# Quantifying Localized Muscle Fatigue of the Forearm during Simulations of High Pressure Cleaning Lance Tasks

By

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## ABSTRACT

Localized muscle fatigue (LMF) has been proposed as a surrogate measure to injury, since the onset of fatigue is rapid rather than months or years required to the onset of work related musculoskeletal disorders (WMSDs). The objectives of this study were to estimate LMF and quantify muscle activity of select forearm muscles during simulations of high pressure cleaning lance tasks common in the chemical production industry. Twenty participants, twelve males and eight females, with no musculoskeletal injuries and meeting criteria for upper extremity fitness, performed the simulated task. Independent variables studied include work height (shoulder, waist, and knuckle), lance orientation (parallel to the operator and parallel to the ground), and duty cycle (33, 50, and 67%) based on task analyses of actual work tasks. Dependent variables included mean RMS and rates of change in mean RMS, mean and median power frequency, MVE, and subjective ratings of fatigue. Repeated measures ANOVA was used to test the main effects of the independent variables and appropriate interactions. In general it was found that working at waist height, at higher duty cycles, and with the lance oriented parallel to the operator resulted in higher fatigue measures. Subjective ratings of fatigue were not well correlated with objective measures, similar to findings in previous studies. The simulated task was found to be extremely fatiguing and modifications to task design or job rotation schedules are required to reduce risk associated with injury development.

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# CHAPTER 1 INTRODUCTION

## 1.1 Background

Work related musculoskeletal disorders (WMSDs) refer to a large category of injuries and illness that affect the soft tissues of the body. WMSDs remain a major research interest due to the multi-factorial nature of the disorders and their prevalence in industry (Figure 1). Sixty-five percent of all non-fatal occupational illness cases reported in 2002 were associated with WMSDs in the manufacturing sector (BLS, 2004). Meatpacking (711 cases per 10,000 workers) and motor vehicles and car body industries (692 cases per 10,000 workers) had the highest rate of WMSDs in 2002 (BLS, 2004).

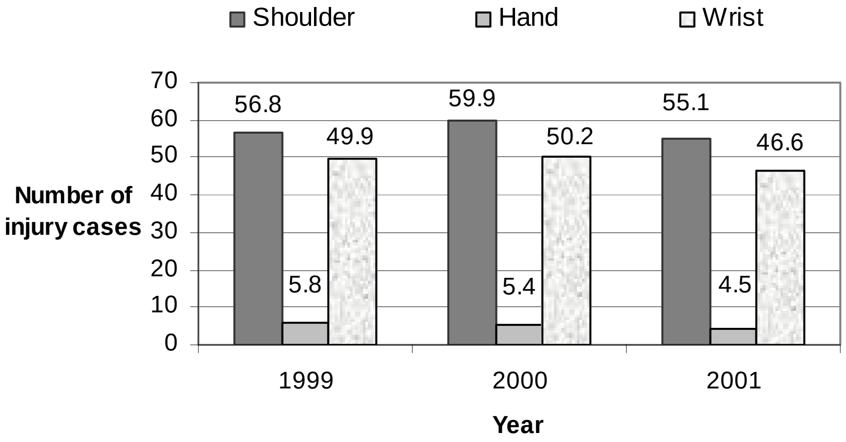


**Figure 1:** Number of shoulder, hand, and wrist injuries cases in (1,000s) involving time away from work (BLS, 2004).

Several risk factors have been hypothesized as contributing to upper extremity WMSDs (UEWMSDs), including repetitive hand/arm motions, deviated wrist postures, and high forces (e.g., Tichauer & Gage, 1977; Silverstein et al., 1987; Babski-Reeves & Crumpton-Young, 2002). Additionally, the use of hand held tools has been associated with increased odds ratios for incidence rates of UEWMSDs by introducing static loading on the musculature through repetitive gripping, supporting the weight of the tool, exposure to vibration, and deviated hand postures (e.g., Armstrong et al., 1982; Mital, 1991; Grant & Habes, 1993).

Due to a lack of research identifying dose-response relationships between risk factors and injury development and the difficulty in accounting for a lack of injury development for all persons performing a particular task, precursors to injury development are being explored. Localized muscle fatigue (LMF), defined as a loss in ability to generate a specific force by specific muscles (Chaffin, 1973), may be one such precursor. Research has identified specific shift changes in the electromyographic signal (EMG) associated with fatigue, primarily an increase in signal strength or amplitude and a shift to lower frequencies (Cobb & Forbes, 1923; Lindstrom et al., 1970; Viitasalo & Komi, 1977; Kadefors, 1978; Moritani et al., 1986; Christensen, 1986; Esposito et al., 1998). It is hypothesized that these shifts are the result of localized muscle fatigue and minimizing fatigue could reduce risk of injury during task performance.

Prolonged exposure to fatiguing conditions is hypothesized to lead to acute or micro-traumas that over time develop into WMSDs. Several indices of the EMG signal have been used to identify the most valid and reliable estimates of fatigue (Hager, 2003), including mean/median power frequency slopes, RMS slopes, time-to-fatigue (TTF), changes in maximum voluntary contractions/exertions, etc. Research findings have been consistent when considering static tasks, in that most of these indices are valid and reliable. However, for dynamic or intermittent tasks, the reliability of many of these indices is questionable, and other methods of quantifying fatigue using EMG may need to be explored (Hager, 2003).

## 1.2 Problem statement

High pressure cleaning lance tasks (HPCLs) in the chemical processing industry require operators to clean various work components using rigid lances which expel water at pressures of 5000-6000 psi and a rate of 30 $\text{gal}\cdot\text{min}^{-1}$. The lances range in length from 1 foot to 24 feet, and range in inner diameter from 1/8th to 1/4th inch. Due to safety hazards, operators are required to wear a wet suit, gloves, and depending on the orientation of the lance (parallel to the ground or parallel to the operator) metal feet and leg covers. Given the job task requirements, operators are at a high risk for UEWMSDs due to the forces required to hold and manipulate the lances, repetitive motions, and non-neutral upper extremity postures.

## 1.3 Objective

The objectives of this study were to: (1) quantify muscle activity requirements during task performance, and (2) estimate LMF associated with this job task. Based on task analyses the factors that were studied included work height (shoulder, waist, and knuckle), lance orientation (parallel to the operator and parallel to the ground), and duty cycle (33, 50, and 67%).

## 1.4 Research hypotheses

Specific research hypotheses investigated include:

1. Muscle activity will be affected by work height, duty cycle, and lance orientation; and
2. LMF will be affected by work height, duty cycle, and lance orientation.

## 1.5 Scope and limitations

For this study, not all possible combinations of work heights and duty cycles were studied. Those selected for evaluation were intended to represent a range of work heights and duty cycles common in the workplace. Additionally, other task factors, such as differing water pressure levels, nozzle or lance sizes, and lance lengths were not considered. The simulated water pressure level and lance length was chosen to represent the most common combination. Due to differences in nozzle design, thrust forces experienced by the operator are significantly different, and therefore, the worst-case scenario was selected for investigation. Other nozzle designs were excluded from evaluation.

Only select forearm muscles were evaluated in this study. While the task requires several muscles of the upper extremity (fingers, upper arm, shoulders, etc.) to be active, the forearm muscles were considered the "drivers" of the task due to required grip forces. Also, due to the characteristics of the actual task, all participants performed the task using a power grip.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Introduction

Work tasks requiring the use of hand held tools are commonplace in today's industrial sector. Previous research has identified several principal factors that affect grip forces required to use and manipulate hand tools during job task performance, such as age, gender, presence of gloves, handle size, wrist/arm posture, tool weight, and vibration, among others. Several measurement techniques have been employed to measure changes in grip force, with a common technique being surface electromyography (EMG). Both muscle activity and localized muscle fatigue (LMF) have been studied in both laboratory and field studies to understand the association between grip requirements and injury development. The following sections discuss these identified research topics further.

## 2.2 Grip force assessment and factors affecting grip force

Often occupational tasks require gripping during task performance. Several grip types have been identified (e.g., power, pulp, pinch, etc.). Power grip (the grip of interest for this research) is defined when the object is against the hand palm and surrounded by fingers (Cacha, 1999). Measurement of grip force is typically accomplished using hand dynamometers (Kirkpatrick, 1957; Casey et al., 2002). Tables have been developed that identify mean grip forces for both men and women of various age groups while the hand was in a power grip (Greenberg & Chaffin, 1977). Several factors both within the workplace and associated with individuals have been found to affect maximum grip forces, including age, gender, presence of gloves, handle size, wrist/arm posture, tool weight, and vibration.

### *2.2.1 Age*

A high correlation has been found between grip force and age, where peak grip force is reported for persons between the ages of 25 and 40 for both genders (Nemethi, 1952; Bechtol, 1954; Mathiowetz et al., 1985). Bemben et al. (1991) studied 153 male participants (aged 20 – 74 years) categorized into five age groups, and found significant decreases in grip force as participants' ages increased. Additionally, these differences were more prominent for the forearm extensor muscles than lower leg muscles. In general, average grip strength increases until 25-34 years for males and 35-44 years for females, and then decreases non-linearly until age 50–62 (Burke et al., 1953; Schmidt & Toews, 1970; Harkonen et al., 1993; Nevill & Holder, 2000).

The loss of muscular strength related to age is hypothesize to occur due to declines in motor unit discharge rates, muscle mass, and muscle cross-sectional area (Lexell et al., 1988, Kallman et al., 1990; Doherty et al., 1993; Cartee, 1994; Thompson, 1994; Grabner & Enoka, 1995; Kamen, 1995; Jubrias et al., 1997). At approximately age 30, muscle size decreases, and by age 50 the number of muscle fibers decreases by 10% (Lexell et al., 1988). However, Jubrias et al. (1997) demonstrated that after age 65 only about 50% of loss in force can be attributed to a diminished muscle cross-sectional area.

### *2.2.2 Gender*

Grip strength for males and females has been found to differ significantly, with the mean grip strength of the females approximately 53% to 70% that of males (Pheasant & Scriven, 1983; Miller & Freivalds, 1987; McMullin & Hallbeck, 1992; Ramakrishnan et al., 1994; Hansen & Hallbeck, 1996. Kellor et al. (1971) found that as females aged, they retained 75% of their peak grip strength, while males only retained 65.9% of their peak grip strength. No recent studies of this type could be found to determine if this relationship has remained constant or to support these findings.

### *2.2.3 Presence of gloves*

The use of gloves is a safety requirement for many work tasks that require forceful hand exertions, use of sharp tools, exposure to hazard chemicals or different thermal conditions, among others. There is some discrepancy whether the presence of gloves decreases or increases grip force. Batra et al. (1994), Cochran et al. (1986), and Sudhakar et al. (1988) showed in their respective studies that glove usage resulted in a 4-18%, 7-17%, and 10-20% decrement in grip force respectively. However, Riley et al. (1985) found an increase in grip force when participants performed forward handle pull, backward handle pull, maximum wrist flexion and extension torque exertions while wearing gloves, though actual increases were not specified. Glove traction, glove thickness, hand orientation, glove material, grip span, and glove size in relation to hand anthropometrics are several reasons for this discrepancy. Bishu et al. (1987) explained that grip force decrements during glove use occur because of a lack of tactile feedback when wearing gloves, improper fit, individual differences, and task differences.

### *2.2.4 Handle size*

According to Eastman Kodak (1983), the recommended diameter for power grip tools is 4 cm (1.5 in) with an acceptable range of 3 to 5 cm (1.25 to 2 in). This recommendation has been supported by other studies. Ayoub & Presti (1971) found that participants could perform more work cycles when using a cylindrical handle 3.81 cm (1.5 in) in diameter, than when the handle was either larger or smaller. Petrofsky et al. (1980), Harkonen et al. (1993), and Hansen & Hallbeck (1996) have shown that the highest grip force occurred during the use of a grip span ranging from 5 to 6 cm for both genders.

### *2.2.5 Arm and hand/wrist posture*

Arm and hand/wrist posture has been found to reduce grip force in several studies (e.g., Terrell & Purswell, 1976; Marley & Wehrman 1992; Hansen & Hallbeck 1996; Richards et al., 1996; De Smet, 1998; Mogk et al. 2003). Pronated forearm postures resulted in an 18% reduction of maximum grip force according to Mogk et al. (2003). Other researchers have found similar results that forearm pronation and wrist deviation reduce static grip force significantly for both men and women (Terrell & Purswell, 1976; Marley & Wehrman 1992; Hansen & Hallbeck 1996; Richards et al., 1996; De Smet, 1998). Terrell & Purswell (1976) found maximal isometric grip force (~ 95 lbs or 43 kg) at a neutral wrist position with the forearm supinated. A reduction in grip force was demonstrated as wrist deviations became more non-neutral for both genders: from neutral position to wrist flexion (30% reduction), hyperextension (22% reduction), radial flexion (18% reduction), and ulnar flexion (15% reduction) (Terrell & Purswell, 1976).

### *2.2.6 Tool weight*

Another important factor to consider is the weight of the tool. Johnson & Childress (1988) found a significant effect of tool weight on subjective assessments of fatigue when the tool was suspended using a tool balancer; however, EMG measurements were not significant or reliable. In general, grip force increases with handle weight or pull resistance, and employers should use light weight tools to reduce muscle exertion and fatigue (Grant & Habes, 1993). Eastman Kodak

(1983) suggested that if the tool weighs more than 2.3 kg (5 lb), operators are more likely to develop hand fatigue. Table 1 shows that commonly used industrial tools exceed this "ideal" weight.

