Exploring Subjective and Objective Localized Muscle Fatigue Responses at Recommended Upper Limb Ergonomics Limits

by

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

Localized muscle fatigue (LMF) has been associated with numerous negative outcomes, including a reduction in task performance and development of musculoskeletal injury. Thus, the quantification of LMF development in response to occupational task demands has become a major focus in the ergonomics literature. In this thesis, Study 1 showed how a familiarization session, including targeted feedback on ratings of perceived fatigue (RPF), resulted in a significant improvement in error between RPF and measures of force output and electromyography. Study 2 compared the LMF response at three different "acceptable" limits along the ACGIH® threshold limit curve, which describes acceptable relative force intensity for a given level of repetitive work (i.e. duty cycle). Exposures at higher duty cycles (and lower force intensity) were found to elicit the largest LMF responses. This thesis concludes with practical recommendations to help ergonomists better assess and prevent the accumulation of excessive LMF in the workplace.

Keywords: muscle fatigue; psychophysics; ergonomics; upper extremity injury; repetitive work

CO-AUTHORSHIP STATEMENT

The manuscripts described in Chapters 3 and 4 of this thesis were co-authored with Fahima Wakeely, Ryan C. A. Foley, Dr. Jeffrey D. Graham, and Dr. Nicholas J. La Delfa. I, **Daniel M. Abdel-Malek**, was the primary contributor to all aspects of these works, including study conception & design, data collection, data analysis and manuscript preparation.

Fahima Wakeely contributed to data collection and processing, alongside **Ryan Foley**. Ryan Foley's contributions also include the design of the experimental apparatus. **Dr. Graham** provided expertise in the collection, analysis and interpretation of psychological data. As the supervisor of this thesis, **Dr. La Delfa** was primarily involved in study conception & design, data analysis and interpretation. He also provided extensive edits to both manuscripts, but all written content presented in this thesis is the work of my own.

AUTHOR'S DECLARATION

I hereby declare that this thesis consists of original work of which I have authored. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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The research work in this thesis that was performed in compliance with the regulations of Ontario Tech's Research Ethics Board/Animal Care Committee under **REB Certificate #14962 & #14969**.

______________________________ DANIEL ABDEL-MALEK

STATEMENT OF CONTRIBUTIONS

The work described in Chapters 3 and 4 was performed within the Occupational Neuromechanics and Ergonomics Laboratory at Ontario Tech University, using equipment and software designed by Ryan Foley and Dr. Nicholas La Delfa. Data collection was primarily conducted by myself, Fahima Wakeely and Ryan Foley. Fahima Wakeely also aided in the processing of electromyography, force and psychophysical data. Under the regular advisement of Dr. La Delfa, I conducted all data synthesis, statistical analyses and primary interpretation of results. Dr. La Delfa provided feedback and made minor editorial adjustments to the manuscripts contained within.

I hereby certify that I am the sole author of this thesis. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

ACKNOWLEDGEMENTS

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To my good friend, Matt, it feels like it was just yesterday we started our undergraduate degrees six years back. Here we are defending our theses, and I could not have asked for a better partner-in-crime to begin and end this journey with. I'm confident this isn't our last chapter.

I would also like to take a moment to acknowledge my gratitude to the Frith family for their incredible financial support throughout my graduate studies, as well as the Canada Graduate Scholarship and CRE-MSD funds.

Lastly, to my wonderful mother and stud of a brother – thank you for always being there for me through the stress and late nights at the lab. Mom, thank you for always whipping up incredible meals to fuel the grueling work. Your support is so selfless in both tangible and intangible ways. David, thanks for making yourself available to help down at the lab, and for sticking around on campus waiting for me on those long nights of collection and analysis.

Words fail to capture how blessed I am to be surrounded by such wonderful people. Thanks for putting up with me during my long, winding academic journey. Excited for this next chapter!

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LIST OF ABBREVIATIONS AND SYMBOLS

ACGIH©	American College of Governmental Industrial Hygienists
aEMG	EMG amplitude
DC	Duty Cycle
EMG	Electromyography
FS	Feeling Scale
IMI	Intrinsic Motivation Inventory
LMF	Localized muscle fatigue
MAE	Maximal acceptable effort
MnPF	EMG mean power frequency
MSD	Musculoskeletal disorder
MVC	Maximal voluntary contraction
NIRS	Near-infrared spectroscopy
RPE	Ratings of perceived exertion
RPF	Ratings of perceived fatigue
TLV	Threshold limit value
TSE	Task self-efficacy
TSI	Tissue saturation index

