonomic and physiological standpoints is still unresolved (Mathiassen and Winkel, 1991).

From a design guideline perspective, it is also crucial that any EMG-based methods employed in evaluating dynamic work should be sufficiently sensitive in indicating localized muscle fatigue. A number of investigators have demonstrated the utility of “dynamic EMG” (Fast Fourier transform spectral analysis) for the evaluation of muscle fatigue from repetitive and stereotypical dynamic efforts. Others, however, have argued that such a technique may violate the underlying assumptions of signal stationarity, and hence interpretations of such analyses can become problematic. While EMG estimates from dynamic efforts might be potential indicators of muscle fatigue, it is also not known whether this approach is applicable for low exercise intensities (Gerdle et al., 2000). In addition, confounding factors (e.g., muscle temperature or electrode locations with respect to the active muscle) and substantial variability reported between subjects and muscles (Petrofsky, 1979; Gerdle et al., 1988; Gerdle and Fugl-Meyer, 1992; Dieën et al., 1996) have resulted in inconsistent findings. Implementation of traditional spectral analysis for assessing fatigue during dynamic contractions is thus still questionable.

Finally, the implementation of methods based on EMG amplitude such as CPDE in indicating fatigue during dynamic work seems promising (Hagberg and Jonsson, 1975; Ericson and Hagberg, 1978; Hagberg, 1979), though its reliability has been questioned (Christensen, 1986). Little information is available that verifies the use of CPDE in describing the muscle fatigue process. The EVA is a potential alternative method for assessing muscular workload, yet it is not known whether this method is useful for characterizing muscle fatigue during dynamic efforts. These contradicting reports, and the fact that no generally accepted methods are in existence, warrant further investigations, and were the prime motivation of this study.

Specific main objectives of this study were twofold: first, to describe muscle fatigue based on several EMG-based methods, including dynamic EMG, CPDE, and EVA; and second, to determine the efficacy of these methods for fatigue during prolonged (1 hr) dynamic efforts. While evidence from isometric-isotonic contractions has been extensively reported, and efforts examining isokinetic and more complex dynamic contractions are underway, very limited knowledge is available from studies investigating isometric-nonisotonic efforts. Investigations on this type of contractions offer a major advantage over fully dynamic efforts in that several factors affecting EMG signal characteristics (e.g., muscle length, or possible variability of inter-electrode distance) can be kept constant, and EMG signals produced will thus be dependent primarily on changes in muscle tension and exercise duration.

4.2 METHODS

4.2.1 Participants

Eight university students (Table 4-1) participated in this study. These participants were engaged in moderate levels of daily physical activity, and had no reported prior (12-months) history of musculoskeletal injuries. For each participant, informed consent was obtained prior to participation using procedures approved by the Virginia Tech Institutional Review Board. A practice session was provided to familiarize participants with the experimental apparatus and procedures. The individuals were compensated ($10/hr) for their participation in the study.

Table 4-1. Participants' descriptive data.

	Age (years)	Stature (cm)	Body Mass (kg)	Upper Arm Length (cm)[a]
Mean	21.4	170.1	62.7	29.6
Std. Dev.	1.6	5.0	9.5	1.0
Range	19 - 24	162.5 – 178.0	48.1 – 79.0	28.0 – 20.5

[a] Distance between the acromion and the lateral epicondyle while standing up, arm abducted at 90^0.

4.2.2 Work Task

Participants in this study adopted a comfortable supine posture, with the right (dominant) arm abducted at 90^0 and supported by two metal platforms (with ball-bearings in between). The platforms allowed the arm to move horizontally with minimal friction, thus reducing gravitational loads. Several straps were used to secure the body, and a padded strap was worn medially to the elbow. A commercially available dynamometer (Biodex System 3 Pro, Biodex Medical System, Inc., Shirley, NY, USA) was used, whose attachment was capable of producing rotating movements (a maximum range of motion of about 320^0). A thin steel cable and a set of springs were used to connect the dynamometer attachment to a force transducer which was attached to the elbow strap (Figure 4-3). With the arm maintained at the noted posture, cyclic rotating movements of the dynamometer attachment resulted in repetitive, time-varying dynamic external forces. Both dynamometer range of motion and attachment velocity could be varied to represent different work conditions. Participants were required to maintain a fixed arm posture against the varying external force (resistance) generated by the dynamometer until exhaustion, or for up to one hour. A mirror hung from the ceiling and frequent feedback from the experimenter was used, enabling the participants to maintain the arm at a correct and fixed location throughout the exercise period. Each participant was involved in eight different work conditions (see the Experimental Design section below), and to minimize possible residual fatigue from a previous session, a minimum of 48-hours of recovery was given between sessions.

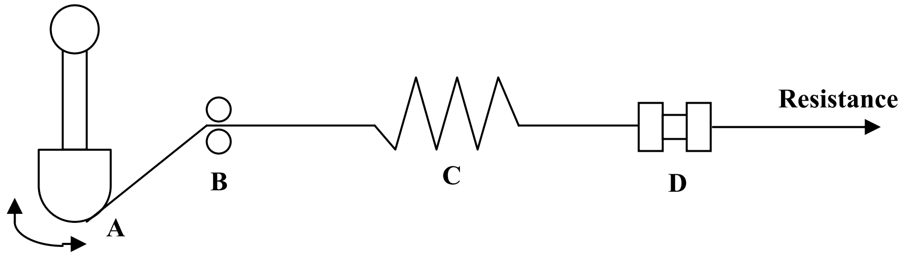

Figure 4-3. Schematic representation of how passive time-varying resistance is generated. A dynamometer arm (A) rotates back and forth which, together with pulleys (B) and spring (C), produces the cyclic time-varying resistance. The load cell (D) (SM-500, Interface, Scottsdale, AZ, USA) registers the actual tension developed between the subject's arm and the dynamometer. A thin steel cable wire connects all parts of the system.

A three-minute warm up and a five-minute rest period were provided prior to the start of each experimental session. Endurance time was noted when a participant failed to maintain the posture (arm abducted against the resistance), even after several standard verbal encouragements.

A maximum exercise duration of 60 minutes was allocated in this experiment. Ratings of perceived muscle discomfort were assessed by using Borg's CR-10 scale (Borg, 1990), and collected every four minutes throughout each experimental session.

Measurements of muscle strength (MVE) were done at the beginning and immediately after every exercise, which required the participants to gradually increase muscle exertion to their maximum, hold the exertion for about one second, and gradually decrease the exertion until complete relaxation. MVEs were completed within five to six seconds, during which EMG and force signals were recorded simultaneously. Four strength test trials were performed, and the largest value was noted as the individual's initial MVE.

4.2.3 Recording and Processing of SEMG and Dynamometer-Arm Position Signal

Pre-gelled bipolar Ag/AgCl electrodes (1 cm diameter) with a 2.5-cm inter-electrode distance were used to obtain EMG signals from the middle deltoid muscle. Selection of the muscle was based on its practical accessibility for surface EMG recording, and due to a pronounced decline in strength observed in this muscle during overhead work (Nussbaum et al., 2001).

To ensure good skin-electrode contact, the skin was shaved, lightly abraded, and cleaned with 70% rubbing alcohol. A 20-minute period was provided in order to stabilize the electrodes on the skin. An inter-electrode resistance of less than 10kΩ was considered acceptable. Electrodes were placed over the middle deltoid muscle according to Hermens et al. (1999). Bony landmarks and a tape measure were used to ensure duplication of electrode locations across experimental sessions.

Continuous EMG signal recording over the whole exercise period was obtained using an EMG amplifier (Measurement Systems Inc., Ann Arbor, MI, USA). A preamplifier increased signal strength by 100, while the amplifier gain setting determined further signal amplification. Both the raw (hardware-filtered at 10-500 Hz, sampled at 2048 Hz) and the root-mean-square (RMS) signals (100 ms time-constant, sampled at 128 Hz) were collected.

Off-line processing of the EMG signals was carried out for the purpose of determining myoelectrical activity levels and spectral measures over time. RMS data were low-pass filtered (Butterworth, 2nd order, 6Hz cutoff frequency), and both CPDE and EVA were employed as RMS data reduction techniques. Dynamic EMGs (RMS means and Mn/MdPFs) were determined based on one-second data windows obtained at maximum positions (angles) of the dynamometer attachment (Figure 4-4). These maximum positions represented the greatest external forces applied to the arm. Spectral measures of the 1-second samples were obtained by dividing the data window into three 0.5-second overlapping windows (Luttmann et al., 1996). Each of these smaller windows was multiplied by a Hanning-weighted window, and later subjected to Fast Fourier Transform (FFT), from which mean power frequency (MnPF) and median power frequency (MdPF) were determined (see descriptions in Chapter II). Additionally, CPDE was derived based on 1-minute RMS data windows, and three percentile values ($CPDE_{10}$, $CPDE_{50}$, and $CPDE_{90}$) describing the EMG distribution were determined accordingly. The same data window was also used to determine nine EVA measures, which were categorized based on levels of EMG activity (less than 10% MVE, between 10% to 30% MVE, and greater than 30% MVE), and the durations associated with each of the levels (less than 1s, between 1-3s, and greater than 3s).

Positions of the dynamometer attachment were collected continuously at 128 Hz, and subsequently low-pass filtered (6 Hz). Software developed in LabVIEW 5.1 (National Instruments) was used for both data collection and processing.