**Table 1:** Some power tool weights (Eastman Kodak Company, 1983)

|  | **Weight** |  |
|---|---|---|
| **Tool Type** | **Kg** | **lb** |
| 1/4 in electric hand drill | 2.3 | 5 |
| 3/8 in electric hand drill | 4.3 | 9.5 |
| 1/2 in electric hand drill | 4.5 | 10 |
| 7 in Sander grinder | 7 | 16 |
| Air hammer | 7 | 16 |
| Chopper hammer | 8 | 17 |
| Air saw | 3 | 7 |
| Air angle drill | 3 | 7 |

### *2.2.7 Vibration*

Vibration has been shown to affect maximum grip force measurements. Vibration is the amount of periodic movement of a surface or body with respect to a reference point. Participants exposed to long-term vibration have reported hand muscle weakness, which it is evident due to the reduction of grip force (McGeoch & Gilmour, 2000; Necking et al., 2002). Necking et al. (2002) compared vibration-exposed workers to a control group of healthy policemen to determine if grip forces were different between the two groups. They found that mean grip force was significantly lower by 7% or ~ 8 to 11 lbs (3.6 to 5 kg) in the vibration-exposed workers than the control group. Bovenzi et al. (1991) showed that workers exposed to higher frequency vibration ($>7.5\ \mathrm{m{\cdot}s^{-1}}$) had less grip force than workers exposed to lower frequency vibration ($< 7.5\ \mathrm{m{\cdot}s^{-1}}$), 64.8- 60 lbs ( 29.4- 27.2 kg) and 59- 55 lbs ( 26.8- 24.9 kg) respectively, though this difference was not significant.

### *2.2.8 Relationship between height and weight on grip force*

Other factors that could affect grip strength are the height and weight of the workers. Schmidt & Toews (1970) found a direct increasing linear relationship between grip strength with participants' height, at least up to 75 inches (190.5 cm), and with participants weighing up to 215 pounds (97.5 kg) in males. In females, average grip strength was positive correlated ($r = 0.22$ and $r = 0.31$) with height and weight (Lunden et al., 1972; Schmidt & Toews, 1970).

## 2.3 Localized muscle fatigue (LMF)

There is no one single accepted definition of localized muscle fatigue (LMF). LMF can be explicitly defined as a loss in ability to generate a specific force by specific muscles (Chaffin, 1973). Surface electromyography (EMG) has been widely used to estimate firing rates of motor units contributing to a muscular contraction to quantify LMF (De Luca, 1997; Vollestad, 1997). LMF results in observable changes in EMG spectral patterns, primarily an increase in EMG amplitude, and a shift in the power frequency spectrum from the high to low band. Though these documented shifts in the EMG signal have been substantiated in several research studies (e.g., Cobb & Forbes, 1923; Lindstrom et al., 1970; Lloyd et al., 1970; Viitasalo & Komi, 1977; Kadefors, 1978; Petrofsky & Lind, 1980; Hagberg, 1981a; Hagberg, 1981b; Bigland-Ritchie et al., 1981; Mills, 1982; Naeije & Zorn, 1982; Stulen & De Luca, 1982; Arendt-Nielse et al., 1984; Arendt-Nielse & Mills, 1985; Moritani et al., 1986; Christensen, 1986; Zwarts et al., 1987; Jorgensen et al., 1988; Esposito et al., 1998; Johnston et al., 2001), these shifts do not necessarily hold true for all exertion levels (i.e., percent of maximum exertions). For example, Petrofsky (1980) demonstrated that at 10% MVC EMG amplitude remained constant, at 20% to 70% MVC amplitude increased, and after 70% MVC amplitude increased but at a slower pace.

### *2.3.1 Maximal voluntary exertion*

Maximum voluntary exertion (MVE) is a common technique used to quantify localized muscle fatigue. Vollestad (1997) defines MVE as the force generated when participants are encouraged to perform at their highest ability. Therefore, participants' motivation is a key factor in obtaining an accurate and reliable measurement.

When looking at reductions in MVE following exertions at specific percentages of MVE over time, Mundale (1970) found that following intermittent exertions (1 sec contraction followed by 1 sec rest, 2 sec contraction followed by 1 sec rest, and 3 sec contraction followed by 1 sec rest), recorded MVEs were significantly reduced over a 10 min period. Muscle exertions at 5% MVE have been shown to result in LMF (Mundale, 1970). It also of interest to note that female participants were able to exert their MVE longer than male participants, (approximately 3 min longer at 20% MVE, 2 min longer at 25% MVE, 30 sec longer at 40% MVE, 1 min longer at

55% MVE, and 25 sec longer at 70% MVE), though they had lower absolute MVEs (Mundale, 1970; Petrofsky, 1980).

Other research supports differences in fatigue rates for males and females. Nussbaum et al. (2001) studied overhead work focusing on shoulder fatigue during intermittent and dynamic conditions, finding that on average female participants could perform tasks longer than males. Lindstrom et al. (1997) assessed thigh muscle fatigue and found that endurance levels of elderly women (aged 69 to 77 years old) was significantly lower than elderly males (aged 71 to 75 years old) and young women (aged 21 to 35 years old). Elderly women also had lower subjective assessments of fatigue than elderly males, indicating that their tolerance level is higher (Lindstrom et al., 1997).

### *2.3.2 LMF during dynamic, intermittent, and static exertions*

There are few studies that have investigated LMF during intermittent and/or dynamic muscle exertions, and they have produced contradictory results. Milerad and Kilbom (1985) studied handgrip exercises during intermittent isometric conditions, and demonstrated that EMG frequency changes of five non-specified forearm muscles were more evident during the first 5-10 min of the tests, though total test duration was not specified. EMG frequency changes of the forearm extensor muscles were more significant than the flexor muscles during a 30 sec contraction, 10 sec rest cycle until exhaustion. In another study comparing the rate of amplitude changes between intermittent isometric, isometric and dynamic exercises, it was found that amplitudes increased at faster rates during isometric and dynamic exercises than during intermittent isometric exercises (Hagberg, 1981a). Masuda et al. (1999) reported that median power frequency decreased in both static and dynamic conditions with the roll-off starting at approximately 45 sec for static contractions and 90 sec for dynamic contractions. Amplitude in the dynamic condition was significantly greater than the static condition in their study.

A limitation of using EMG parameters to estimate LMF is that the parameters are unstable during intermittent and dynamic conditions. Therefore, subjective assessments of fatigue have been used to capture participant perceptions of fatigue during task performance. The most commonly used subjective assessment tool in the ergonomics field is the Borg CR-10 Perceived

Level of Exertion Scale (Pepermans and Corlett, 1983). The CR-10 scale is a category ratio scale that requires participants to rate their perceived level of exertion, or fatigue, on a scale ranging from 0 = none to 10 = maximal, with verbal anchors attached to specific values non-uniformly throughout the scale. There are several identified problems in using this, or any, subjective assessment technique. Problems such as ambiguity of scale anchor definitions, participant confusion in using the scale, and large variability in ratings due to inconsistency in use have been reported (Shen and Parsons, 1997; Bobjer et al., 1993). However, there has been at least one study that showed a positive correlation (ranging from 0.33 to 0.72) between subjective ratings using the Borg scale and EMG parameters (Grant et al., 1994), with grip force performed every 5 sec with 3 min rest periods between trials.

### *2.3.3 Physiological effects of LMF*

Muscle fatigue occurs due to the impossibility of maintaining the required energy supply (Edwards, 1981) and due to lactate accumulation during muscular contractions (Karlsson et al., 1975; Karlsson et al., 1981). The reduction of energy supplied results from a decrease in blood circulation that obstructs the elimination of lactic acid from the active muscle. Therefore, it is hypothesized that lactic acid accumulation produces changes in force development during physical exercise (Karlsson et al., 1981; Hermansen, 1981). Hagberg (1981b) suggested that during the rest period of intermittent isometric exercises, blood flow removes the accumulation of metabolites in the muscles, decreasing localized muscle fatigue. Other researchers have found that during rest periods of intermittent isometric handgrip exercises, blood flow was higher than during continuous contractions (Sjogaard et al., 1988; Bystrom & Kilbom, 1990; Bystrom et al., 1991). Bystrom & Kilbom (1990) and Bystrom et al (1991) did not find significant EMG spectral parameter changes during intermittent handgrip exercises, and that subjective ratings of perceived exertion (RPE) were lower for intermittent handgrip exercises than for continuous handgrip exercises.

## **2.4 Summary**

Several factors have been identified as having an effect on grip strength, some of which were discussed previously. However, grip force assessment during task performance is limited. Prolonged gripping, even at low intensities, has been shown to result in LMF. Documented

EMG changes during muscle fatigue include increased EMG amplitudes, and shifting in power from the high to low frequency band. However, the extent of these changes during intermittent, isometric, and dynamic conditions are insufficient, thus more research is needed to understand this complex concept and the implications of fatigue on job task design.

# CHAPTER 3 METHODOLOGY

## 3.1 Experimental design

A laboratory based, 4x3 within subjects design was used to study the effects of task condition (consisting of lance orientation and work height) and duty cycles (33, 50, and 67%) on EMG measures of localized muscle fatigue (LMF) and subjective assessments of fatigue. An incomplete randomized block design, with the subjects as blocks, was used to assign participants to treatment conditions. Balance of treatment conditions was achieved by having each treatment condition appear the same number of times across participants (Table 2 and 3).

**Table 2:** Experimental conditions

| | Task Condition | | | |
|---|---|---|---|---|
| Duty Cycle | Parallel to Operator | Parallel to Ground, Shoulder Height | Parallel to Ground, Waist Height | Parallel to Ground, Knuckle Height |
| 33% | O1 | GS1 | GW1 | GK1 |
| 50% | O2 | GS2 | GW2 | GK2 |
| 67% | O3 | GS3 | GW3 | GK3 |

**Table 3:** Exposure scheme using a balance incomplete block design

| | Participant | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 1 | GW1 | O1 | O3 | O2 | GS2 | GW2 | GS1 | GK1 | O2 | GS3 | GK2 | O2 | GW1 | GK2 | GK2 | GW3 | GK2 | O1 | GK2 | O3 |
| 2 | O3 | GS2 | GW2 | GW3 | O2 | GS1 | GS3 | GW1 | GW3 | O1 | O1 | GW1 | GW3 | O3 | GW2 | GS2 | GK1 | O3 | GS3 | O2 |
| 3 | GW2 | GK1 | GS1 | GK1 | GW1 | GS3 | O1 | GW3 | GS2 | O3 | GW2 | GW3 | GS2 | GS1 | GS3 | GK1 | GS1 | GS2 | GK1 | GW1 |
| 4 | O2 | GK2 | GK2 | GK3 | GK3 | GK2 | GK3 | GK3 | GK2 | GK2 | O3 | GK3 | GK3 | O1 | GS1 | GK3 | GW1 | GK3 | O1 | GK3 |
| 5 | GW3 | GS1 | GS3 | GW1 | GW3 | O1 | GS2 | O2 | GW1 | GW2 | GS2 | GS1 | GK1 | GW2 | O1 | O2 | GW3 | GW2 | GW2 | GW3 |
| 6 | GK3 | GS3 | O1 | GS2 | GK1 | O3 | O2 | GW2 | GK1 | GS1 | GS3 | GK1 | O2 | GS3 | O3 | GW1 | O3 | GS3 | GS1 | GS2 |

## 3.2 Independent variables

The independent variables were task condition (work height and lance orientation) and duty cycle. Three work heights, representative of actual task work heights were studied, shoulder, waist, and knuckle height. Work heights were determined based on participants' anthropometrics. Shoulder height was measured from the upper surface of the outermost part of the acromion to the floor, waist height was measured from the omphalion bone landmark to the floor, and knuckle height was measured from the metacarpophalangeal joint to the floor (Lohman et al., 1988). Lance orientation, parallel to the ground or to the operator, again was intended to represent the most common postures assumed during actual work tasks. The cycle time of the task, 3 minutes, was provided by a chemical producer for use in this research. Three duty cycles (33%, 50%, and 67%) were investigated. Therefore, performing the task at a 33% duty cycle involved 60 sec of working followed by 120 sec of rest, 50% duty cycle involved 90 sec of working followed by 90 sec of resting, and 67% duty cycle was 135 sec of working followed by 45 sec of resting.

## 3.3 Dependent variables

The dependent variables were muscle activity of selected forearm muscles measured through surface EMG, and subjective fatigue assessments associated with task performance. The objective measures included mean RMS (overall estimate muscle activity), and slopes for mean RMS, and median power frequency, and changes in MVE (estimates of LMF).

### *3.3.1 Surface EMG*

EMG signals were captured using pregelled Ag/AgCl electrodes adhered to the skin over four forearm muscles: the extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), flexor carpi radialis (FCR) and flexor carpi ulnaris (FCU). Skin preparation procedures included shaving of arm hair as necessary, slightly abrading the skin using a fine grain polishing stone to improve signal fidelity, and cleansing of the skin with alcohol. The electrodes were oriented perpendicular to the length of the muscle fiber and placed over the bulk of the muscle (Zipp, 1982; De Luca, 1997). Electrode placement was performed following clinical procedures. Electrodes for the ECR were located two finger breadths distal to the lateral epicondyle (Perrotto, 1994). Electrodes for the ECU were located in the middle of the forearm (Perrotto, 1994). Electrodes for the FCR were located four finger breadths distal to the midpoint of a line connecting the medial epicondyle and biceps tendon (Perrotto, 1994). Electrodes for the FCU were located one-fourth of the distance between to the medial epicondyle of the humerus to the ulna (Zipp, 1982). Interelectrode distance was set to 2.5 cm and a ground electrode was placed at the lateral epicondyle (Ludin, 1995). Only the non-dominant arm was assessed based on pilot study work by Babski-Reeves (2004) that showed that while muscles in both arms were active, the muscles in the non-dominant arm were significantly more active and therefore, will fatigue at a faster rate.

Signals were transmitted through short (less than 30 cm) leads to preamplifiers (100 gain). The leads were secured to the arm with tape to reduce noise and minimize displacement during task performance. EMG signals were hardware amplified, band-pass filtered (5-500 Hz), RMS converted (110 ms time constant), and AD converted. The gain was set such that the signal does not exceed 2-3 volts. Resistance within each electrode pair was within acceptable levels (0-10 k Ohms) following a 10-min stabilization period.

Resting and MVE assessments were collected following resistance measurements. For resting muscle activity assessments, participants sat with their arms resting on their lap with the hands fully relaxed for a 6-sec period. MVE assessments were collected using a hand dynamometer (Model MicroFET4, Hogan Health Industries, Draper, UT). A single task, power grip assessment, was used to elicit maximal activity of all the muscles. A single task was chosen over a task for each individual muscle, to more accurately simulate the maximum activity the selected muscles can produce during actual task performance. One hand posture was assumed to simulate the range of work postures assumed by workers employed in the high pressure cleaning task: functional neutral posture (arms resting at sides, elbows flexed at 90°, wrist straight in a handshake position). Participants performed three 6-sec exertions using a ramp-up, ramp-down procedure, with a 30-sec rest period between exertions. The largest measurement for each muscle was recorded as the participants MVE for that muscle and used for normalization purposes. In the event the third trial resulted in a maximum for any muscle, additional trials were performed until a decrement in MVE was identified.

Task EMG data was sampled at 1024 Hz using a National Instruments, AD bit card, and LabView software, which smoothed (10 Hz low pass filter) and stored data. Mean RMS and median and mean power frequency (MdPF and MnPF) data were extracted using programs developed in LabView. RMS, MdPF and MnPF data were extracted (averaged) for every second of data (excluding the first and last 10-sec of data of each cycle) and these values averaged to provide a mean for each cycle. Smoothed data was used to estimate normalized force levels for RMS data using:

$$\% \text{ Max Muscle Activity} = \frac{EMG_{RMS} - EMG_{rest}}{EMG_{Max} - EMG_{rest}}$$

Additionally, MVE assessments were taken every four cycles after the rest period using the same procedures described above. The final MVE assessment occurred at the end of the testing session.

### *3.3.2 Subjective assessment of fatigue*

In addition to EMG data, subjective assessments of fatigue were taken after every rest cycle using a modified Borg-CR10 scale (Table 4). Participants verbally indicated their level of fatigue following a verbal cue by an experimenter. All participants were given the same instruction on the use of the scale at the onset of each experimental condition (Appendix A).

**Table 4:** Borg CR-10 Scale (Borg, 1982)

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

## 3.4 Task description

The task was a laboratory simulation of HPCLs, which are intermittent in nature with a 3-min cycle time. The task consisted of compressing an air cylinder inserted into an actual HPCL lance positioned against a frame with small holes that were used to hold the lance in place (Figure 2). The lance was a 55 inch straight lance with an inner diameter of 0.25 inch and an outer diameter of 0.66 inches. Thrust forces, estimated to be 32 – 36 lbs, for the actual task were measured by a chemical producer. Details on their testing procedures were not available. The air cylinder was used to output equivalent forces. A small disc and spring was added to the end of the cylinder to identify the required compression region to mimic the force requirements (Figure 3). Participants performed the tasks for a 24-min period while wearing personal protective equipment supplied by the chemical producer (gloves). During the rest periods, participants continued holding the lance. Auditory cues were used to identify the start and end of work and rest cycles.

**Figure 2:** Participant performing condition in which the lance in parallel to the operator.

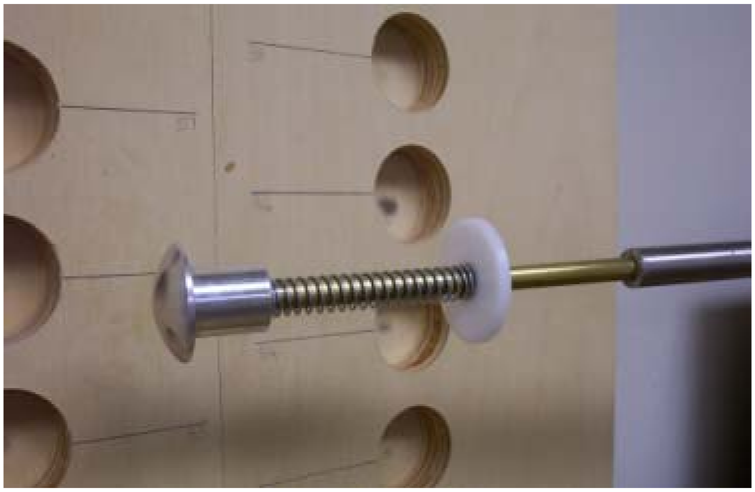


**Figure 3:** Small disc and spring to identify the required compression

### *3.4.1 Postures*

Participants stood with their feet aligned with their shoulders and legs straight when the lance was parallel to the operator. Participants were standing with one foot in front of another approximately shoulder width apart when the lance was parallel to the ground. For both lance orientations the dominant hand held the handle of the lance and the non-dominant hand was positioned on the length of the lance at a point that the participants determined was comfortable.

## 3.5 Participants

Twenty participants (12 male and 8 female) from the Virginia Polytechnic Institute and State University community were recruited for this research. Right hand dominance was self-reported by all except for one male. Ages ranged from 18 to 36 years of age (mean = 22.95 years; SD = 4.51 years), and all had normal body mass indexes (BMI) (18.5-24.9 $kg \cdot m^{-2}$) (Table 5).

**Table 5:** Participants demographics

| **Demographics** | **Males** (n=12) | **Females** (n=8) |
|---|---|---|
| **Age** (years) | 22.8 | 23.3 |
| **Stature** (cm) | 175.8 | 164.8 |
| **Weight** (Kg) | 74.3 | 64.1 |
| **BMI %** | 21.0 | 19.4 |
| **Activity level** (average days of weight training) | 3.75 | 3 |

Power was estimated using power tables in Cohen (1988). Using a t-test for means power table, at an alpha level of 0.05 and effect size of 0.80, twenty participants resulted in a power of 80. Participants were screened for current upper extremity injuries and illnesses using a modified Nordic Questionnaire (Kuorinka et al., 1987) (Appendix B). They had to be healthy and pain free without any history of neuromuscular, cardiovascular, or orthopedic conditions assessed using a health history questionnaire. Grip strength was collected using a hand dynamometer and participants were required to have a grip strength of ≥ 70 lbs (instituted at the request of the chemical producer). Demographic information such as age, height, weight, work experience, and fitness activity were collected using a custom questionnaire (Appendix C). To obtain a representative study population, participants were required to be currently employed in occupations that require significant upper extremity exertions or perform weight training exercises a minimum of three times a week.

### 3.6 Procedure

Participants first completed informed consent documents approved through the Institutional Review Board for Research involving human subjects (Appendix D). They performed an exercise to ensure understanding on how to use the Borg CR-10 scale. The exercise consisted of assuming a stand in squat position with the back against the wall and thighs parallel to the floor. Participants verbally walked through the scale until exhaustion. The squat position was chosen to minimize residual fatigue of the muscles under investigation. EMG electrodes were applied, resting activity, and MVEs were collected and a familiarization session commenced, during which participants were trained on lance usage. Participants were allowed to practice compressing the lance at each work height and orientation. No specific time limit was set for this familiarization session, and participants did not practice the task at a specify duty cycle or cycle time. The objective of the familiarization session was to introduce them to the task since the workload is higher than preconceived ideas (based on pilot study responses). Participants then completed an experimental session and scheduled subsequent test sessions. Participants completed a total of six 24 min with a minimum of 48 hours and no more than 78 hours between sessions.

### 3.7 Data analysis

Appropriate descriptive statistics were generated for each dependent variable (means, standard deviation, etc.). Hypotheses 1 and 2 (work height, duty cycle, and lance orientation will affect muscle activity and LMF measures) were tested using repeated measures ANOVA. Additionally, gender was included as a between subjects variable to determine if there are gender differences. As previously stated, task data was averaged every cycle and these values were plotted and a linear regression line was fit to the data to obtain slopes (or rates of changes in fatigue measures). Additionally, data were qualitatively and visually inspected to ensure intercept were appropriate to minimize carry over effect in the generated slopes. Generated slopes were extracted for each dependent measure and compared across the conditions. In order to identify the sources of differences, Tukey's HSD was used to compare any significant results. All results were considered significant at alpha $\leq 0.05$. Spearman's for non-normal data, correlation coefficients were calculated between participants subjective fatigue assessments (Borg Ratings) and objective fatigue measures (EMG parameters).

# CHAPTER 4 RESULTS

## 4.1 Descriptive statistics

Descriptive statistics are presented below (Table 6). These values were pooled across all participants. In general, EMG parameters had higher slopes when the lance was parallel to the operator than when it was parallel to the ground. RMS slopes were lower when working at shoulder height. Mn/MdPF slopes were higher when working at knuckle height and the 50% duty cycle had a lower RMS slope but higher Mn/MdPF slopes. In contrast to all other treatment conditions, working at waist height at a 67% duty cycle had a higher RMS slope, and the lowest RMS slope was observed when working at shoulder height with a 33% duty cycle. Working at knuckle height at a 67% duty cycle had higher Mn/MdPF slopes, but the lowest Mn/MdPF slopes were observed when working at waist height with a 33% duty cycle. A table showing each dependent variable at different significant levels is presented in Appendix E. In additional, intercept results for each dependent variable are given in Appendix F.

## 4.2 Surface EMG

### *4.2.1 Maximum voluntary exertions (MVEs)*

Participants performed maximal exertions at 12 min intervals for each treatment condition. Representative changes in peak forces are shown as a function of time for a particular participant and treatment condition (Figure 4).

**Table 6:** Descriptive statistics of the different parameters

| | | Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Condition** | | **RMS slope** | **RMS intercept** | **MnPF slope** | **MnPF intercept** | **MdPF slope** | **MdPF intercept** | **MVE slope** | **MVE intercept** | **Borg slope** |
| **Parallel to the operator** | mean | 0.0011 | 0.0683 | 0.3897 | 124.76 | 0.3635 | 104.38 | -0.2449 | 2.52 | 0.4698 |
| | SD | 0.0090 | 0.0430 | 1.8175 | 23.37 | 1.8921 | 21.78 | 0.1917 | 1.24 | 0.3667 |
| | max | 0.0605 | 0.1844 | 7.1613 | 200.58 | 8.3101 | 184.00 | 0.4346 | 6.50 | 1.3274 |
| | min | 0.7991 | -0.0321 | -5.6327 | 80.03 | -6.6759 | 60.25 | -1.2378 | 0.81 | 0.0000 |
| **Parallel to the ground** | mean | 0.0009 | 0.1173 | 0.1556 | 117.01 | 0.1283 | 97.89 | -0.2469 | 2.39 | 0.4304 |
| | SD | 0.0112 | 0.0866 | 1.7004 | 19.50 | 1.6324 | 17.40 | 0.2156 | 1.18 | 0.2845 |
| | max | 0.0706 | 0.7815 | 15.6180 | 180.20 | 14.5870 | 160.28 | 0.1654 | 7.15 | 0.0000 |
| | min | -0.0997 | -0.0406 | -4.0927 | 73.11 | -4.8007 | 60.57 | -1.8701 | 0.64 | 1.1607 |
| **Waist Height** | mean | 0.0025 | 0.1158 | 0.1343 | 116.31 | 0.1014 | 98.02 | -0.2512 | 2.42 | 0.4267 |
| | SD | 0.0080 | 0.0736 | 1.4186 | 18.57 | 1.4366 | 16.89 | 0.1990 | 1.18 | 0.2851 |
| | max | 0.0414 | 0.2871 | 4.2405 | 169.24 | 4.3463 | 150.28 | -0.0009 | 6.28 | 1.0952 |
| | min | -0.0236 | -0.0406 | -4.0336 | 74.48 | -4.6288 | 60.64 | -0.9839 | 0.64 | 0.0000 |