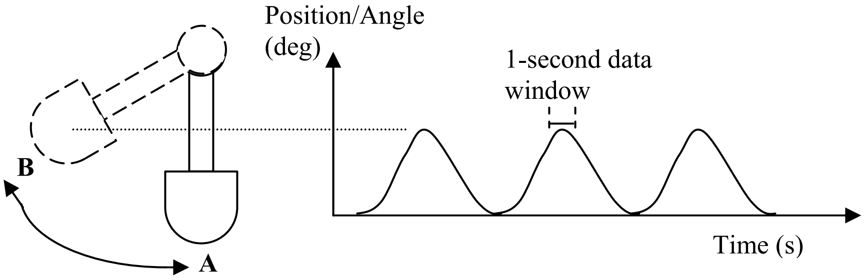

Figure 4-4. The dynamometer attachment moves back and forth from A to B. Dynamic EMGs were derived from 1-second data windows, collected at the peak dynamometer arm position (B).

4.2.4 Experimental Design and Analysis

Two percentile values (P_{10} and P_{90}) were derived from the cumulative distributions of external force (CPDF) generated by the dynamometer. The 10th percentile of this force distribution ($CPDF_{10}$) was varied at two levels (2.5% or 10% MVE), whereas the 90th percentile value (CPDF$_{90}$) was set at 20% or 30% MVE. These different workload intensities, however, were an approximation since the complexity of the mechanism did not allow for achieving exact target values. A percentile value within 5 N of the target value was considered acceptable. Angular velocity of the dynamometer attachment was fixed at either 20^0 or 45^0 per second, representing muscle contractions at different rates. It was intended that these combinations represented at least a portion of the wide variability in external loads found in industrial jobs. A repeated measures, full factorial design was employed, which thus required each participant to attend and perform eight different work conditions (Table 4-2). A balanced Latin square was used to determine the presentation order of the experimental conditions each participant performed.

Table 4-2. Naming of work conditions in this study.

		CPDF$_{10}$			
		2.5% MVE		10% MVE	
		CPDF$_{90}$		CPDF$_{90}$	
		20% MVE	30% MVE	20% MVE	30% MVE
Velocity	20 deg/s	LLS	LHS	HLS	HHS
	45 deg/s	LLF	LHF	HLF	HHF

L:Low; H:High; S:Slow; F:Fast

Response variables included rates of MVE changes (SMVE, in %/minute), endurance time (ET), and rates of RPD changes (SRPD). EMG-based dependent variables included slopes of dynamic EMG (SRMS, SMnPF, and SMdPF), and rates of changes for CPDE and EVA measures. Except for MVE, linear regressions were used to estimate slopes for each of the time-dependent measures. Orders of experimental conditions could potentially affect the response variable, and analysis of variance (ANOVA) was utilized to decide if such effects were significant. ANOVA was also used to test the effects of the noted dependent variables, except when gross deviations from normality were found, in which case the use of a non-parametric method (Kruskal-Wallis test) was preferred. Significance of these statistical tests was based on $P < 0.05$. Both linear regression analyses and coefficient of correlations were used to draw inferences on the degree of associations among the response variables.

4.3 RESULTS

4.3.1 Endurance Time (ET)

As demonstrated by ET data (Figure 4-5), in six experimental conditions participants in this study were forced to end the experimental session due to exhaustion. The majority of the participants were able to maintain the two lightest (LLS and LLF) conditions for the entire hour. Results from the Kruskal-Wallis test showed that the presentation order of the experimental conditions was not significant ($P=0.39$). The same analysis further indicated that higher workloads were closely related to shorter endurance, while lighter conditions resulted in longer exercise durations ($P<0.001$). Endurance during HHS or HHF conditions, for example, was roughly 20 minutes. In contrast, any other lighter condition was associated with ET of 30 minutes or longer. Though a general trend in ET was observed with respect to levels of workload involved, moderate levels of workload apparently yielded mixed endurance data. ET was also affected by the rates of resistance change ($P<0.001$); i.e., slower velocity of attachment movements was associated with shorter endurance. No two-way effects were found for this dependent measure.

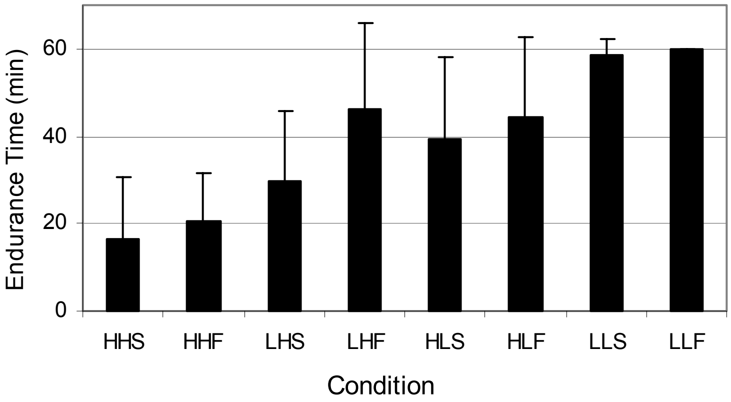

Figure 4-5. Endurance time data averaged over all participants.

4.3.2 Maximum Voluntary Exertion (MVE)

Within a session, means of muscular strength obtained at the beginning of an experimental session ranged from 52.5 to 62.0 N, but comparisons among sessions did not reveal any significant ($P = 0.42 – 0.68$) difference in initial MVEs. Non-parametric ANOVA showed that rates of MVE changes (SMVE) were not dependent on the presentation order of the experimental condition (*P*=0.62). Increased exercise workload was closely related to greater SMVE (Figure 4-6). Regardless of the velocity, the HHS and HHF conditions resulted in strength reductions of approximately 2%/min. Much lower rates of MVE reduction (about 0.3% – 0.8%/min) were found in the other experimental conditions. SMVE was significantly affected by CPDF$_{10}$ ($P<0.001$), CPDF$_{90}$ ($P<0.001$), and their interaction ($P<0.05$). Although not significant ($P=0.06$), the results (Figure 4-6) suggest that velocity might contribute to MVE changes, and the effects seemed to be more pronounced for conditions with higher workload intensities.

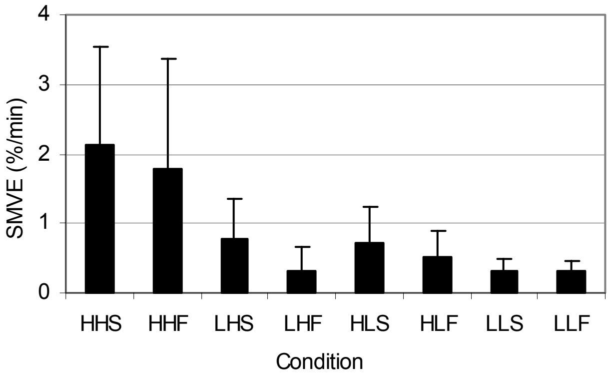

Figure 4-6. Rates of MVE change (SMVE).

4.3.3 Ratings of Perceived Discomfort (RPD)

All of the participants reported an RPD of zero at the commencement of the exercise, and the majority requested to stop when the RPD had reached a value of 9 (close to “extreme” levels of discomfort). Order effects were not present (*P*=0.10), and across experimental conditions, rates of RPD changes (Figure 4-7) showed a significant ($P < 0.001$) declining pattern as the work load decreased. HHS and HHF conditions, for example, resulted in rapid RPD changes in the order of 0.8 and 0.6 per minute, respectively. Lower rates of changes (about 0.3 to 0.4 per minute) were achieved during moderate levels of work intensities. Low-intensity work conditions (LLS and LLF) were associated with much lower rates of changes (0.09 to 0.1 per minute).

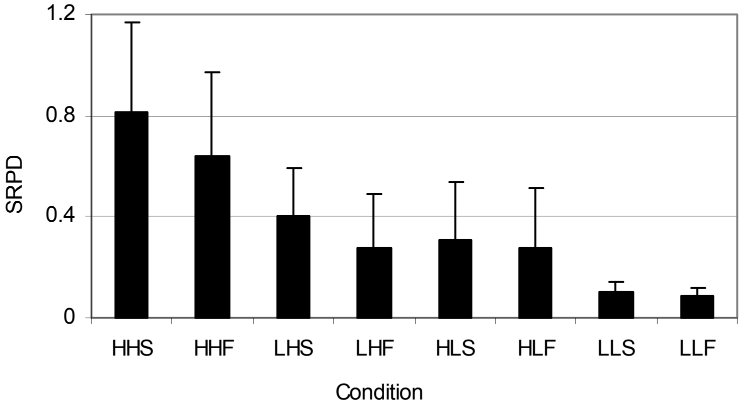

Figure 4-7. Means of rates of RPD changes (unit/minute).

Across all conditions, there was an influence of attachment velocity on rates of RPD changes (*P*<0.01). The effects were noticeable when comparing HHS vs. HHF, or LHS vs. LHF conditions. Relatively smaller (negligible) differences due to attachment velocity were found when comparing the remaining work conditions.