**Table 6:** Descriptive statistics of the different parameters (continued)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Knuckle Height** | mean | 0.0012 | 0.1398 | 0.2394 | 112.29 | 0.2663 | 93.78 | -0.2585 | 2.46 | 0.4443 |
| | SD | 0.0140 | 0.1041 | 1.3129 | 16.89 | 1.1349 | 14.89 | 0.2507 | 1.27 | 0.2973 |
| | max | 0.0706 | 0.7815 | 3.8151 | 153.50 | 3.6039 | 137.18 | 0.1954 | 7.15 | 1.0893 |
| | min | -0.0997 | -0.0223 | -4.9277 | 73.11 | -4.0903 | 60.57 | -1.8701 | 0.80 | 0.0417 |
| **Shoulder Height** | mean | 0.0011 | 0.0956 | 0.0930 | 122.42 | 0.0173 | 101.86 | -0.2310 | 2.31 | 0.4202 |
| | SD | 0.0107 | 0.0729 | 2.2304 | 21.55 | 2.1575 | 19.32 | 0.1934 | 1.09 | 0.2801 |
| | max | 0.0137 | 0.4769 | 15.6180 | 180.20 | 14.5870 | 160.28 | 0.0000 | 6.46 | 1.1607 |
| | min | -0.0894 | -0.0140 | -4.8712 | 82.03 | -4.8007 | 67.63 | -1.0010 | 0.75 | 0.0857 |
| **Duty Cycle 33%** | mean | 0.0018 | 0.0996 | 0.4506 | 117.70 | 0.4023 | 98.35 | -0.2293 | 2.43 | 0.2706 |
| | SD | 0.0089 | 0.0784 | 1.6492 | 19.94 | 1.6744 | 18.19 | 0.2307 | 1.24 | 0.1928 |
| | max | 0.0706 | 0.4431 | 7.1613 | 181.14 | 8.3101 | 168.51 | 0.0000 | 7.15 | 0.6607 |
| | min | -0.0311 | -0.0406 | -5.6327 | 73.11 | -6.6759 | 60.25 | -1.8701 | 0.75 | 0.0000 |
| **Duty Cycle 50%** | mean | 0.0004 | 0.1065 | 0.0446 | 120.21 | -0.0188 | 100.85 | -0.2672 | 2.49 | 0.5158 |
| | SD | 0.0066 | 0.0698 | 1.8711 | 22.37 | 1.8237 | 19.76 | 0.2147 | 1.23 | 0.3256 |
| | max | 0.031 | 0.3493 | 15.62 | 200.58 | 14.587 | 184.00 | 0.4346 | 6.84 | 1.3274 |
| | min | -0.0224 | -0.0047 | -4.8712 | 74.48 | -4.8007 | 60.64 | -1.1084 | 0.80 | 0.0714 |
| **Duty Cycle 67%** | mean | 0.0007 | 0.109 | 0.1471 | 118.94 | 0.1766 | 99.34 | -0.2427 | 2.35 | 0.5343 |
| | SD | 0.015 | 0.0929 | 1.6496 | 19.99 | 1.5816 | 18.37 | 0.1801 | 1.11 | 0.313 |
| | max | 0.0605 | 0.7815 | 5.1277 | 174.73 | 5.4885 | 160.28 | -0.001 | 6.28 | 1.1429 |
| | min | -0.0997 | -0.0321 | -4.9277 | 81.58 | -4.0903 | 67.90 | -1.2378 | 0.64 | 0.0714 |
| **Waist Height 33%** | mean | 0.0011 | 0.0675 | -1.0581 | 124.08 | -0.8449 | 102.96 | -0.3710 | 3.57 | 0.2525 |
| | SD | 0.0075 | 0.0612 | 0.9238 | 17.13 | 0.8751 | 15.01 | 0.2564 | 1.41 | 0.1895 |
| | max | 0.0103 | 0.1312 | 0.1312 | 148.41 | 0.3088 | 120.96 | -0.0119 | 6.51 | 0.5238 |
| | min | -0.0135 | -0.0135 | -3.0665 | 95.51 | -2.0959 | 76.32 | -0.8447 | 2.10 | 0.0000 |
| **Waist Height 50%** | mean | 0.0004 | 0.0583 | -0.3298 | 125.51 | -0.5540 | 108.30 | -0.3237 | 2.85 | 0.3477 |
| | SD | 0.0038 | 0.0642 | 1.2334 | 23.81 | 1.4372 | 21.72 | 0.2028 | 1.03 | 0.1697 |
| | max | 0.0070 | 0.1943 | 1.9644 | 158.13 | 1.8436 | 137.00 | -0.0928 | 4.41 | 0.6071 |
| | min | -0.0058 | -0.0091 | -2.1529 | 97.96 | -2.8022 | 81.25 | -0.7642 | 1.38 | 0.0714 |
| **Waist Height 67%** | mean | 0.00765 | 0.0898 | 1.0624 | 131.88 | 1.2421 | 112.28 | -0.3101 | 2.67 | 0.6800 |
| | SD | 0.0144 | 0.0737 | 1.2795 | 27.37 | 1.1809 | 22.75 | 0.2729 | 0.92 | 0.2922 |
| | max | 0.0376 | 0.2657 | 3.9373 | 161.37 | 3.5746 | 132.84 | -0.0928 | 4.13 | 1.0952 |
| | min | -0.0034 | 0.0244 | -0.8409 | 79.22 | -0.6860 | 68.11 | -0.8838 | 1.23 | 0.2143 |
| **Parallel to the operator 33%** | mean | 0.0010 | 0.0914 | -0.2618 | 121.50 | -0.3110 | 101.25 | -0.2978 | 3.42 | 0.2166 |
| | SD | 0.0052 | 0.0870 | 2.0708 | 18.02 | 1.3151 | 14.82 | 0.2317 | 1.52 | 0.2374 |
| | max | 0.0141 | 0.2253 | 4.2405 | 142.84 | 2.0931 | 117.25 | -0.0366 | 5.63 | 0.6071 |
| | min | -0.0051 | -0.0047 | -4.1259 | 85.78 | -3.0215 | 73.32 | -0.7739 | 0.96 | 0.0000 |
| **Parallel to the operator 50%** | mean | 0.0012 | 0.0667 | 1.0641 | 124.31 | 0.8008 | 103.28 | -0.1774 | 2.70 | 0.6491 |
| | SD | 0.0049 | 0.0655 | 2.4252 | 25.57 | 2..8612 | 24.34 | 0.1471 | 0.97 | 0.4048 |
| | max | 0.0078 | 0.1877 | 7.1613 | 171.42 | 8.3101 | 147.10 | -0.0010 | 3.90 | 1.3274 |
| | min | -0.0098 | -0.0030 | -1.7951 | 88.78 | -1.8193 | 60.25 | -0.4419 | 0.64 | 0.0798 |
| **Parallel to the operator 67%** | mean | -0.0014 | 0.0986 | -0.1355 | 131.24 | -0.2365 | 113.82 | -0.3284 | 3.31 | 0.5486 |
| | SD | 0.0050 | 0.0925 | 1.6278 | 31.96 | 1.7164 | 30.95 | 0.0904 | 1.46 | 0.3106 |
| | max | 0.0078 | 0.3093 | 2.5717 | 200.58 | 2.5181 | 184.00 | -0.1684 | 6.28 | 1.1429 |
| | min | -0.0106 | -0.0055 | -3.4929 | 97.07 | -4.1196 | 80.58 | -0.4419 | 1.33 | 0.0929 |
| **Knuckle Height 33%** | mean | 0.0028 | 0.0677 | 1.4472 | 125.79 | 1.5483 | 103.73 | -0.1619 | 3.15 | 0.3109 |
| | SD | 0.0086 | 0.0682 | 3.0054 | 23.42 | 2.6096 | 21.86 | 0.1222 | 1.39 | 0.1844 |
| | max | 0.0258 | 0.2330 | 9.4007 | 169.24 | 8.4588 | 150.28 | -0.0048 | 5.50 | 0.6607 |
| | min | -0.0052 | -0.0065 | -0.0052 | 81.58 | -1.0258 | 69.02 | -0.4126 | 0.96 | 0.0417 |

**Table 6:** Descriptive statistics of the different parameters (continued)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Knuckle Height 50%** | mean | -0.0002 | 0.0842 | 0.1177 | 128.15 | 0.0488 | 111.69 | -0.2996 | 3.05 | 0.5357 |
| | SD | 0.0039 | 0.0429 | 0.8565 | 12.20 | 0.8678 | 10.80 | 0.1887 | 1.36 | 0.2847 |
| | max | 0.0076 | 0.1595 | 1.9475 | 144.04 | 2.0283 | 128.22 | -0.0537 | 6.01 | 0.9643 |
| | min | -0.0048 | 0.0154 | -1.1254 | 106.80 | -0.9609 | 94.51 | -0.6738 | 1.06 | 0.0714 |
| **Knuckle Height 67%** | mean | 0.0014 | 0.0808 | 2.1392 | 127.34 | 2.2776 | 106.78 | -0.1936 | 2.66 | 0.4862 |
| | SD | 0.0038 | 0.0790 | 4.8872 | 18.16 | 4.8401 | 15.36 | 0.1368 | 1.30 | 0.3724 |
| | max | 0.0089 | 0.2863 | 15.6180 | 155.66 | 14.5870 | 129.16 | -0.0342 | 5.51 | 1.0893 |
| | min | -0.0042 | 0.0165 | -1.7210 | 95.89 | -1.8205 | 86.17 | -0.4810 | 0.82 | 0.0714 |
| **Shoulder Height 33%** | mean | -0.0039 | 0.0886 | -0.3132 | 119.15 | -0.5939 | 105.14 | -0.3142 | 3.72 | 0.3072 |
| | SD | 0.0064 | 0.0812 | 0.4504 | 16.06 | 0.7154 | 17.06 | 0.1605 | 0.92 | 0.1652 |
| | max | 0.0047 | 0.2861 | 0.1061 | 142.96 | 0.3113 | 130.50 | -0.0268 | 5.63 | 0.5714 |
| | min | -0.0171 | -0.0047 | -1.1531 | 91.98 | -2.0026 | 77.06 | -0.5523 | 2.87 | 0.0857 |
| **Shoulder Height 50%** | mean | 0.0013 | 0.1192 | -0.2460 | 124.64 | -0.3601 | 105.56 | -0.2116 | 2.80 | 0.5307 |
| | SD | 0.0060 | 0.1007 | 2.5321 | 17.89 | 2.7786 | 14.57 | 0.1384 | 0.90 | 0.3661 |
| | max | 0.0107 | 0.2869 | 3.9831 | 155.81 | 4.3463 | 133.07 | -0.0317 | 4.78 | 1.1607 |
| | min | -0.0086 | 0.0274 | -5.6327 | 100.79 | -6.6759 | 88.63 | -0.4516 | 1.62 | 0.1310 |
| **Shoulder Height 67%** | mean | 0.0026 | 0.1318 | 0.3269 | 117.96 | 0.4019 | 102.02 | -0.4187 | 3.25 | 0.4225 |
| | SD | 0.0043 | 0.0902 | 1.0114 | 17.08 | 0.9447 | 13.08 | 0.3544 | 1.19 | 0.2526 |
| | max | 0.0078 | 0.2464 | 2.4647 | 140.80 | 2.4776 | 118.50 | -0.1001 | 5.58 | 0.8869 |
| | min | -0.0053 | 0.0123 | -1.3748 | 90.11 | -0.9427 | 78.90 | -1.1084 | 1.87 | 0.1310 |

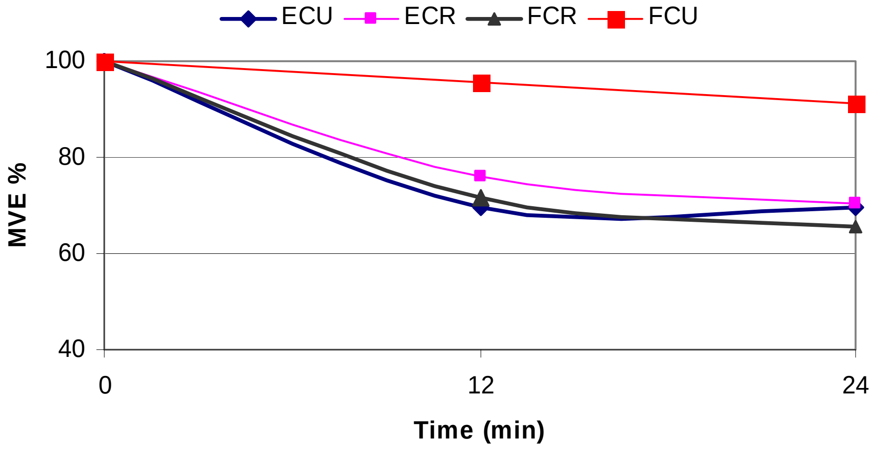


**Figure 4:** Evidence of gradual decrease of force capability

Only gender was found to significantly affect MVE slopes (p=0.0141), where females participants had a lower slope (-0.1898) than males (-0.2835).

### *4.2.2 Muscle activity*

Statistically significant differences were found in ECU muscle activity across treatment conditions (p=0.0020) and genders (p=0.0209). Post hoc analysis indicated that ECU had significantly higher muscle activity when participants worked at knuckle height (Table 7). Female participants had significantly higher muscles activity than males; the least square mean for females was 0.0968 and for males was 0.0644.

**Table 7:** Tukey's pairwise comparisons for ECU

| Condition | Mean | Grouping | |
|---|---|---|---|
| Parallel to the operator | 0.0620 | A | |
| Shoulder height | 0.0719 | A | |
| Waist height | 0.0833 | A | |
| Knuckle height | 0.1051 | | B |

Significant differences were found in ECR muscle activity across treatment conditions (p=0.0124) and genders (p=0.0011). Working at shoulder height resulted in significantly higher muscle activity levels than the other treatment conditions (Table 8). Female participants had significantly higher muscles activity than males; the least square mean for females was 0.1218 and for males was 0.0731.

**Table 8:** Tukey's pairwise comparisons for ECR

| Condition | Mean | Grouping | |
|---|---|---|---|
| Parallel to the operator | 0.0726 | A | |
| Waist height | 0.0966 | A | |
| Knuckle height | 0.0973 | A | |
| Shoulder height | 0.1234 | | B |

Only treatment condition was found to affect muscle activity of the FCR and FCU (Table 9). The FCR and FCU were significantly more active when participants worked at knuckle and waist heights. An average of muscle activity per each treatment condition is presented in Figure 5.

**Table 9:** Tukey's pairwise comparisons for FCR and FCU

| Condition | Mean (FCR) | Grouping | |
|---|---|---|---|
| Parallel to the operator | 0.0631 | A | |
| Shoulder height | 0.0677 | A | |
| Waist height | 0.1436 | | B |
| Knuckle height | 0.1517 | | B |
| **Condition** | **Mean (FCU)** | **Grouping** | |
| Parallel to the operator | 0.0930 | A | |
| Shoulder height | 0.1136 | A | |
| Waist height | 0.1841 | | B |
| Knuckle height | 0.2126 | | B |

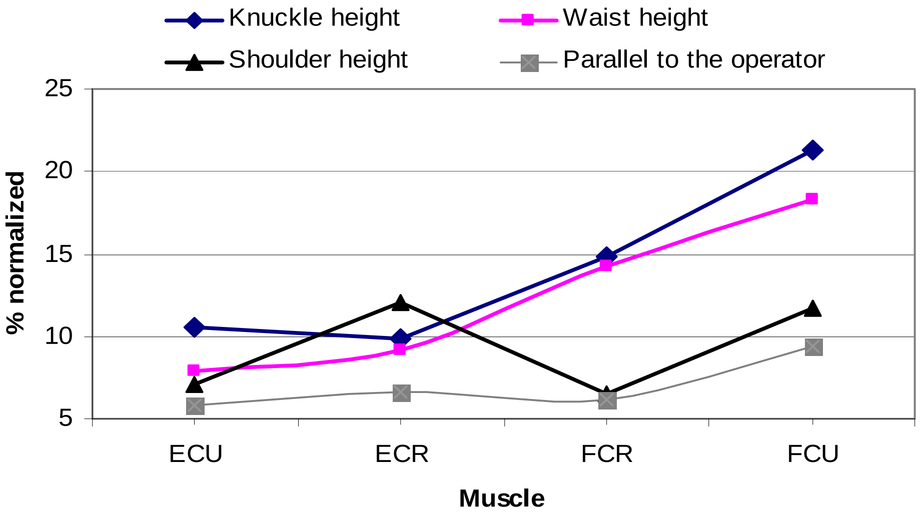


**Figure 5:** Average of muscle activity per each treatment condition

*4.2.3 Root means square (RMS)*

Significant differences were found in the RMS slope for treatment condition (p=0.0347), the gender-treatment condition interaction (p=0.0021) and the duty cycle-gender interaction (p=0.0160). Post hoc comparisons showed that working at waist height caused significantly higher rates of fatigue than working at shoulder height, although no other differences were found (Table 10). Females working at waist height had higher fatigue levels than males for each treatment condition (Table 11 and Figure 6). No other pair-wise comparisons were significant.

**Table 10:** Tukey's pairwise comparisons for RMS slope

| Condition | Mean | Grouping |
|---|---|---|
| Shoulder height | -0.0010 | A |
| Knuckle height | 0.0009 | A B |
| Parallel to the operator | 0.0010 | A B |
| Waist height | 0.0031 | B |

**Table 11:** Tukey's pairwise comparisons for gender-treatment condition interaction for RMS slope

| Condition | Gender | Mean | Grouping |
|---|---|---|---|
| Waist height | Males | -0.0001 | A B |
| Shoulder height | | -0.0016 | A B |
| Knuckle height | | 0.0023 | A |
| Parallel to the operator | | 0.0024 | A |
| Knuckle height | Females | -0.0004 | A |
| Shoulder height | | -0.0004 | A |
| Parallel to the operator | | -0.0004 | A |
| Waist height | | 0.0064 | C |

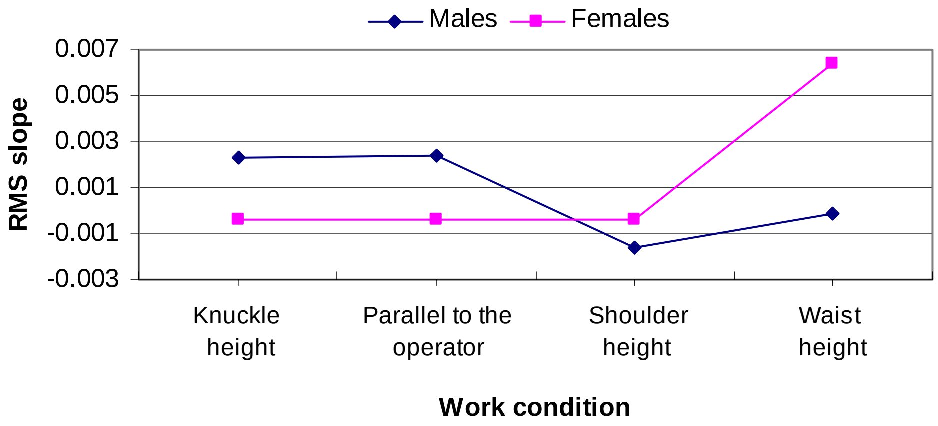


**Figure 6**: Gender-treatment condition interaction for RMS slope

*4.2.4 Mean/median power frequency (Mn/MdPF)*

Statistically significant differences were found in MnPF slopes for duty cycle (p=0.0303), muscle (p= 0.0197), the duty cycle-gender interaction (p=0.0060), and the gender-treatment condition interaction (p=0.0037). Participants fatigued at faster rates for the 50% duty cycle than for the 33% and 67% duty cycles (Table 12). The ECU fatigued at a significantly slower rate than the other muscles investigated. For the duty cycle-gender interaction, the 50% duty cycle was found to be significantly more fatiguing than the 33% and 67% duty cycles for female participants (Table 13 and Figure 7).

**Table 12**: Tukey's pairwise comparisons for MnPF slope

| Duty Cycle | Mean | Grouping |
|---|---|---|
| 50% | -0.0171 | A |
| 67% | 0.1541 | B |
| 33% | 0.4781 | B |
| **Muscle** | **Mean** | **Grouping** |
| ECR | 0.0469 | A |
| FCR | 0.0638 | A |
| FCU | 0.0883 | A |
| ECU | 0.6213 | B |

**Table 13:** Tukey's pairwise comparisons for duty cycle-gender interaction for MnPF slope

| Duty cycle | Gender | Mean | Grouping |
|---|---|---|---|
| 67% | Males | -0.0383 | A |
| 33% | | 0.3201 | A |
| 50% | | 0.3334 | A |
| 50% | Females | -0.3676 | B |
| 67% | | 0.3466 | A |
| 33% | | 0.6362 | A |

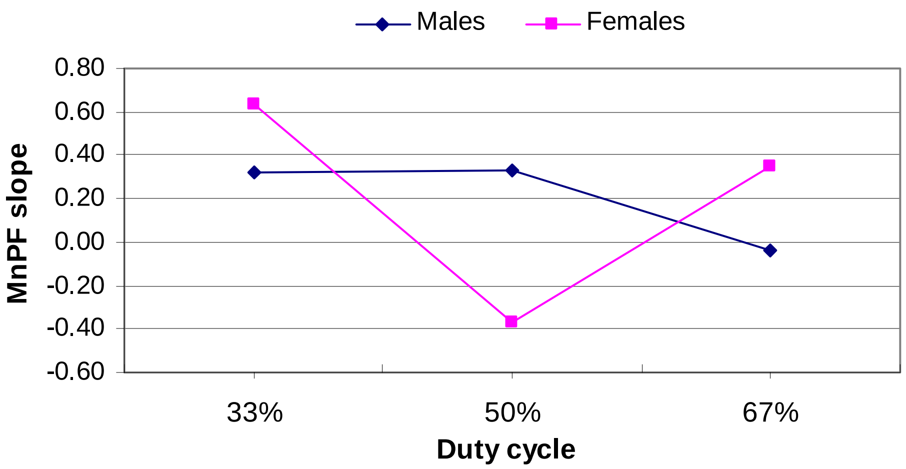


**Figure 7**: Gender-duty cycle interaction for MnPF slope

MdPF slopes were significantly different for duty cycle (p=0.0367) and muscle (p= 0.0175) (Table 14). Post hoc analysis indicated that the 50% duty cycle had significantly higher fatigue rates than 33% and 67% duty cycle. The ECR had significantly slower fatigue rates than the other muscles investigated.

**Table 14:** Tukey's pairwise comparisons for MdPF slope

| Duty Cycle | Mean | Grouping | |
|---|---|---|---|
| 50% | -0.0730 | A | |
| 67% | 0.1938 | | B |
| 33% | 0.4183 | | B |
| **Muscle** | **Mean** | **Grouping** | |
| FCU | 0.0107 | A | |
| FCR | 0.0428 | A | |
| ECU | 0.0608 | A | |
| ECR | 0.6044 | | B |

### 4.3 Subjective Assessment of Fatigue

Ratings of perceived fatigue (RPF) slopes were found to be significantly different between duty cycles ($p<0.0001$), the treatment condition-duty cycle interaction ($p=0.0138$) and the gender-treatment condition interaction ($p=0.0017$). Participants reported significantly lower fatigue rates for the 33% duty cycle (0.2701), though the 50% and 67% duty cycles did not differ (0.4929 and 0.5143 respectively). Participants reported significantly higher fatigue rates when working at waist and knuckle heights for the 67% duty cycle and at shoulder height and parallel to the operator condition for 50% and 67% duty cycles (Table 15). Lower fatigue rates were found for the 33% duty cycle for each treatment condition except when working at shoulder height (Figure 8). Male participants had higher fatigue rates than female participants for each treatment condition (Table 16); though significant differences were only found for the parallel to operator condition (Figure 9).

**Table 15:** Borg Slope Tukey's comparisons for treatment condition-duty cycle interaction

| Condition | Duty cycle | Mean | Grouping | | |
|---|---|---|---|---|---|
| Waist height | 33% | 0.1589 | A | | |
| | 50% | 0.3783 | | B | |
| | 67% | 0.5799 | | | C |
| Parallel to the operator | 33% | 0.2586 | A | | |
| | 50% | 0.5360 | | | C |
| | 67% | 0.5527 | | | C |
| Knuckle height | 33% | 0.2632 | A | | |
| | 67% | 0.4306 | | B | |
| | 50% | 0.5741 | | | C |
| Shoulder height | 33% | 0.4000 | | B | |
| | 50% | 0.4831 | | B | C |
| | 67% | 0.4942 | | B | C |

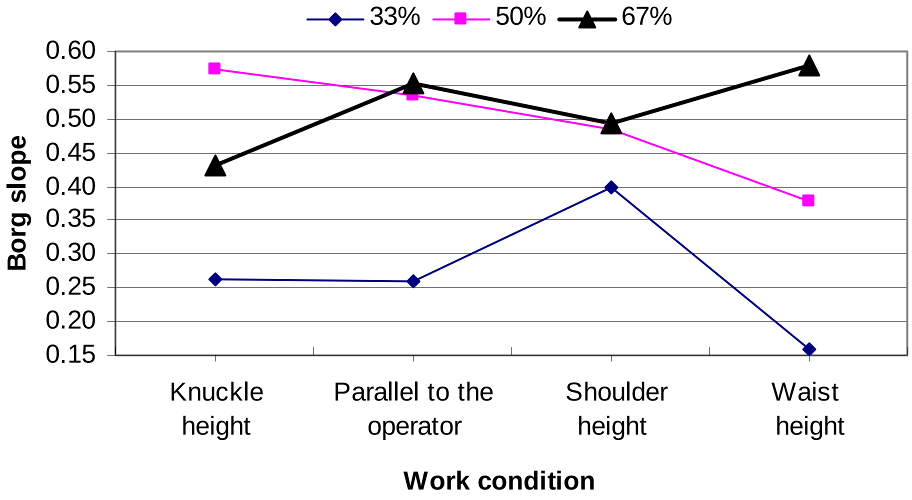


**Figure 8**: Treatment condition-duty cycle interaction for Borg slope

**Table 16:** Tukey's pairwise comparisons for gender-treatment condition interaction for Borg slope

| Condition | Gender | Mean | Grouping | | |
|---|---|---|---|---|---|
| Waist height | Males | 0.4154 | A | | |
| Knuckle height | | 0.4657 | A | | |
| Shoulder height | | 0.4933 | A | | |
| Parallel to the operator | | 0.6393 | | B | |
| Parallel to the operator | Females | 0.2589 | | | C |
| Waist height | | 0.3293 | A | | |
| Knuckle height | | 0.3796 | A | | |
| Shoulder height | | 0.4248 | A | | |

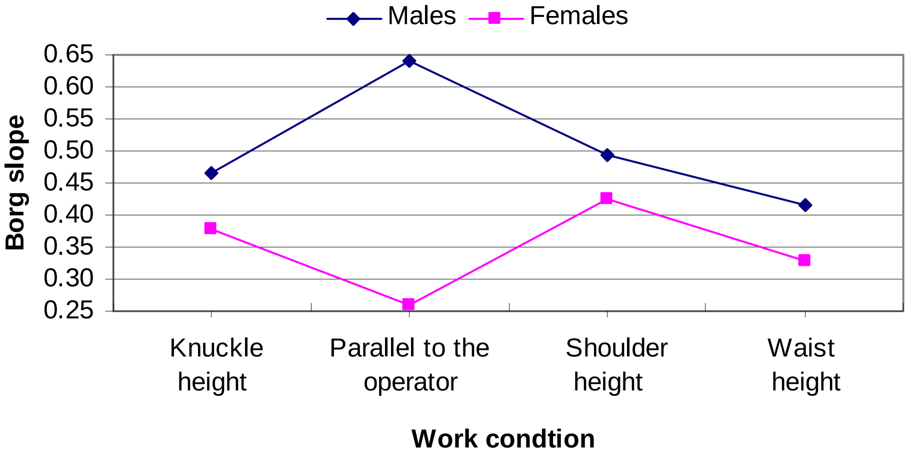
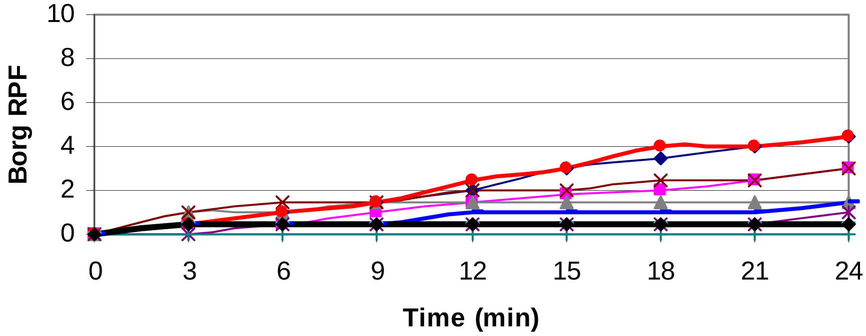
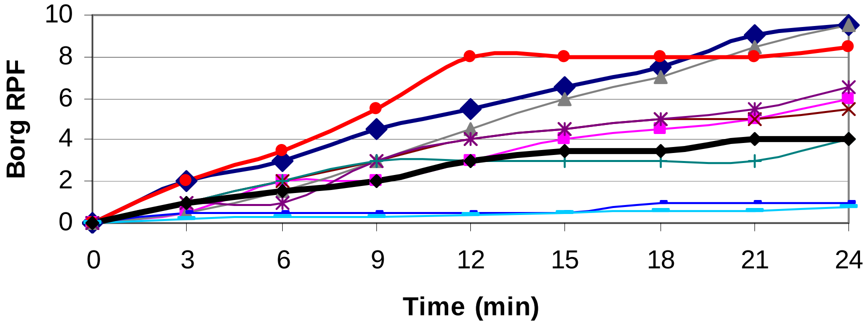


**Figure 9**: Gender-treatment condition interaction for Borg slope

Figures 10 through 13 present participant RPFs across treatment conditions. RPF increased linearly over time from a reported a RPF of 0 before starting the task.  Lower RPEs were reported for the 33% duty cycle, with the lance parallel to the operator, and when working at waist height.