4.3.4 Dynamic EMG

Figure 4-8 presents the time-varying changes in dynamometer attachment position and the associated changes in EMG raw and amplitude. Changes in myoelectrical signals clearly mimicked the pattern of attachment positions. Both raw signals and RMS were greatest when the attachment was at its peak position (i.e., maximum resistance), while low EMG activities were closely associated with minimum attachment position (i.e., lowest resistance).

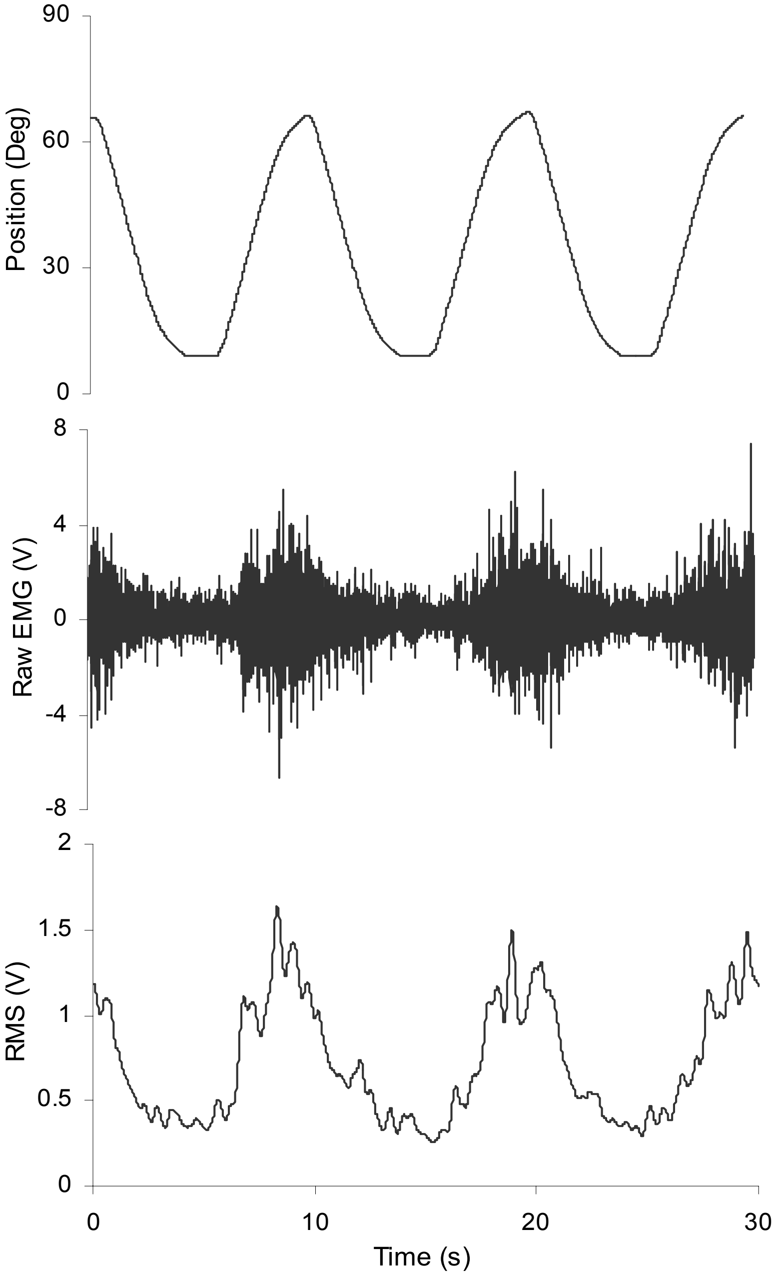

Figure 4-8. Time varying changes in attachment position, and the associated EMG response.

Order effects were not significant (*P*=0.94), and none of the experimental factors investigated ($CPDF_{10}$, $CPDF_{90}$, and velocity) had any significant effects on changes in RMS slopes (*P* = 0.20 – 0.85). Additionally, no specific pattern of RMS rates of change was observed that could probably be attributed to the differences in the work conditions. In fact, somewhat opposing results of similar magnitude were observed when comparing a pair of conditions (Table

4-3). For example, the HHS condition resulted in an increase in rates of RMS change of 0.167 %MVE/min, almost the opposite results from a comparable condition (HHF). A similar phenomenon was observed when comparisons were made for LLS vs. LLF conditions. Also, higher intensity work conditions (e.g., HHF) were characterized by a decrease in RMS, while lighter conditions (e.g., LLS) were associated with positive (an increase in) RMS rates of change.

ANOVA results showed that order effects were not significant for slopes of both MnPF (P=0.40) and MdPF (P=0.54). In contrast to RMS data, more consistent patterns were found for spectral measure (MnPF and MdPF) changes (Table 4-3). Higher intensity conditions resulted in greater (downward) spectral shifts; likewise, lighter work conditions yielded smaller rates of changes. Though different in magnitude, the greatest changes in both MnPF and MdPF were observed during HHS condition (slope of about -0.7 to -0.9 Hz/min). Much smaller rates of changes were observed for the lighter work conditions (slope of lower than -0.17 Hz/min). These differences, however, could only be attributed to $CPDF_{90}$ ($P<0.05$), and non significant effects were found for $CPDF_{10}$. Attachment velocity also seemed to affect slopes of MnPF and MdPF, although such observation was not significant (P=0.30-0.43), and was found only when examining the HHS vs. HHF, and LLS vs. LLF conditions.

Table 4-3. Rates of EMG changes.

Condition	EMG Measure		
	SRMS (%MVE/min)	SMnPF (Hz/min)	SMdPF (Hz/min)
HHS	0.167	-0.686	-0.874
HHF	-0.125	-0.138	-0.271
LHS	-0.002	-0.139	-0.074
LHF	-0.154	-0.133	-0.147
HLS	0.098	-0.016	0.004
HLF	0.189	-0.166	-0.132
LLS	0.011	-0.079	-0.073
LLF	-0.049	-0.001	-0.040

4.3.5 CPDE

Regardless of the angular velocity, the initial values of the three CPDE measures (Table 4-4) were closely related to differences in workload intensities ($P<0.05$). These values were also similar to levels of $CPDF_{10}$ and $CPDF_{90}$ used in this study, although the magnitude of the

CPDE measures was slightly greater than those of the CPDF. For example, the LLF condition was based on $CPDF_{10}$ and $CPDF_{90}$ of 2.5% and 20% MVE, respectively. This work condition resulted in initial $CPDE_{10}$ and $CPDE_{90}$ of about 5% and 21% MVE, demonstrating minimal differences between the distribution of the EMG data and those of the external forces.

Table 4-4. Initial CPDE measures (%MVE).

Measure	Work Condition							
	HHS	HHF	LHS	LHF	HLS	HLF	LLS	LLF
$CPDE_{10}$	11.09	9.22	5.88	6.17	9.60	7.44	6.47	4.90
$CPDE_{50}$	21.36	17.04	17.00	14.78	15.96	12.68	13.57	10.40
$CPDE_{90}$	39.93	34.94	33.34	32.37	24.78	21.27	22.57	20.68

Derived from stepwise regressions, the following models show the relationships between initial values of the CPDE measures and the first three measures of muscle fatigue. Across these fatigue measures, only a maximum of roughly 30% of the variation could be explained by the models.

$$ET = 67.51 - 187.02(CPDE_{10}) + 66.40(CPDE_{50}) - 82.52(CPDE_{90})$$ Adj. $R^2 = 0.18$
Std. Error = 18.61

$$SMVE = -0.43 + 18.09(CPDE_{10}) - 18.70(CPDE_{50}) + 9.70(CPDE_{90})$$ Adj. $R^2 = 0.31$
Std. Error = 0.85

$$SRPD = -0.09 + 4.48(CPDE_{10}) - 3.03(CPDE_{50}) + 2.00(CPDE_{90})$$ Adj. $R^2 = 0.25$
Std. Error = 0.28

As presented in Table 4-5, CPDE measures showed increasing rates of changes in some conditions, while a declining pattern was observed in others. The HHS work condition, for example, showed an increase in EMG amplitude throughout an experimental duration, as represented by positive slopes of $CPDE_{10}$, $CPDE_{50}$, and $CPDE_{90}$ of about 0.04, 0.21, and 0.14 %MVE/min, respectively. Similar results with respect to positive slopes of the CPDE measures were also found in LHS, HLS, HLF, and LLS conditions. In contrast, an inconsistent pattern (i.e., positive slope in one measure, but negative in others) was observed in the HHF condition. Negative values for all of the measures were found in two work conditions (LHF and LLF). Across conditions, the increase in CPDE measures seemed to be correlated with the work intensity and velocity. However, none of the independent variables had significant ($P = 0.08 - 0.92$) contributions to the differences in slopes of the CPDE measures, except the effect of $CPDF_{90}$ on $CPDE_{10}$ ($P<0.05$).

Table 4-5. Rates of CPDE changes (%MVE/min).

Condition	CPDE Measure		
	$CPDE_{10}$	$CPDE_{50}$	$CPDE_{90}$
HHS	0.0368	0.206	0.135
HHF	-0.0815	0.008	-0.111
LHS	0.0066	0.051	0.029
LHF	-0.0541	-0.036	-0.134
HLS	0.0015	0.041	0.130
HLF	0.0055	0.031	0.194
LLS	0.0017	0.015	0.010
LLF	-0.0039	-0.007	-0.030

4.3.6 EVA

The nine EVA measures represented levels and durations of muscle contractions involved, and thus potentially discriminate one work condition over another. Table 4-6 presents the cumulative distributions (percentage) of EMG amplitude at the beginning of an exercise, during a particular work condition. The data demonstrate, for example, that the higher workload conditions (HHS and HHF) were characterized by muscle activities less than or equal to 10% MVE (10%), between 10% and 30% MVE (62%), and greater than 30% MVE (28%). Most (80%) muscle contractions between 10% and 30% MVE were associated with contraction durations greater than one second. The influence of attachment velocity on HHS and HHF conditions also seemed to be captured by these EVA measures. For instance, EVA6 and EVA9 values revealed longer muscle contraction durations for HHS, when compared against HHF.

Table 4-6. Intercepts of EVA measures. The quantity in each cell represents average time distribution (%) of EMG-RMS at the commencement of a work condition.

EVA Measure	Work Condition							
	HHS	HHF	LHS	LHF	HLS	HLF	LLS	LLF
EVA1 (WL<=10%MVE; D<=1s)	4.0	5.8	5.8	6.9	6.8	10.8	6.3	8.7
EVA2 (WL<=10%MVE; 1s<D<=3s)	2.8	5.8	7.1	12.7	5.2	10.7	9.6	15.0
EVA3 (WL<=10%MVE; D>3s)	3.1	4.2	13.1	11.5	4.4	9.3	12.9	19.3
EVA4 (10%MVE<WL<=30%MVE; D<=1s)	12.6	12.9	13.5	16.1	10.5	12.9	9.1	9.2
EVA5 (10%MVE<WL<=30%MVE; 1s<D<=3s)	23.6	28.5	22.9	25.6	14.4	28.9	17.2	27.7
EVA6 (10%MVE<WL<=30%MVE; D>3s)	25.9	21.2	20.9	10.5	52.2	25.8	41.0	19.1
EVA7 (WL>30%MVE; D<=1s)	8.7	8.4	7.6	8.3	4.3	2.2	3.1	1.2
EVA8 (WL>30%MVE; 1s<D<=3s)	5.3	12.6	4.0	7.7	2.2	-0.7	0.8	0.0
EVA9 (WL>30%MVE; D>3s)	14.0	0.5	5.2	0.8	0.0	0.0	0.0	-0.2

Table 4-7. Levels of significance for EVA intercepts.

EVA Measure	Independent Variable		
	$CPDF_{10}$	$CPDF_{90}$	Velocity
EVA1 (WL<=10%MVE; D<=1s)	-	++	++
EVA2 (WL<=10%MVE; 1s<D<=3s)	++	+	++
EVA3 (WL<=10%MVE; D>3s)	++	-	-
EVA4 (10%MVE<WL<=30%MVE; D<=1s)	-	++	-
EVA5 (10%MVE<WL<=30%MVE; 1s<D<=3s)	-	-	++
EVA6 (10%MVE<WL<=30%MVE; D>3s)	+	++	++
EVA7 (WL>30%MVE; D<=1s)	-	++	-
EVA8 (WL>30%MVE; 1s<D<=3s)	-	++	-
EVA9 (WL>30%MVE; D>3s)	-	+	+

- Non significant; + Significant at P<0.05; ++ Significant at P<0.01

The discriminating property of EVA measures could also be shown when evaluating the lighter conditions (e.g., LLS vs. LLF). For these two lighter conditions, EVA measures indicated a negligible amount of muscle contractions greater than 30% MVE, and about 56% of the time the contraction levels were around 10% to 30%MVE. Slower velocity for these two conditions tended to be associated with the EVA6 measure, in which the duration of muscle contractions of 10% - 30% MVE for LLS was roughly twice that of LLF. Comparisons could also be performed for the other four conditions (LHS, LHF, HLS, and HLF). Without regard to the velocity factor and when compared to HLS and HLF, the LHS and LHF conditions were apparently indicated by fewer muscle contractions in the range of 10% - 30% MVE, but a higher percentage for contractions greater than 30% MVE. Table 4-7 was derived from ANOVA, and the results indicated there were at least two measures (EVA2 and EVA6) that were sensitive to changes in $CPDF_{10}$, $CPDF_{90}$, and velocity variables. Additionally, most (seven out of nine) measures were sensitive to changes in $CPDF_{90}$, followed by velocity and $CPDF_{10}$ factors, respectively.

Several models representing muscle endurance, changes in strength or RPD as a function of initial EVAs are presented below. Of the nine EVA measures, only five to seven measures were considered important for the models. From the steps performed during model buildings, two of these measures could be considered critical, including EVA4 and EVA8.

$$\begin{aligned} ET = {} & 40.96 + 43.91(EVA2) + 55.05(EVA4) - 147.13(EVA7) & \text{Adj. } R^2 = 0.23 \\ & - 75.57(EVA8) - 21.56(EVA9) & \text{Std. Error} = 18.11 \end{aligned}$$

$$\begin{aligned} SMVE = {} & 3.22 - 3.20(EVA2) - 3.16(EVA3) - 11.77(EVA4) & \text{Adj. } R^2 = 0.48 \\ & - 2.24(EVA6) + 6.32(EVA8) & \text{Std. Error} = 0.74 \end{aligned}$$

$$\begin{aligned} SRPD = {} & 0.31 + 2.13(EVA1) - 0.66(EVA2) - 3.75(EVA4) & \text{Adj. } R^2 = 0.31 \\ & + 0.47(EVA5) + 4.41(EVA7) + 1.26(EVA8) + 0.58(EVA9) & \text{Std. Error} = 0.27 \end{aligned}$$

Rates of change of the EVA measures throughout the different work conditions are shown in Table 4-8, and certain patterns could be observed with respect to the data obtained. Taking EVA4 as an example, HHS and HHF conditions were associated with fairly large positive (0.4 – 0.5%/min) changes, and this figure became smaller as the workload decreased. This tendency, however, was not observed in other conditions. In fact, EVA4 was the only measure that was sensitive to changes in workload intensity (Table 4-9), and even this observation was specific to changes in $CPDF_{10}$ ($P < 0.05$). The effects of velocity were significant ($P < 0.05$) on two EVA measures (EVA3 and EVA6). The data in Table 4-8 indicated these effects, in which faster velocity almost consistently resulted in greater (positive) slopes.

Table 4-8. Slopes (%/min) of EVA measures.

EVA Parameter	Work Condition							
	HHS	HHF	LHS	LHF	HLS	HLF	LLS	LLF
EVA1 (WL<=10%MVE; D<=1s)	0.134	0.038	-0.023	-0.068	-0.007	0.008	-0.002	-0.003
EVA2 (WL<=10%MVE; 1s<D<=3s)	-0.042	0.054	0.114	0.017	-0.040	-0.170	0.036	0.013
EVA3 (WL<=10%MVE; D>3s)	-0.069	0.185	-0.182	0.212	-0.049	0.036	-0.044	0.033
EVA4 (10%MVE<WL<=30%MVE; D<=1s)	0.500	0.368	0.056	-0.076	0.114	0.077	-0.020	-0.027
EVA5 (10%MVE<WL<=30%MVE; 1s<D<=3s)	-0.273	-0.567	0.180	0.037	0.310	-0.115	-0.043	-0.112
EVA6 (10%MVE<WL<=30%MVE; D>3s)	-0.992	0.197	-0.255	0.095	-0.486	-0.164	0.102	0.105
EVA7 (WL>30%MVE; D<=1s)	0.249	0.001	0.103	-0.012	0.101	0.127	-0.015	-0.021
EVA8 (WL>30%MVE; 1s<D<=3s)	0.440	-0.892	0.067	-0.177	0.000	0.201	-0.014	0.001
EVA9 (WL>30%MVE; D>3s)	0.053	0.617	-0.060	-0.027	0.058	0.000	0.000	0.011
Sum of absolute slope values	2.751	2.918	1.040	0.722	1.164	0.898	0.277	0.326

Table 4-9. Levels of significance for EVA slopes.

EVA Parameter	Independent Variable		
	$CPDF_{10}$	$CPDF_{90}$	Velocity
EVA1 (WL<=10%MVE; D<=1s)	-	-	-
EVA2 (WL<=10%MVE; 1s<D<=3s)	-	-	-
EVA3 (WL<=10%MVE; D>3s)	-	-	+
EVA4 (10%MVE<WL<=30%MVE; D<=1s)	+	-	-
EVA5 (10%MVE<WL<=30%MVE; 1s<D<=3s)	-	-	-
EVA6 (10%MVE<WL<=30%MVE; D>3s)	-	-	+
EVA7 (WL>30%MVE; D<=1s)	-	-	-
EVA8 (WL>30%MVE; 1s<D<=3s)	-	-	-
EVA9 (WL>30%MVE; D>3s)	-	-	-
Sum of Absolute Slope Values	++	++	-

- Non significant; + Significant at $P<0.05$; ++ Significant at $P<0.01$

Interesting trends were noticed when each work condition was examined individually. The HHS condition, for instance, was characterized by large (positive and negative) rates of changes, as indicated by EVA4, EVA6, and EVA8 measures. For this condition, a relatively rapid increase (0.5%/min) was observed for levels of muscle contractions between 10% and 30% MVE with contraction durations of less than or equal to one second. In addition, the same condition resulted in fairly steep negative slopes (roughly -1%/min) for the same levels, but longer durations (greater than three seconds) of muscle contractions. In contrast, smaller magnitude of changes was found for less demanding work conditions (such as LHS and LHF). Furthermore, minimal changes were observed across EVA measures for the low intensity work conditions (LLS and LLF). These observations lead to a potentially valuable approach, that the magnitude (instead of the direction) of the slopes might be related to changes in the work conditions. The last row of Table 4-8 provides the sum of the absolute values of the EVA slopes for each of the work conditions, and both $CPDF_{10}$ and $CPDF_{90}$ resulted in significant ($P < 0.01$, Table 4-9) changes on this last EVA measure.