Parallel to the operator 33%


Parallel to the operator 50%

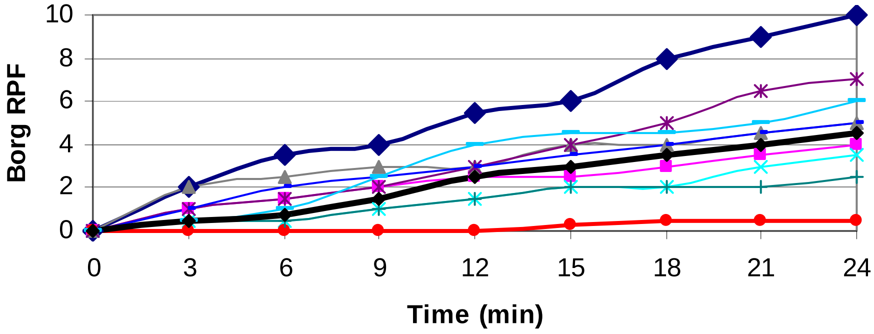

Parallel to the operator 67%

**Figure 10:** RPF as a function of time for condition parallel to the operator at each duty cycle

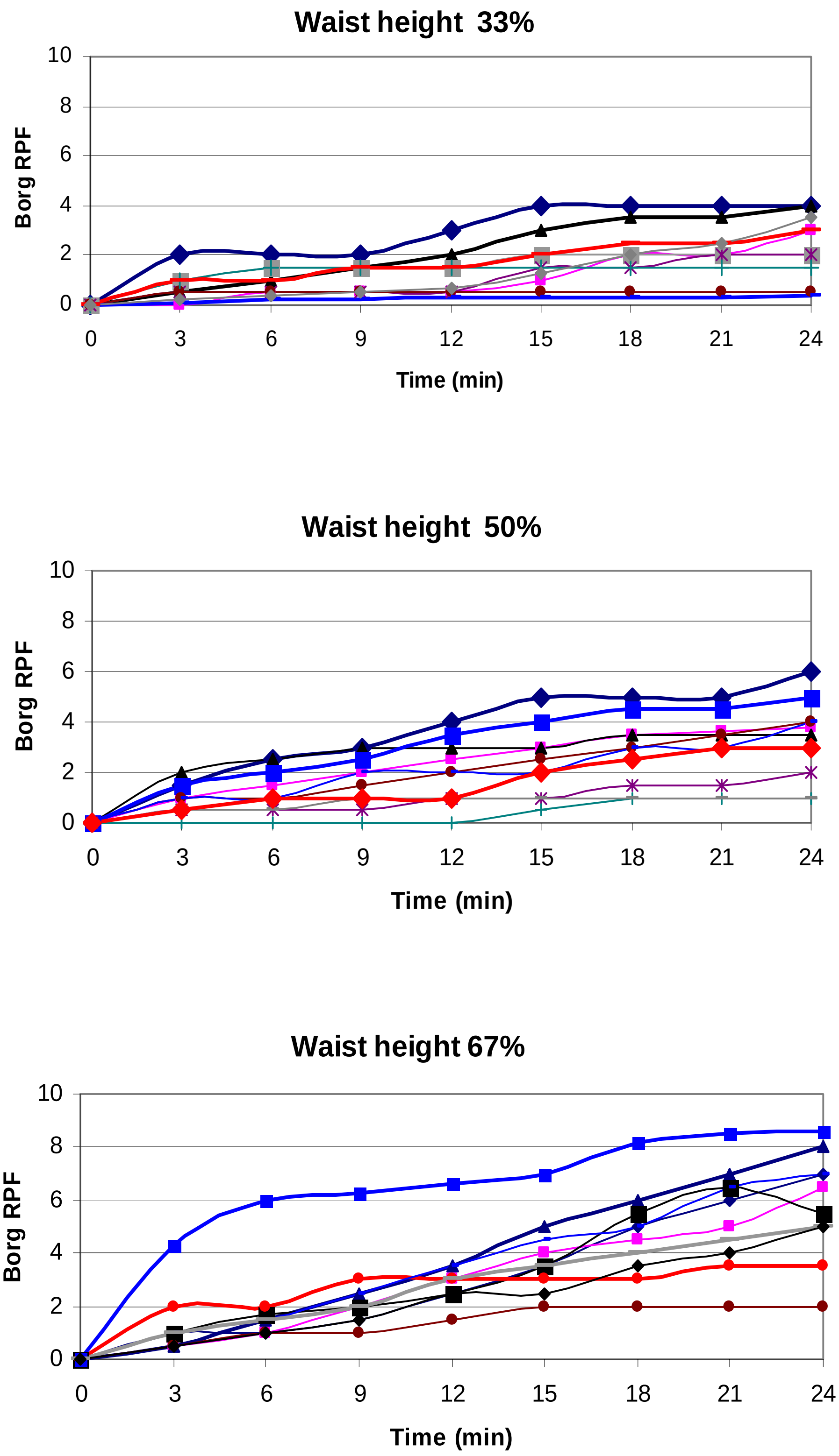


**Figure 11:** RPF as a function of time for waist height at each duty cycle

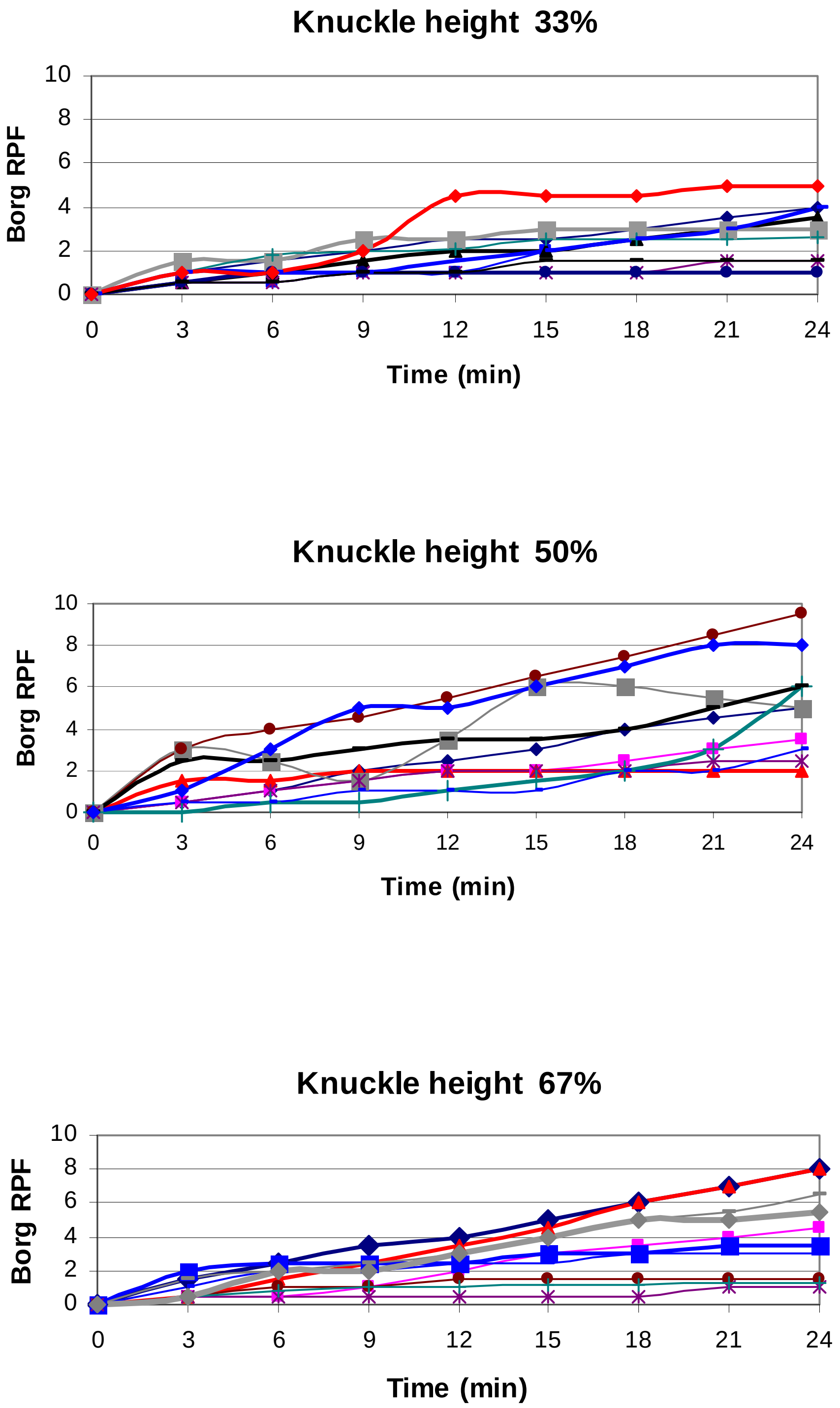
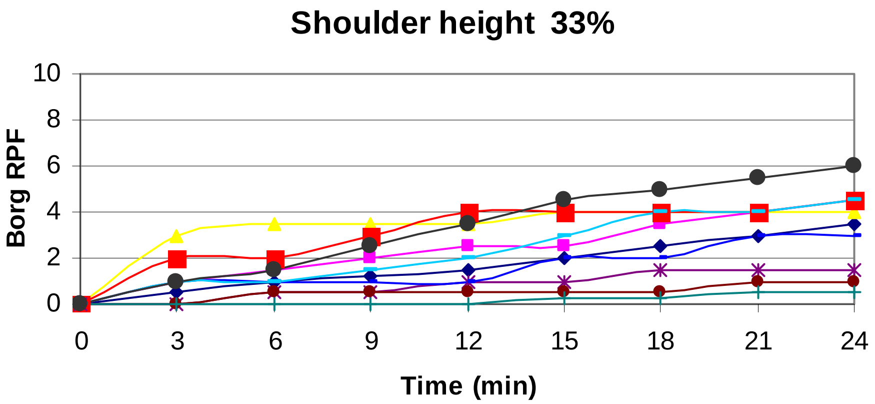
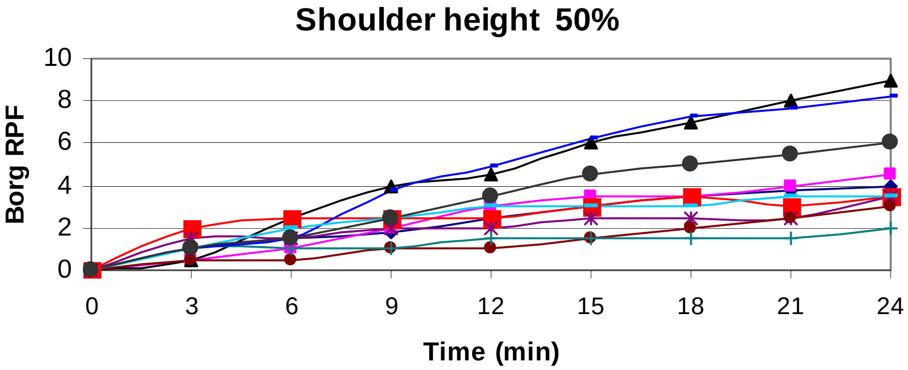


**Figure 12:** RPF as a function of time for knuckle height at each duty cycle





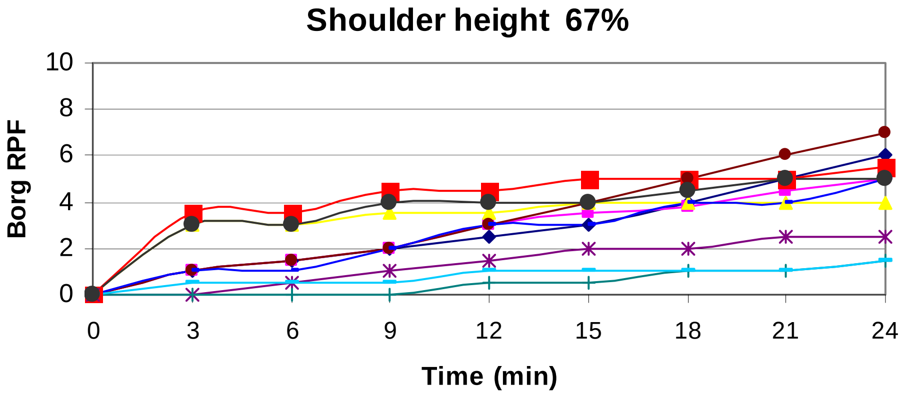


**Figure 13:** RPF as a function of time for shoulder height at each duty cycle

### 4.4 EMG and RPF correlation

Due to non-normal distribution of the EMG slopes, Spearman correlation coefficients were calculated between objective and subjective dependent variables (Table 17). Two correlation coefficients were significant: ECR MVE slope and Borg slope and FCR MVE slope and Borg slope. No other significant correlations were found.

**Table 17:** Spearman correlation coefficients between EMG measures and RPF

| EMG | Muscle | Correlation | p=value |
|---|---|---|---|
| **RMS slope** | ECU | 0.0264 | 0.7753 |
| | ECR | 0.1582 | 0.0857 |
| | FCR | -0.0152 | 0.8699 |
| | FCU | 0.1127 | 0.2223 |
| **MnPF slope** | ECU | -0.0066 | 0.9426 |
| | ECR | 0.0509 | 0.5809 |
| | FCR | -0.0467 | 0.6127 |
| | FCU | -0.0547 | 0.5528 |
| **MdPF slope** | ECU | 0.0130 | 0.8881 |
| | ECR | 0.0557 | 0.5474 |
| | FCR | 0.0050 | 0.9564 |
| | FCU | 0.0058 | 0.9501 |
| **MVE slope** | ECU | -0.0863 | 0.3486 |
| | ECR | -0.2890 | 0.0014 |
| | FCR | -0.2176 | 0.0170 |
| | FCU | -0.1022 | 0.2669 |

# CHAPTER 5 DISCUSSION

The objective of this study was to quantify muscle activity and estimate LMF of select forearm muscles during a simulation of HPCL tasks. There were two hypotheses, which are discussed below.