4.3.7 Relationship Between Fatigue Measures

Degree of relationships between rates of muscle strength change vs. the different fatigue measures is presented in Table 4-10. Pearson's r was used based on individual data, while Spearman's ρ utilized means of eight individual data. Based on both methods, correlation of coefficients were high for both measures of muscle endurance and subjective perception of discomfort. Relatively high correlations were also found for dynamic EMG, but not for slopes of EMG amplitude. Very poor correlations were generally observed for CPDE measures, except for $CPDE_{50}$ based on the aggregate data. With respect to EVA measures, fairly high and consistent correlation values were found for only EVA1, EVA4, EVA5, and sum of absolute EVA slopes.

Table 4-10. Correlation coefficients for the different fatigue measures against rates of MVE change

Fatigue Measure	Pearson's r	Spearman's ρ
ET	-0.70	-1.00
SRPD	0.84	0.97
SRMS	-0.22	0.20
SMnPF	-0.65	-0.76
SMdPF	-0.72	-0.83
$CPDE_{10}$	-0.22	0.00
$CPDE_{50}$	0.16	0.73
$CPDE_{90}$	-0.18	0.11
EVA1	0.50	0.84
EVA2	0.03	0.03
EVA3	-0.10	-0.03
EVA4	0.80	0.99
EVA5	-0.58	-0.61
EVA6	-0.09	-0.55
EVA7	0.48	0.59
EVA8	-0.38	-0.12
EVA9	0.06	0.59
Sum of EVA	0.82	0.59

Regression analyses were performed, particularly for fatigue measures characterized by fairly high degree of associations. Muscular endurance has often been the variable of interest, and relationships between this measure and other fatigue measures could be quantified.

Individual data between endurance time and slopes of MVE or RPD did not seem to be linear, and quadratic polynomial fit resulted in the following equations:

$$ET = 58.1412 - 27.6109(SMVE) + 5.2886(SMVE-0.8609)^2 \qquad Adj.R^2 = 0.65$$

$$ET = 63.3902 - 82.1572(SRPD) + 60.9104(SRPD-0.3626)^2 \qquad Adj.\ R^2 = 0.93$$

Linear regressions were also used to describe relationships between SMVE and several other fatigue measures based on dynamic EMG or EVA, and the resulting equations are presented below:

$$SMVE = 0.6565 - 1.2011(SMnPF) \qquad Adj.\ R^2 = 0.41$$

$$SMVE = 0.6264 - 1.1652(SMdPF) \qquad Adj.\ R^2 = 0.51$$

$$\begin{aligned} SMVE = {} & 0.3607 + 33.0953(SEVA1) + 49.9313(SEVA4) \\ & - 47.9929(SEVA5) + 16.3750(SumEVA) \qquad Adj.\ R^2 = 0.81 \end{aligned}$$

4.4 DISCUSSION

The present study was conducted with the primary goal of characterizing the endurance and the development of local muscle fatigue associated with dynamic muscular activities. A great amount of effort has been devoted to the investigations of fatigue during purely static (isometric-isotonic) work. Similarly, more attention has been given to work conditions involving (completely) dynamic muscle exercises. Much less information exists, however, that addresses isometric, but non-isotonic muscle efforts, and it was the intention of this study to better understand the muscular responses during static, but non-isotonic, activities.

4.4.1 Evidence of Muscle Fatigue

The present work was intentionally designed so that a range of fatiguing conditions could be examined. Across individuals, substantial fatigue effects were evident in six out of eight work conditions, as confirmed by fairly short (less than 60 minutes) exercise durations. Using endurance data, HHS and HHF could be considered as the most fatiguing, whereas the least fatiguing conditions were both LLS and LLF. Moderate levels of fatigue could probably be assigned to the remaining four work conditions (LHS, LHF, HLS, and HLF). Of these four, LHS was evidently the hardest condition, followed by HLS, HLF, and LHF, respectively. This finding might suggest the potential of using endurance data for discriminating fatiguing conditions during dynamic efforts.

Exercise-induced reductions in muscular capacity (ability to generate maximal force) have been commonly used as a “gold standard” in indicating the development of muscle fatigue. Strength data in the present study clearly demonstrated that fatigue effects were present in all work conditions, as indicated by strength reduction of 14% to 26% at the cessation of the sessions. These figures were markedly greater than those reported during 20-minute submaximal dynamic repetitive exercise (Hoffman et al., 1985). A substantial amount of fatigue was, in fact, found in the majority of conditions, suggesting the magnitude of the unfavorable task protocols that participants had to undergo. As a measure of fatigue magnitude, rates of strength decline have been reported in a number of studies. Light (5% MVE) continuous static exercise of the knee extensors resulted in a decrement of muscle strength of about 0.2%/min (Sjøgaard et al., 1986), while 15% MVE of static elbow flexions maintained to exhaustion were associated with strength decline of 4%/min (Krogh-Lund and Jørgensen, 1992). In a study involving a very exhausting intermittent-static protocol, a rate of decline of about 2%/min was reported (Corcos et al., 2002). For completely dynamic efforts, Nussbaum (2001) investigated muscle fatigue during a simulated overhead assembly task, and reported a decrease in muscle strength in the order of 0.03% – 0.13%/min. The work conditions tested here yielded fairly high rates of strength declines in the amount of 0.3%/min to more than 2%/min.

The fact that the work conditions examined were fatiguing was also supported by the data on perceptions of muscular discomfort. At the termination of an experimental session, it was not uncommon for an individual to report very high levels of discomfort (e.g., an RPD of 9), and this phenomenon was observed over the majority of conditions. The lower intensity work conditions (LLS and LLF) were associated with moderate levels of muscle discomfort (final RPD of about 5). However, the rate of RPD increase for these two conditions ranged from about 0.09 to 0.1/min, suggesting that such protocols could not be sustained for more than roughly 90 minutes before one will be forced to quit. This particular subjective measure of fatigue was also sensitive to changes in work conditions, and therefore, might also be used to distinguish one dynamic condition over another.

4.4.2 Myoelectrical Measures of Fatigue

In contrast to those examining static work, investigations on myoelectrical activities during dynamic efforts have faced a number of challenges, particularly due to the time-varying nature of the signals. Common processing techniques for EMG signals obtained from static contractions have been applied extensively, and more attention has been given to the application of the procedures during dynamic efforts. A number of investigators, however, have criticized the use of power spectral measures for muscle fatigue evaluation during more complex tasks, particularly due to potential confounding results. But others argued that the method may not represent any problem, particularly when used during cyclic and/or well-defined dynamic activities. Another challenge associated with dynamic EMG is the relatively large amount of data involved. CPDE , as proposed by Jonsson and Hagberg (1974) and Hagberg and Jonsson (1975), is attractive since it substantially reduces the amount of data, while at the same time allows for more meaningful interpretation of muscular load throughout the duration of a dynamic task. More detailed representation of EMG activities could also be demonstrated by the use of EVA. The present investigation attempted to elucidate the efficacy of the noted procedures when applied during cyclic dynamic efforts.

Dynamic EMG

The acceptability of common data processing technique applied to dynamic EMG has been a debatable issue. More advanced data processing techniques have been investigated that do not rely on data stationarity (e.g., Bonato et al., 2001), but proponents of the traditional techniques have presented considerable evidence for the use of dynamic EMG to assess muscle fatigue (e.g., Christensen et al., 1995). This latter approach, however, could be task specific, and is largely dependent on the types of muscles and muscle contractions involved. This study examined muscle fatigue from highly repetitive, cyclic efforts, and length of muscle fibers could be assumed to be constant. The dynamic nature of the tasks was, thus, merely due to the variability of muscle force generated.

Myeolectrical data apparently yielded low confidence for the use of amplitude to describe the muscle fatigue progressions. Except for HHS, more exhausting work conditions were actually characterized by a declining trend of EMG amplitude, a finding that is in contrast to typical changes found during a fatiguing static work. Disagreement was also found when comparing results of this study to those obtained from a vocational study (e.g., Hammarskjöld and Ringdahl-Harms, 1992). Fatigue characteristics during sustained static work should typically be observed during muscle contractions greater than 20% - 30% MVE (e.g., De Luca, 1997), yet they were not shown in some conditions with peak force of 30% MVE. Since dynamic EMGs were recorded during one-second of peak muscle tensions, it was also possible that higher amplitudes were not always consistently shown during these moments, but were indicated in overall EMG activities. Moreover, the middle deltoid muscle could respond differently under dynamic conditions, resulting in a different pattern of motor unit recruitments and firing rates. This could be explained by the fact that more varied recruitment patterns are associated with variation in velocity (Sjøgaard and Søgaard, 1998). Compared to static work, similar patterns of recruitments have been demonstrated for slow, low-intensity dynamic efforts (Christensen et al., 1995), but it is unclear if the finding applies to faster and/or higher intensity dynamic contractions, such as the one investigated in this study.