***Hypothesis 1: Muscle activity will be affected by work height, duty cycle, and lance orientation.***

This hypothesis was only partially supported. Muscle activity was not found to be affect by lance orientation or duty cycle. However, work height did result in significant differences in muscle activity. Working at knuckle height resulted in significantly higher muscle activity for ECU, FCR, and FCU, though higher muscle activity of the ECR was observed when working at shoulder height. Several studies have found higher muscle activity for the extensors than the flexors during gripping tasks (Fagarasanu et al. 2004; Lariviere et al. 2004; Hagg & Milerad, 1997; Hagg et al. 1997; Milerad & Kilbom, 1985), suggesting that the extensors, especially ECR, act as wrist stabilizers and primary movers during wrist extension but none of these research studied working at different heights. Contrary to the research, in this study higher muscle activity was found for the flexors than the extensors.

***Hypothesis 2: LMF will be affected by work height, duty cycle, and lance orientation.***

There were several mixed results with respect to this hypothesis. Work height significantly affected RMS slopes, as working at shoulder height resulted in lower rates of fatigue compared to working at waist height, but not Mn/MdPF slopes. The interaction of gender and treatment condition however did affect Mn/MdPF slopes. Duty cycle significantly affected Mn/MdPF slopes, with the 50% duty cycle resulting in higher rates of fatigue, but did not affect RMS slopes by itself. However, there was a significant interaction of gender and duty cycle. Lance orientation was not found significant for any EMG slopes. These inconsistency findings may be attributed to a lack of sensibility EMG parameters slopes during this particular intermittent task (Bystrom & Kilbom, 1990; Bystrom et al. 1991; Hager, 2003).

### 5.1 Subjective Assessment of Fatigue

An expected and logical finding associated with RPEs was that lower rates of fatigue were observed at the 33% duty cycle as compared to the 50% and 67% duty cycles. Similar results were found for the interaction of treatment condition and duty cycle, where for each treatment condition except when working at shoulder height, lower rates of fatigue were reported at the 33% duty cycle unlike the 50% and 67% duty cycles. Another interesting finding was when working at shoulder height participants observed no significant difference between duty cycles. This finding indicates that shoulder height was considered the most fatiguing treatment condition. Females reported less subjective fatigue than males. This result is consistent with previous research (Lindstrom, 1997: Nussbaum, 2001), which found that females have higher tolerance level than males.

### 5.2 EMG and RPF Correlation

Few objective fatigue estimates were correlated with subjective ratings of fatigue. RMS and Mn/MdPF slope parameters were not significantly correlated with RPF slopes. FCR and ECR MVE slopes and Borg ratings had a negative correlation. Some possible explanations for this include there is an upper limit for the subjective scales that doesn't necessarily exist for the EMG measures. Further, it has been argued that EMG does not directly measure the fatigue process, and therefore, may not be valid assessment technique.

### 5.3 Limitations

There were several limitations associated with this study. Several studies have indicated that EMG is not a valid and/or reliable tool for assessing muscle fatigue for intermittent/dynamic tasks (Bystrom & Kilbom, 1990; Bystrom et al. 1991; Hager, 2003). This study was not able to find consistency on the expected increase in RMS slopes and the decrease in Mn/MdPF slopes. Also it is important to mention that increased muscle temperature associated with the strenuous task demands may have influenced the inconsistency of the results (Petrofsky, 1979; Winkel & Jorgensen, 1991).

Regarding the realism of the task, three major differences between the actual and simulated task should be mentioned. Participants movement during the laboratory simulations was limited, which may not representative of the actual job task. As a result, fatigue rates may be higher or lower during actual work due to increased task demands, though this may be offset by varying duty cycles in the field (i.e., there may be more or increased duration of rest breaks. Interruption of the job task, to collect MVEs could have influenced the rate of fatigue by reducing recovery time (Fitts, 1996). Further, the student population may not be representative of the working population. When Johnson (2001) compared student and worker participants found that students performed between 69%-77% MVE of the working population. This may occur due to the working population exert to their complete capacity during the task performance. Using students as participants may have a direct effect on motivation to perform the experiment and may have influenced the results.

Only select forearm muscles were evaluated in this study. Other muscles of the upper extremity (such as the upper arm, shoulder, and upper back muscles) may also have experienced significant rates of fatigue. Whether fatigue in these muscles would be higher, lower, or equivalent is unknown. Kluth et al. (2004) found, for a similar task, that the muscle activity is higher for the triceps, biceps and forearm muscles, therefore considering other muscles may be of interest, though it appears that the muscles selected are comparable to those found to previously been the most active.

### 5.4 Summary

This study utilized typical EMG LMF measures (MVC, RMS, Mn and MdPF, and subjective measures) to quantify fatigue levels of select forearm muscles during simulations of high pressure cleaning lance tasks (common in the chemical producing industry). As found in other studies of intermittent work tasks, EMG parameters did not consistently follow expected patterns. However, fatigue levels were high as reported by participants. Therefore, appropriate interventions should be implemented to reduce operator fatigue and potentially resultant injuries.

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# APPENDIX A

## Borg CR-10 RPE scale instructions

All participants will give the same instruction on the use of Borg Scale. These instructions will be repeated at the onset of each condition.

**Instructions:**

Every work cycle, you will be asked for a general, forearms, and hands rating of exertion and/ or fatigue. For the general rating, you should consider your entire body as a whole and not focus on one specific area that may be fatigued, although if one such area exists, you should tell to the experimenter. For the hands and forearms, you should focus on both hands and forearms.

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

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

Do you have any questions about using the scale?

# APPENDIX B

## Modified Nordic Questionnaire

Date: ____/____/____ (mm/dd/yy)

Please answer the following questions, circling one of the following, where appropriate. You may skip any question you feel uncomfortable answering.

| Have you at any time during the last 12 months had trouble (ache, pain, discomfort) in: | **To be answered only by those who have had trouble** | |
|---|---|---|
| | Have you at any time during the last 12 months been prevented from doing your normal work (at home or away from home) because of the trouble? | Have you had trouble at any time during the last 7 days? |
| Wrists:<br>1. no<br>2. yes, in right wrist<br>3. yes, in left wrist<br>4. yes, in both wrists | 1. no 2. yes | 1. no 2. yes |
| Hands/fingers:<br>1. no<br>2. yes, in right hand/fingers<br>3. yes, in left hand/fingers<br>4. yes, in both hands/fingers | 1. no 2. yes | 1. no 2. yes |
| Forearms/arms:<br>1. no<br>2. yes, in right forearm/arm<br>3. yes, in left forearm/arm<br>4. yes, in both forearm/arm | 1. no 2. yes | 1. no 2. yes |

# APPENDIX C

## Demographic Information

Age: ________ Ethnic:__________________________________________________

Gender: 1. female 2. male

Dominant hand: 1. right-handed 2. left-handed

Occupation: ____________________________________________

How long have you been employed at your current job? _____ yrs. _____ mos.

Have you been previously employed in a job(s) that required significant amounts of hand tools usage? 1. no 2. yes

_____ yrs. _____ mos.

- If yes, how many years were you employed at that job(s).

# APPENDIX D

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
Informed Consent Form for:

**Project: Quantifying Localized Muscle Fatigue of the Forearm during a Simulation of a High Pressure Cleaning Lance Task**

**Investigators:** Kari Babski-Reeves, Ph.D., Assistant Professor, Grado Department of Industrial and Systems Engineering and Sandra Quinones-Vientos, Graduate Student

## I. Purpose

You are being asked to participate in a study aimed at determining the amount of forearm muscle activity is required to hold a high pressure cleaning lance (HPCL). Very few studies exist that identifying dose-response relationships between exposure to risk factors and injury development and the difficulty in accounting for a lack of injury development for all persons performing a particular task, precursors to injury development are being explored.

The objectives of this study are to: (1) quantify grip force, (2) measure muscle activity at the forearm during task performance and (3) using time to fatigue metric (TTF) identify when fatigue begins. Muscle activity will be determined using surface electromyography (EMG) of the forearm muscles (extensor carpi radialis, extensor carpi ulnaris, flexor carpi radialis, and flexor carpi ulnaris).

## II. Procedures

You will first be provided with a verbal and written description of the project, its objectives, and the protocols, and complete informed consent documents. You will then complete a questionnaire to determine if you have any pre-existing conditions (such as hand/finger, wrist or forearm injuries) which may influence the results. Over the past three weeks, you will need to have participated in six 24-minute test sessions with a minimum of 48 hrs and no more than 78 hrs between sessions; otherwise you will be excluded from this study. Finally, you will be asked to stand on a weight scale that will be used to measure you weight and height. You must have a body mass index of 24.9 or less to continue as a participant.

Muscle activity will be measured using surface electromyography (EMG) of the 4 forearm muscles (extensor carpi radialis, extensor carpi ulnaris, flexor carpi radialis, and flexor carpi ulnaris) will be collected. Because EMG requires the application of small self-adhesive circles to be applied directly to the skin, you will be asked to wear a short sleeve shirt during testing.

The skin will be prepared by cleansing with alcohol, lightly abrading using a polishing stone, and shaving as needed. A pair of electrodes (with diameter 3 cm) will be placed 2.5 cm apart over each site per standard clinical practice. Following a 10-minute stabilization period, resting muscle activity (over a 5-sec period) will be collected. For resting muscle activity assessments, you will be asked to continue holding the lance.

You will perform maximum voluntary exertion (MVE) which will be collected using a hand dynamometer (Model MicroFET4, Hogan Health Industries, Draper, UT). A single task, power grip assessment, will be used to elicit maximal activity of all the muscles. One hand posture will be assumed to simulate the range of work postures assumed by workers employed in the high pressure cleaning task: functional neutral posture (arms resting at sides, elbows flexed at $90^o$, wrist straight in a handshake position). You will be instructed to hold the position per 6-sec for each posture using a ramp-up, ramp-down procedure, with a 30-sec rest period between every other assessment (the left and right arm will be assessed before each rest period).

The task simulation will consist of a 55 inches straight lance with an inner diameter of ¼ inch. Thrust forces from the actual task were measured by a chemical producer and provided to the researcher, 32-36lbs. You will have to compress the hydraulic cylinder by pressing against a plastic sheet either attached to the wall or on the floor, to an identified range that represents 32-36lbs of force and maintain that compression for the specified work cycle. You will perform the tasks for a 24-minute period while wearing personal protective equipment supplied by the chemical producer. Also, you will indicate verbally their level of fatigue following a verbal cue by the experimenter. You will be asked every work cycle using a modified Borg-CR10 scale. All trials will be completed within a six testing sessions with total of six 1 hour test sessions (including set up and testing) per participant.

## III. Risk and Benefits

There is not more than minimal risk associated with asking you to perform the described task. Potential risks include muscle strain and soreness from having to hold posture for 2 hours. You are encouraged, however, to inform the researcher if you experience any discomfort. You will be compensated monetarily for their participation at a rate of $7.00 per hour.

## IV. Confidentiality/Anonymity

The results of the study will be kept strictly confidential. Your data will be numbered without the use of any names on the data collection forms or any other data-recording medium.

## V. Compensation

You will be compensated for your participation at a rate of $7 per hour.

## VI. Freedom to Withdraw

You are free to not respond to experimental situations you choose and withdraw from this study at any time for any reason with no penalty.

## VII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board (IRB) #03-547 for research involving human subjects at Virginia Polytechnic Institute and State University and by the Department of Industrial and Systems Engineering.

## VIII. Subject Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

1. Provide an honest level of effort.
2. Report any injuries to Virginia Tech Health Services medical personnel if you are a Virginia Tech student. Otherwise, obtain appropriate medical evaluation and treatment from your personal physician.
3. To notify the investigator at any time about a desire to discontinue participation.
4. To notify the investigator of any medical conditions which may be negatively influenced by the research study. This may include any medical problems that may interfere with results or increase the risk of Injury or illness.
5. To inform the investigator of any discomfort experienced during testing.

IX. Subject's Permission

Before you sign the signature page of this form, please make sure that you understand, to your complete satisfaction, the nature of the study and your rights as a participant. If you have question, please ask the investigator at this time. Then if you decide to participate, please sign your name above and on the following pages (one of which will be for your records).

**Signature Page**

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

_________________________________________ ______________________
Signature Date

_________________________________________
Printed Name

Any questions about this research or its conduct, you may contact:

Dr. Kari Babski-Reeves (Faculty Advisor)
Grado Department of Industrial Systems and Engineering
250 Durham Hall
Blacksburg, VA 24061
(540) 231-9093

Sandra Quinones-Vientos (Graduate Student)
(540) 961-5933

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

Dr. David Moore
IRB Chair
Assistant Vice Provost Research Compliance Director, Animal Resources
CMV Phase II
Virginia Tech (0442)
Blacksburg, VA 24061
(540) 231-9359

# APPENDIX E

## Factor effects on each EMG parameter

| Factor | Dependent variable<br>RMS | <br>MnPF | <br>MdPF | <br>MVE | <br>Borg |
|---|---|---|---|---|---|
| Treatment condition | * | | | | |
| Duty cycle | | * | * | | *** |
| Muscle | | * | * | | |
| Gender | | | | ** | |
| Treatment condition X Duty cycle | * | | | | * |
| Treatment condition X Muscle | | | | | |
| Treatment condition X Gender | ** | ** | | | ** |
| Duty cycle X Muscle | | | | | |
| Duty cycle X Gender | | ** | | | |
| Muscle X Gender | | | | | |

*Significant at P≤ 0.05; **significant at P≤ 0.01; *** significant at P≤0.001

# APPENDIX F

## Intercept results for each dependent variable

MVE intercepts were significant for gender ($p=0.0147$), muscle ($p<0.0001$) (Table 16) and the muscle-gender interaction ($p=0.0075$).