Results pertaining to patterns of spectral measure (MnPF and MdPF) changes demonstrated shifts toward the lower frequency. Depending on the conditions, these spectral measure declines varied from -0.001 to -0.900 Hz/min. Dynamic EMG obtained during vocational or simulated tasks have also demonstrated these downward shifts of the spectral measures (Kadefors et al., 1976; Christensen, 1986; Sundelin, 1993; Morlock et al., 1997; Potvin, 1997; Masuda et al., 2001; Nussbaum, 2001). Accumulations of metabolic byproducts leading to slower muscle fiber conduction velocities may be responsible for these spectral changes (Hagg et al., 2000; Luttmann et al., 2000), although a uniform relationship may not always be found (Masuda et al., 1999; Lowery et al., 2000).

It is interesting to note that relatively consistent results were found when only the $CPDF_{10}$ and $CPDF_{90}$ were taken into account, disregarding the effect of dynamometer attachment velocity. Observations on grouped data indicated that conditions that were more fatiguing, were associated with greater changes in spectral measures, and vice versa. Less consistency of spectral measure changes was probably due to the higher angular velocities (20^0 and 45^0/sec) adopted in this study. These velocities resulted in rapid changes in muscle force generation, which could possibly lead to variability of the spectral measures (Westgaard, 1988; Gerdle et al., 1990). Inconsistencies in patterns of spectral measures have also been reported in some studies investigating dynamic work (e.g., Petrofsky, 1979; Dieën et al., 1996). Nevertheless, the findings suggest the applicability of the use of dynamic EMG for the assessments of muscle fatigue.

CPDE

The present study utilized CPDE as a data reduction technique, and it was hypothesized that the distributions of EMG amplitude could be used to characterize dynamic activities. Results obtained indeed suggest the potential of using percentile values of CPDE to discriminate different work conditions. Based on initial distribution percentiles, the most strenuous conditions were characterized by higher percentile values, whereas lighter tasks resulted in substantially lower figures. This observation was generally found for all three percentile values selected. Initial CPDEs also presented an interesting finding, that CPDE values seemed to mimic the chosen CPDF settings. Differences between the two (force and EMG) distributions were present, but the magnitude was typically less than 5% MVE. This finding was, thus, in agreement with Hagberg's (1979) proposition that EMG distribution is representative of workloads of the tasks involved. Several models have been presented previously that could be used for the purpose of estimating muscular endurance or the magnitude of muscle fatigue (i.e. changes in MVE or RPD), given the CPDE of the job. The main benefit of using these models was that endurance or muscle fatigue could be predicted by obtaining myoelectrical data from a relatively small number of work cycles. In spite of this potential, however, the models were associated with low coefficient of determination values, which severely limited the applicability of the models.

Based on the activities of the middle deltoid muscle, the work conditions investigated in this study could be deemed strenuous, as reflected by relatively high $CPDE_{10}$ values, ranging from around 5% to 11% MVE. Higher figures were also shown for $CPDE_{50}$ and $CPDE_{90}$, which varied from 10% to 21% MVE and 21% to 40% MVE, respectively. Except for $CPDE_{90}$, these figures were considerably higher than guidelines proposed by Jonsson (1978), a finding that has also been reported during a drilling operation (Christensen, 1986). Much lower figures have been reported for the same technique used to evaluate muscular workload among industrial workers (Jensen et al., 1999), hospital and office employees (Hansson et al., 2000), computer operators (Hagberg and Sundelin, 1986), and during simulated manual tasks (Nakata et al., 1992). CPDE percentiles of the present work were probably comparable to more strenuous industrial jobs, such as those commonly observed in the steel industry (Winkel and Gard, 1988).

Though questionable (Christensen, 1986), an assessment of fatigue development could be performed by examining shifts in EMG amplitude distribution (Hagberg and Jonsson, 1975; Ericson and Hagberg, 1978; Hagberg, 1979). Assuming that prolonged dynamic tasks result in greater myoelectrical activities, progressions of fatigue during such efforts can be indicated by an increase in percentile values of the CPDEs. Such an approach (e.g., an increasing pattern of CPDE_{50}) was employed to indicate fatigue induced by manual tasks (Nakata et al., 1992). This same approach, however, did not seem to be applicable for the data obtained in the present investigation. In fact, examinations of individual data revealed conflicting results within a particular work condition, resulting in relatively minimal net right-shift of the EMG distributions. Even the hardest condition was only associated with a mean CPDE_{50} increase in the amount of 0.2% MVE/min, which translates to an amplitude increase of merely 2% MVE, assuming the task could be sustained for only 10 minutes. This finding might suggest that, in some individuals, fatigue apparently progressed without a concomitant increase in myoelectrical activities.

EVA

Several job design approaches are available for the purpose of minimizing musculoskeletal complaints and injuries in the workplace, which include reducing the workload associated with the job, or incorporating an appropriate work-rest regimen. Providing muscular workload variations, such as introducing light-intensity, complementary work tasks, throughout the duration of a job have also been viewed as a viable resort. Tasks with time-varying workload intensities, however, are more difficult to characterize, and EVA has been proposed as a method for quantifying this kind of exposure variation.

EVA data in this study suggest the applicability of this method in discriminating one work condition over another. At least two EVA measures were sensitive to differences in work conditions, and every measure was dependent upon at least one independent (task) variable. Hence, both levels of muscle activities and time durations associated with these activities seemed to be representative of the varying workload involved during the dynamic efforts. Research typically supports the application of this data reduction technique for field studies. In a vocational study, this procedure allowed investigators to discriminate muscle activities during industrial and more sedentary activities (Jensen et al., 1999). A similar approach was also used in a study investigating differences in biomechanical demands of the upper trapezius muscle among symptomatic vs. healthy workers (Hägg and Åström, 1997). Evaluations of EMG activities among different muscle groups could also be performed during surgery procedures (Hagg et al., 2000).

In the present work, several models were developed that allowed for estimating endurance time and muscle fatigue (as assessed by changes in strength and subjective rating), assuming the initial EVA measures were known. However, the associated (adjusted) R^2 values for these models were considerably low. For example, only roughly 50% of variability of SMVE data could be explained by the corresponding model. Nevertheless, this finding showed that muscular performance could be predicted by knowing the (EVA) characteristics of a dynamic task.

EVA has not been intended to be employed as an alternative approach for the evaluation of muscle fatigue (Mathiassen and Winkel, 1991; Hagg et al., 2000). In this study, however, it was of interest if such procedure could describe fatigue characteristics during prolonged efforts. There were three measures that were evidently sensitive to changes in work condition, but each measure was affected by only one of the three independent variables investigated. While two measures were sensitive to attachment velocity, EVA4 was dependent on workload intensity ($CPDF_{10}$). This latter measure reflected variations of brief duration (less than one second) of EMG activities greater than 10% MVE, but less than 30% MVE. Force intensity tested in this study ranged from 2.5% to 30% MVE, and it is probably not surprising that EVA4 was the best measure that captured variations in force exposures. Rates of EVA changes also demonstrated an interesting phenomenon in that, within one work condition, negative values were observed in some measures, while simultaneous increase was found in others. The overall (absolute) magnitude of these changes was closely associated with differences in work conditions, and hence, this measure (sum of EVA slopes) may serve as a better estimator of muscle fatigue. Mathiassen (2003) has proposed different methods to quantify workload variations, and suggested that the introduction of these variations into a repetitive work schedule could offer beneficial effects. Empirical studies are needed to validate this hypothesis, and a few sensitive EVA measures (as shown in this study) can be employed to serve for this purpose.

4.4.3 Evaluations of Work Conditions and Fatigue Measures

As noted above, the majority of the dynamic work conditions tested were judged to be fatiguing. Strong evidence of muscle fatigue was demonstrated by marked reductions in muscle strength, coupled by high levels of perceived discomfort toward the end of each session. Half of the conditions examined involved CPDF_{10} of 10% MVE, implying continuous contractions of the muscle throughout the experimental sessions. Complete muscular relaxations though fairly brief, were possible during two other conditions (LHS and LHF), but these conditions were also associated with high peak muscle tensions. The LLS and LLF were probably the only acceptable conditions, at least as indicated by longer ET and relatively low final RPD. Except during these two latter conditions, it was possible that blood flow in the other conditions was compromised, resulting in disturbance of the muscle metabolism processes. This condition, in turn, was manifested by higher perceptions of muscle discomfort or pain (Edwards, 1988; Mense, 1993), and resulted in impaired muscle force generating mechanisms (Vøllestad and Sejersted, 1988), which were likely to correlate with shorter endurance time.

A good measure should be sensitive to differences in work conditions, and thus has the potential to discriminate one condition over another. Both CPDE and EVA have been proposed as EMG data reduction techniques, suitable for evaluations of task workloads. Existing evidence has been reported in the literature, indicating the acceptability of such techniques. In this present work, CPDE_{50} has been shown to be sensitive to task intensities, a finding that corroborated the work of Hansson et al. (2000). For job design purposes, EVA could be more preferable (Jensen et al., 1999), though the number of parameters involved could present some inferences difficulties. Nonetheless, the present work demonstrated the effectiveness of both procedures in discriminating dynamic tasks.