**Table F.1:** Tukey's pairwise comparison for MVE intercepts

| Gender | Mean | Grouping |
|---|---|---|
| Females | 2.0364 | A |
| Males | 2.7411 | B |
| **Muscle** | **Mean** | **Grouping** |
| FCR | 2.0544 | A |
| ECR | 2.1897 | A |
| FCU | 2.5608 | B |
| ECU | 2.7502 | B |

**Table F.2:** Tukey's pairwise comparison for muscle-gender interaction for MVE intercepts

| Muscle | Gender | Mean | Grouping |
|---|---|---|---|
| FCR | Females | 1.7607 | A |
| ECR | | 1.8780 | A |
| ECU | | 2.1370 | A |
| FCU | | 2.3699 | A |
| FCR | Males | 2.3480 | A |
| ECR | | 2.5015 | A |
| FCU | | 2.6432 | A |
| ECU | | 3.3634 | B |

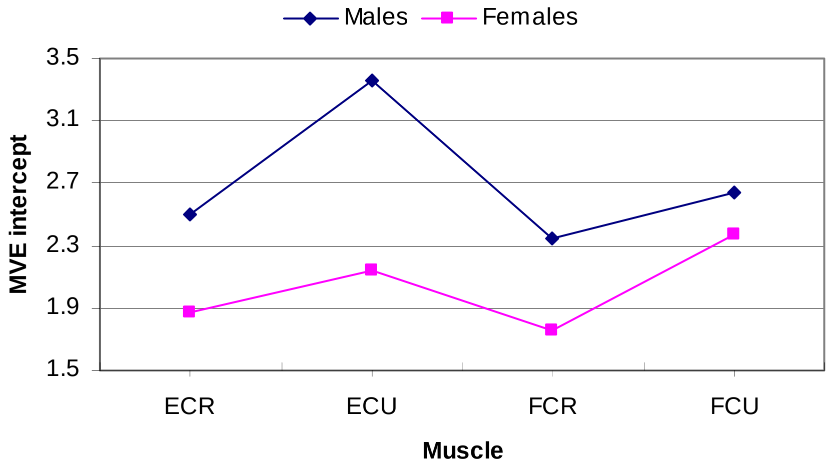

**Figure F.1:** Muscle-gender interaction for MVE intercepts

RMS intercepts differed significantly for gender (p=0.0201), treatment condition (p<0.0001), muscle (p<0.0001) (Table 18), and the treatment condition-muscle interaction (p<0.0001), and the muscle-gender interaction (p=0.0040).

**Table F.3:** Tukey's pairwise comparison for RMS intercepts

| Condition | Mean | Grouping |
|---|---|---|
| Parallel to the operator | 0.0712 | A |
| Shoulder height | 0.0970 | B |
| Waist height | 0.1185 | B |
| Knuckle height | 0.1424 | C |
| **Gender** | **Mean** | **Grouping** |
| Males | 0.0941 | A |
| Females | 0.1205 | B |
| **Muscle** | **Mean** | **Grouping** |
| ECU | 0.0768 | A |
| ECR | 0.0989 | A |
| FCR | 0.1086 | B |
| FCU | 0.1449 | C |

**Table F.4:** Tukey's pairwise comparison for treatment condition-muscle interaction for RMS intercepts

| Condition | Muscle | Mean | Grouping |
|---|---|---|---|
| Parallel to the operator | ECU | 0.0602 | A |
| Shoulder height | | 0.0699 | A |
| Waist height | | 0.0795 | A |
| Knuckle height | | 0.0976 | A |
| Parallel to the operator | FCR | 0.0667 | A |
| Shoulder height | | 0.0718 | A |
| Waist height | | 0.1279 | A |
| Knuckle height | | 0.1682 | B |
| Parallel to the operator | ECR | 0.0728 | A |
| Waist height | | 0.0959 | A |
| Knuckle height | | 0.0974 | A |
| Shoulder height | | 0.1291 | A |
| Parallel to the operator | FCU | 0.0854 | A |
| Shoulder height | | 0.1173 | A |
| Waist height | | 0.1706 | B |
| Knuckle height | | 0.2063 | B |

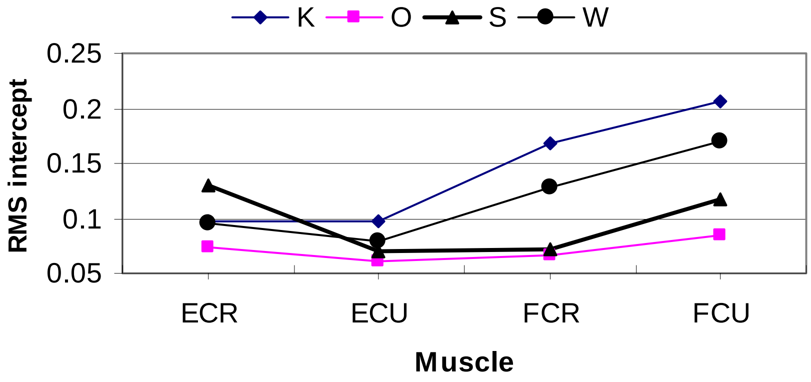

**Figure F.2:** Treatment condition-muscle interaction for RMS intercepts

**Table F.5:** Tukey's pairwise comparison for muscle-gender interaction for MVE intercepts

| Muscle | Gender | Mean | Grouping | |
|---|---|---|---|---|
| ECU | Males | 0.0624 | A | |
| ECR | | 0.0727 | A | |
| FCR | | 0.0913 | A | |
| FCU | | 0.1498 | | B |
| ECU | Females | 0.0912 | A | |
| ECR | | 0.1249 | A | B |
| FCR | | 0.1259 | A | B |
| FCU | | 0.1400 | | B |

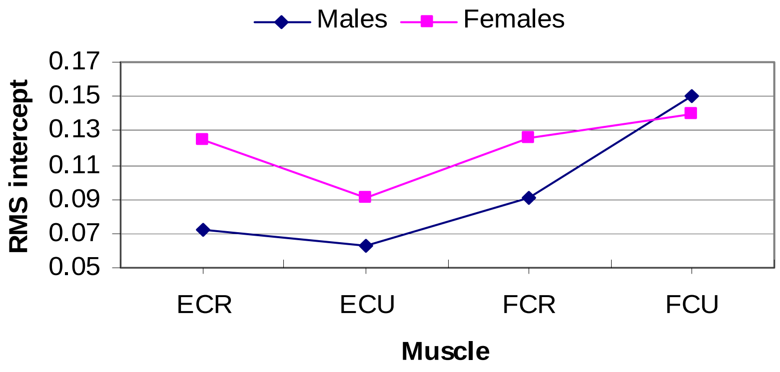

**Figure F.3:** Muscle-gender interaction for RMS intercepts

MnPF intercepts differed significantly for treatment condition (p<0.0001), muscle (p<0.0001), and the treatment condition-muscle interaction (p<0.0001), and the muscle-gender interaction (p=0.0043). MdPF intercepts were significant for treatment condition (p<0.0001), gender (0.0315), muscle (p<0.0001), and the muscle-treatment condition interaction (p<0.0001).

**Table F.6:** Tukey's pairwise comparison for MnPF intercepts

| Condition | Mean | Grouping |
|---|---|---|
| Knuckle height | 111.66 | A |
| Waist height | 115.59 | A |
| Shoulder height | 122.00 | B |
| Parallel to the operator | 123.63 | B |
| **Muscle** | **Mean** | **Grouping** |
| FCU | 108.85 | A |
| FCR | 110.85 | A |
| ECR | 123.36 | B |
| ECU | 130.46 | C |

**Table F.7:** Tukey's pairwise comparison for treatment condition-muscle interaction for MnPF intercepts

| Condition | Muscle | Mean | Grouping |
|---|---|---|---|
| Waist height | FCU | 105.38 | A |
| Parallel to the operator | | 106.48 | A |
| Knuckle height | | 110.02 | A |
| Shoulder height | | 110.96 | A |
| Knuckle height | FCR | 105.73 | A |
| Waist height | | 109.19 | A |
| Shoulder height | | 113.87 | B |
| Parallel to the operator | | 114.60 | B |
| Knuckle height | ECR | 115.68 | B |
| Waist height | | 122.63 | B |
| Shoulder height | | 126.79 | B |
| Parallel to the operator | | 128.36 | B |
| Knuckle height | ECU | 115.20 | B |
| Waist height | | 125.16 | B |
| Shoulder height | | 136.38 | C |
| Parallel to the operator | | 145.09 | C |

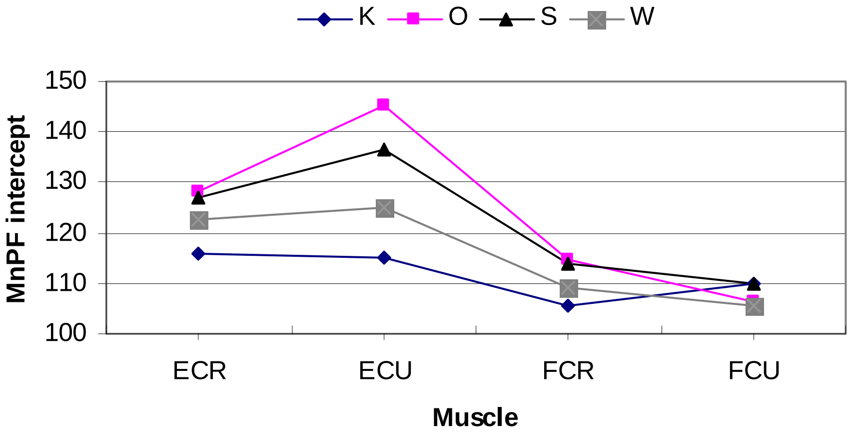

**Figure F.4:** Treatment condition-muscle interaction for MnPF intercepts

**Table F.8:** Tukey's pairwise comparison for muscle-gender interaction for MnPF intercepts

| Muscle | Gender | Mean | Grouping | | |
|---|---|---|---|---|---|
| FCU | Females | 105.76 | A | | |
| FCR | | 110.12 | A | B | |
| ECR | | 115.66 | | B | |
| ECU | | 126.17 | | | C |
| FCU | Males | 110.66 | A | B | |
| FCR | | 111.58 | A | B | |
| ECR | | 131.07 | | | C |
| ECU | | 134.75 | | | C |

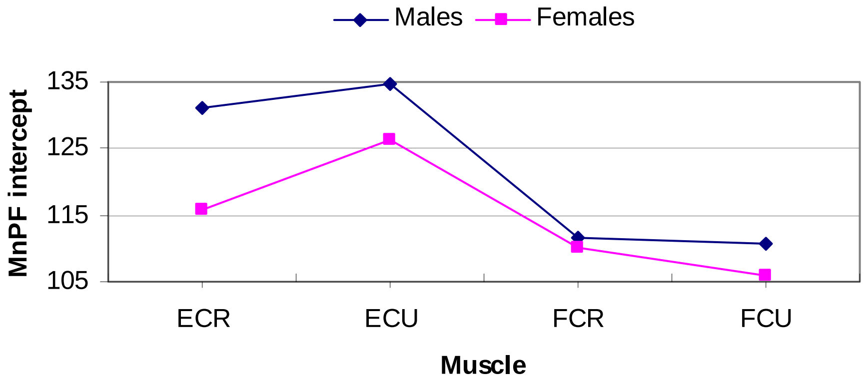

**Figure F.5:** Muscle-gender interaction for MnPF intercepts

**Table F.9:** Tukey’s pairwise comparison for MdPF intercepts

| **Condition** | **Mean** | **Grouping** |
|---|---|---|
| Knuckle height | 92.98 | A |
| Waist height | 96.89 | A |
| Shoulder height | 101.49 | B |
| Parallel to the operator | 103.43 | B |
| **Gender** | **Mean** | **Grouping** |
| Females | 94.44 | A |
| Males | 102.96 | B |
| **Muscle** | Mean | **Grouping** |
| FCR | 90.05 | A |
| FCU | 90.97 | A |
| ECR | 103.98 | B |
| ECU | 109.54 | C |

**Table F.10:** Tukey’s pairwise comparison for treatment condition-muscle interaction for MdPF intercepts

| **Condition** | **Muscle** | **Mean** | **Grouping** |
|---|---|---|---|
| Knuckle height | FCR | 86.16 | A |
| Waist height | | 89.76 | A |
| Shoulder height | | 92.49 | A |
| Parallel to the operator | | 92.81 | A |
| Waist height | FCU | 88.55 | A |
| Parallel to the operator | | 89.97 | A |
| Shoulder height | | 92.49 | A |
| Knuckle height | | 92.86 | A |
| Knuckle height | ECR | 96.67 | A |
| Waist height | | 103.93 | B |
| Shoulder height | | 107.10 | B |
| Parallel to the operator | | 108.22 | B |
| Knuckle height | ECU | 96.23 | A |
| Waist height | | 105.31 | B |
| Shoulder height | | 113.88 | B C |
| Parallel to the operator | | 122.73 | C |

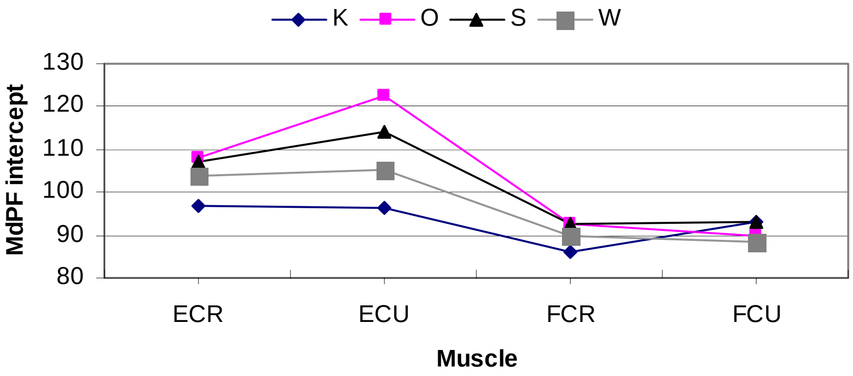

**Figure F.6:** Treatment condition-muscle interaction for MdPF intercepts