For evaluations of muscular fatigue during dynamic efforts, however, both benefits and drawbacks were evident for any of the measures used. Endurance time and reductions in muscular performance seemed to truly distinguish the different work conditions, but endurance did not allow for observations of fatigue progressions. Perceived discomfort has been shown to be a good fatigue measure during more complex tasks (Grant et al., 1994), and could potentially outweigh this drawback, although the subjectivity of the measure might undermine its value. Despite their subjective nature, this study demonstrated that the three measures noted were sensitive to different conditions, and closely related to each other, suggesting their value for assessments of local fatigue.

This investigation also showed that fatigue inferences from dynamic EMG, though possible, should be done with caution. Hagg et al. (2000) and Luttmann et al. (2000) noted that simultaneous (typical) changes in myoelectrical amplitude and power spectra represented strong evidence of muscle fatigue. Findings from this work showed that fatigue development did not necessarily correlate with amplitude increase, which consequently makes the use of EMG amplitude of little value. However, downward shifts of the power spectra were found in all work conditions, and good associations with changes in muscle strength were found. In this regard, dynamic MnPF and MdPF could be considered as a good measure of muscle fatigue, although their sensitivity was limited to workload intensity factors (i.e., $CPDF_{10}$ and $CPDF_{90}$).

Higher data variability could be expected in this present research, particularly due to the dynamic nature of muscle contractions and the relatively higher dynamometer attachment velocities selected. Changes in muscular force have been often cited as one of the key reasons for the presence of signal artifacts (Bonato, 2001). Assumptions of signal stationarity may not hold for 1s recordings obtained during higher velocities, but a shorter (e.g., 0.5s) data epoch could result in lower frequency resolutions. Aside from the methodological issue, the shoulder girdle is obviously a complex system comprised by a number of different muscles. Any shoulder activity, such as arm abductions, to a certain degree could result in activations of the majority of shoulder muscles (Bente et al., 2002). Participants in this study were asked to do their best to maintain the task until exhaustion, and it was frequently observed that an RPD of 9 or 10 was given before they ceased the exercise. Though comparable muscle response has been reported between low dynamic and static work (MacIsaac et al., 2001), higher intensity dynamic efforts, coupled by strong individual’s motivation to complete the task, could potentially result in changes in muscle activation strategy, and dynamic activations of other (adjacent) muscles. Such interplay could ultimately produce higher signal variability.

The use of CPDE to assess muscle fatigue has been suggested in the literature, assuming an increase in EMG amplitude does occur. Results of this work, however, did not substantiate the application of the method. None of the measures was sensitive to work condition differences, and fairly low correlations with changes in muscle strength were found. This finding suggests that the use of CPDE measures may not be satisfactory for muscle fatigue evaluation during dynamic tasks. A rather promising finding was found with respect to implementing EVA for the assessments of fatigue that, at least, a couple of candidates could be used to describe muscle fatigue development. Not only were these two measures sensitive to work conditions, they were also highly related to reductions in muscular strength. In fact, the correlation coefficients were the highest among the remaining of EMG-based fatigue measures. Such a finding could be of importance, particularly assuming that variability of muscular load could provide critical physiological information that is valuable for understanding the development of musculoskeletal disorders (Mathiassen and Winkel, 1991).

Over all fatigue measures investigated, it is probably safe to assume that muscular strength and endurance can adequately describe muscle fatigue. In spite of its subjective nature, ratings of perceived muscle discomfort can be also considered as a reliable measure of local fatigue. Having well-motivated participants could considerably improve the consistency of these noted measures. A wide range of sensitivity of EMG-based measure was found, that their use for fatigue assessments should be very selective. MnPF and MdPF of the dynamic EMG could probably be satisfactory for restricted, repetitive dynamic tasks. EVA-based measure (especially the sum of absolute change) could be employed for fatigue evaluations, though further investigations should be carried out to validate its effectiveness.

4.4.4 Study Limitations

A few limitations of the present study should be noted. Exercise-induced muscle fatigue is obviously task-specific, and the protocols involved will determine the magnitude of changes. This study employed highly controlled dynamic conditions, where contraction intensities and velocities were the only variables of interest. The findings, therefore, may not be applicable to other dynamic conditions (e.g., non-isometric, non-isotonic). Different angular velocities coupled with maximal or near maximal dynamic exertions could also produce different results.

The middle deltoid muscle is not the only muscle group responsible for arm abductions, and to certain degree, other muscles of the shoulder complex may play a role in this activity. Differences in muscle response, both within and between individuals, could therefore be expected, which could possibly result in higher EMG data variability. In this regard, the number of participants involved in this study might not be sufficient. The complexity of the experimental protocol, however, did not allow for having larger number of participants.

Finally, a supine posture was adopted, together with limited arm movements. This condition may not resemble real dynamic situations, where manual tasks are typically performed while standing, and the postures assumed are not fixed. Discrepancies in the assumed posture could lead to marked deviations in muscular response. Thus, inferences from this study could be implemented in work characterized by similar conditions.

4.5 CONCLUSION

Vast evidence of muscle fatigue during continuous static work has been presented in the literature, and some attention has been given towards describing the phenomena during intermittent work. Recently, more work has been devoted toward understanding muscle fatigue associated with dynamic efforts, a need that has been pointed out by a number of investigators. The present work was an effort to describe muscle fatigue development during moderate levels of dynamic efforts. The majority of the work conditions examined were fatiguing, and regardless of the contraction velocity, light dynamic work characterized by low $CPDF_{10}$ (2.5% MVE) and $CPDF_{90}$ (20% MVE) could only be acceptable for one hour.

Several fatigue measures may indicate the presence of muscle fatigue during dynamic efforts. Reductions in muscle strength have been shown to be an acceptable measure of muscular performance. It has also been demonstrated that both muscle endurance and perceptions of muscle discomfort could be used as a satisfactory predictor of fatigue. EMG-based fatigue measures, while widely used, may not be adequately describe fatigue processes. Dynamic power spectral measures, to some extent, were representative of muscle fatigue progressions. Care should be exercised, though, for fatigue inferences based on these measures. CPDE measures were probably of little value in describing fatigue, but a few EVA-based measures may have potentials for this purpose.

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CHAPTER V

STUDY CONTRIBUTION, AND DIRECTIONS FOR FUTURE WORK

5.1 STUDY CONTRIBUTION

Three separate studies were conducted that addressed research issues pertinent to the development of localized muscle fatigue in more complex work situations. The first study was carried out to evaluate the repeatability and recovery of several commonly employed measures of muscle fatigue. Findings from this study showed relatively low repeatability for EMG-based fatigue measures. Good repeatability, on the other hand, was found for other measures including changes in muscle strength and perceptions of muscular discomfort. A good amount of evidence has been reported that addressed the repeatability of fatigue measures during sustained static contractions, but very few have examined the same research question during intermittent static efforts. Understanding the repeatability of these fatigue measures is essential, since it affects our decision when evaluating the presence and magnitude of muscle fatigue in a given situation. It is the intention of the present work to serve this purpose. Furthermore, muscle fatigue is a complex process that involves both the central nervous system and the peripheral mechanisms. Though the long lasting effects of local fatigue might be present, a number of investigations have often assumed that recovery is complete within a short period of time. This study indeed showed the inadequacy of one-day recovery, and thus strongly suggests that a minimum of two days of recovery be allotted for studies involving repeated exposures of fatiguing protocols.

The second study was motivated by the fact that very little information is available on the combined effects of task parameters on muscle fatigue during intermittent work. Low intensity and repetitive manual activities are commonly found in various industrial sectors, yet only a few design guidelines exist that pertain to these activities. Though the protocols in this study did not necessarily resemble activities performed in industry, the present work offered design guidelines that could be valuable in evaluating similar work conditions.

More complex and dynamic activities are also typical in many industrial settings, and it was the intention of the third study to characterize muscle fatigue during such activities. One of the major challenges is to determine the appropriate fatigue measures, particularly with regard to the use of EMG as an assessment method. Findings from this study suggest that traditional EMG-based measures could be used for the evaluation of cyclic dynamic work. A few additional measures based on continuous collection of EMG amplitude could also potentially be used.

5.2 DIRECTIONS FOR FUTURE WORK

The present work was a small step toward understanding localized muscle fatigue and the processes and mechanisms involved. Due to practical constraints, a number of other research issues were not addressed in this study, which could be part of future investigations. Musculoskeletal symptoms and complaints have been reported with regard to working with arms elevated. The shoulder girdle is a complex structure, and the middle deltoid is not the only muscle group responsible for arm/shoulder movements. Therefore, further studies are suggested that investigate different shoulder muscles simultaneously. Specific important information, such as recruitment patterns within or between muscle groups, could be derived from such studies. In addition, the development of muscle fatigue is presumably task dependent that various types of tasks involving arm/shoulder activities are worth investigating.

Another major research issue that deserves a greater attention is muscle fatigue during more complex and dynamic efforts. Compared to sustained static work, substantially different muscle activation patterns have been found, that muscle fatigue could also be manifested differently. Also important is the fact that no specific measures of muscle fatigue have been widely accepted for the evaluations of dynamic work. Specific to the use of EMG, further studies can be directed toward the development of data reduction techniques and establishing reliable measures. The present study has shown that a few EMG-based fatigue measures could potentially be used to evaluate muscular fatigue during dynamic activities, but more studies are certainly needed to gauge their effectiveness.

APPENDIX A

INFORMED CONSENT FOR PARTICIPANTS OF INVESTIGATIVE PROJECTS

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

DEPARTMENT OF INDUSTRIAL AND SYSTEMS ENGINEERING (ISE)

Informed Consent for Participants of Investigative Projects

Title of Project: "Characterizing Localized Muscle Fatigue During Intermittent Isometric Efforts"

Principal Investigators: Dr. M.A. Nussbaum, Assistant Professor, ISE
Hardianto Iridiastadi, Graduate Student, ISE

I. THE PURPOSE OF THIS RESEARCH

This study is aimed at examining muscle fatigue and endurance during prolonged elevations of the right arm. Knowledge gained from this study will allow for better understanding of the shoulder/arm physical capability, which can be helpful in designing occupational activities involving elevated arms. A total of approximately 66 subjects will be involved in this study.

II. PROCEDURES

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

1) You will be involved in a single or a series of five experimental sessions consisting of endurance exercise of the shoulder muscle. The exercise will consist of active exertions of the middle deltoid muscle, performed intermittently at a predetermined workload, cycle time, and duty cycle. You will be required to sustain the exercise until exhaustion, or up to a maximum of one hour.
2) The exercise will be performed in a supine posture (lying down on your back) with your body secured to the experimental apparatus, while your right (dominant) arm abducted at 90^0.
3) Strength tests of the middle deltoid and/or the trapezius muscle will be performed prior to, and every 10 minutes throughout an exercise.
4) The investigator will also ask you to rate the levels of muscle discomfort (e.g., fatigue or pain) throughout the exercise period.
5) For the purpose of collecting muscle electrical activities, two pairs of electrodes will be attached to the skin over the middle deltoid and the trapezius muscles. The electrodes are used to collect electrical activities of the muscles. To obtain good quality signals, a skin preparation has to be performed prior to the exercise, which involves abrading the skin lightly and rubbing the area with alcohol. Shaving the area might be necessary to improve signal quality. A non-washable marker will be

used to indicate electrodes location, and adhesive tapes will be used to keep the electrodes in place.

4) A practice session will be provided several days prior to the first experimental session to help you become familiar with the experimental procedures, during which physical and demographic data are also obtained. Sufficient time during this session will be given to ensure that you are completely comfortable with both the strength test and exercise procedures.

III. RISKS AND BENEFITS OF THIS RESEARCH

The experiment will involve prolonged muscle exertions, and there is a chance that the exercise will result in muscle fatigue and/or soreness. The discomforts, however, will not be substantially different from those you might experience after a light to moderate exercise, which will typically be gone in a few hours or within a day. Careful attention will also be given by the investigator to ensure that no increased risk of musculoskeletal injury is present during an experiment.

Knowledge gained from this study will be helpful in the design of safer occupational tasks, particularly those involving prolonged and repetitive shoulder/arm activities.

IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY

It is expected that results of this study will be published, but no names will be reported. Subjects will be identified by numbers throughout the data collection, analysis, and reporting processes.

V. COMPENSATION

You will be compensated $10 per hour for your time spent during the practice and the experimental sessions. The compensation will be paid at the end of each experimental session. Depending on the experimental conditions involved, each session may generally last up to 1 - 2 hours.

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 and Systems Engineering.

March 31, 2002	March 31, 2004
IRB Approval Date	Approval Expiration Date

VIII. SUBJECT'S RESPONSIBILITIES

I voluntarily agree to participate in this study and to follow the responsibilities listed below:

- To inform the investigator as early as possible about a desire to discontinue participation in the study.
- To inform the investigator of any medical conditions that might be adversely affected by the experiment, or those that might interfere with results of the experiment.

IX. SUBJECT’S PERMISSION

I have read and understand the Informed Consent and descriptions of the study. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this study.

I understand that if I participate, I may withdraw at any time without penalty.

Signature ______________________________

Printed Name ______________________________

Date ______________________________

Should I have any questions about this study or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

1. Hardianto Iridiastadi (Investigator)
   Graduate Student
   The Department of Industrial and Systems Engineering (0118)
   250 Durham Hall, Virginia Tech
   Blacksburg, VA 24061
   Phone: (540) 231-1720
   Email: dadi@vt.edu

2. Dr. Maury A. Nussbaum (Faculty Advisor)
   Assistant Professor
   The Department of Industrial and Systems Engineering (0118)
   250 Durham Hall, Virginia Tech
   Blacksburg, VA 24061
   Phone: (540) 231-6053
   Email: nussbaum@vt.edu

3. David M. Moore
   Chair, IRB
   Office of Research Compliance
   Research & Graduate Studies
   Phone: (540) 231-4991
   Email: moored@vt.edu

This Informed Consent is valid from 3/31/2002 to 3/31/2004.

APPENDIX B

INTERVIEW SCREENING FORM

Experiment #: ___ Participant # : ___

Part A

1. Name : ____________________ (Last) ___________________ (First)

2. Birth date (m/d/y) : __________

3. Gender : M – F (circle one) Height/Weight: _______/_______

4. Local Address : ____

5. Phone : __________ (Home) __________ (Work)

6. Email : ________________

7. Dominant hand : ☐ Right ☐ Left

8. Ethnic Category : ☐ Hispanic/Latino ☐ Not Hispanic/Latino

9. Racial Category : ☐ White ☐ Black / African-American

☐ Asian ☐ American Indian/Alaska Native

☐ Other ☐ Native Hawaiian/Pacific Islander

10. Currently held (or previous) job(s): ____

Please describe: ____

____

Part B

1. How often do you exercise?

___ times/month OR ___ times/week Types of exercise: _______________

2. Other than regular exercise, does your daily live involve moderate to heavy physical activities?

☐ No

☐ Yes (please describe) ____

____

Part C

1. Have you at any time during the last **12 months** had trouble (such as pain, ache, discomfort, or injury) in your:

☐ Neck ☐ Shoulders ☐ Elbows ☐ Wrist/hands

☐ Upper back ☐ Lower back

Please describe time, type, extent, duration, and limitations on activity on any of the problems.

____

____

____

____

2. Have you at any time during the last **6 months** had trouble (such as pain, ache, discomfort, or injury) in your (please refer to the picture shown on the next page):

☐ Neck ☐ Shoulders ☐ Elbows ☐ Wrist/hands

☐ Upper back ☐ Lower back

Please describe time, type, extent, duration, and limitations on activity on any of the problems.

____

____

____

____

APPENDIX C

Vita

Hardianto Iridiastadi
311 Owens St. #3 **(540) 552-8453**
Blacksburg, VA 24060 **dadi@vt.edu**

EDUCATION

Virginia Polytechnic Institute and State University, Blacksburg, VA

Ph.D., Industrial Engineering, 2003
Dissertation: *Localized Muscle Fatigue during Isotonic- and Nonisotonic-Isometric Efforts*
Advisor: Dr. Maury A. Nussbaum

Louisiana State University, Baton Rouge, LA

M.S., Industrial Engineering, 1997
Thesis: *Maximum Aerobic Capacity and Physiological Fatigue Limit of Combined Manual Materials Handling Tasks*
Advisor: Dr. Fereydoun Aghazadeh

Bandung Institute of Technology, Indonesia

B.S., Industrial Engineering, 1990
Senior Thesis: *The Design of Ergonomic Train Passenger's Seat*
Advisor: Dr. Jann Hidajat

RESEARCH INTEREST

Work physiology, industrial ergonomics, occupational safety and health, work design and measurements.

PROFESSIONAL EXPERIENCE

Virginia Polytechnic Institute and State University

Instructor
  Work Design and Measurement, 2000

Research Assistant
  Age Effects on Localized Muscle Fatigue, 2001 – 2003

Teaching Assistant
  Occupational Safety Engineering and Management, 1999
  Human Physical Capabilities, 2000

Louisiana State University

Teaching Assistant
  Introduction to C++, 1995
  Occupational Biomechanics (graduate course), 1996-1997

Bandung Institute of Technology

Instructor
  Methods Engineering and work measurement, 1991-1994
  Introduction to Ergonomics, 1991-1994

PROFESSIONAL ORGANIZATIONS

Institute of Industrial Engineers (IIE)
Alpha Pi Mu (APM)
Human Factors and Ergonomics Society (HFES)
American Society of Safety Engineers (ASSE)

AWARD

James Langston Parker Memorial Scholarship (Awarded to outstanding student in the fields of Safety and Human Factors, $3000, Fall 2000 – Spring 2001).

Scholarship in the amount of $4000, from the Indonesian Cultural Foundation, Inc., 2002.

Scholarship for attending the Professional Development Conference, American Society of Safety Engineers, September 2002.

SERVICE

Graduate Representative, IIE LSU Chapter, 1996-1997.
President, Indonesian Student Association at LSU, 1996-1997.
President, Indonesian Student Association at Virginia Tech, 1998-1999
Vice President, ASSE – Virginia Tech Student Section, 2001-2002.
Secretary, HFES – Virginia Tech Chapter, 2002.