Chapter 1. Thesis Introduction

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Since the mechanization of industrial work brought about by the Industrial Revolution, an increased proportion of repetitive manual tasks has been reported (Luopajärvi, Kuorinka, Virolainen, & Holmberg, 1979). Musculoskeletal overexertion injuries accounted for 19% of lost-time claims in 2017, and now represent the leading injury event in the past decade (WSIB, 2017). As such, a major focus of ergonomics is the mitigation of work-related musculoskeletal disorders (MSDs) by identifying and quantifying key risk factors associated with work-related injury and decrements in performance. Excessive force, poor posture, and high repetitions are linked to the development of localized muscle fatigue (LMF), as task demands exceed the worker's capacity, leading to increased likeliness of injury (Enoka & Duchateau, 2008; Kumar, 2001). The description of worker capacities and evaluation of task demands is necessary to develop threshold limits of exposure that help mitigate fatigue-related events of injury.

This thesis will begin with a brief outline of the literature surrounding current definitions and components of neuromuscular fatigue, along with its quantification in response to various task demands in ergonomics studies in the formation of current thresholds for physical work. This sets the stage for a discussion of the two lines of inquiry in this thesis:

Chapter 3 describes the first laboratory study of this thesis, which aims to enhance the accuracy of a widely-used psychophysical metric of LMF, obtained via self-reported ratings of perceived fatigue (RPF). Despite strong correlations to objective measures of LMF, including force declines and myoelectric changes in the amplitude and frequency domains (Hummel et al., 2005; Troiano et al., 2008; Whittaker, Sonne, & Potvin, 2019), RPF can be easily misunderstood by individuals providing ratings, given its subjective nature and lack of prior familiarization. Given the existing opportunity to improve an already unique and powerful indicator of fatigue, the purpose of study 1 is to explore whether a familiarization session would improve psychophysical estimations of LMF relative to traditionally-used assessments of LMF. Findings may positively impact RPF implementation in workplace and laboratory settings that require efficient and accurate techniques to assess LMF development.

Chapter 4 outlines the second study of this thesis, which evaluates the LMF response to currently used threshold limits for repetitive upper extremity work. Threshold limit values (TLVs) for task repetition/duration (i.e. duty cycle [DC]) and effort intensity (i.e. % maximal voluntary contraction [MVC] are currently predicted by a model published by the American College of Governmental Industrial Hygienists (ACGIH®, 2016). Acceptable work limits, described in order to avoid excessive amounts of LMF, are defined by an inverse exponential curve that demonstrates a reduction in maximal acceptable efforts (MAEs) with increasing DC. Despite its basis on psychophysical data from several studies (Potvin, 2012b), a lack of data in the high DC range (over 0.50) forced the model to use refitted data to predict thresholds at higher DCs. Thus, the purpose of study 2 is to evaluate LMF responses at three different TLVs along this curve using neuromuscular, psychophysical, and physiological assessments of fatigue during an intermittent upper limb task. While similar fatigue responses between these TLVs expected, differences in LMF between these workloads may shed light on the predictive utility of these thresholds at various levels of DC and load.

1. Research Questions

1.1. Study 1

Does a period of familiarization improve the accuracy of RPF relative to classical measures of LMF (e.g. force output, EMG amplitude & mean power frequency)?

1.2. Study 2

Does the LMF response differ when a repetitive upper limb task is performed at three different threshold limit values along the ACGIH curve?

2. Hypotheses

The following hypotheses were tested, where H_O represents the null hypothesis, and H_A represents an alternative hypothesis:

2.1. *Study 1: Does a period of familiarization improve the accuracy of RPF relative to classical measures of LMF (force output, EMG amplitude, & mean power frequency)?*

H_O: RPF error of feedback group = RPF error of control group

H_A: RPF error of feedback group ≠ RPF error of control group

2.2. Study 2: Does the LMF response differ when a repetitive upper limb task is performed at three different TLVs along the ACGIH curve?

H_O: LMF at workload A = LMF at workload B = LMF at workload C

H_A: LMF at workload A ≠ LMF at workload B ≠ LMF at workload C

3. References

ACGIH®. (2016). The American Conference of Governmental Industrial Hygienists. TLVs® and BEIs® based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of physiology, 586*(1), 11-23.

Hummel, A., Läubli, T., Pozzo, M., Schenk, P., Spillmann, S., & Klipstein, A. (2005). Relationship between perceived exertion and mean power frequency of the EMG signal from the upper trapezius muscle during isometric shoulder elevation. *European journal of applied physiology, 95*(4), 321-326. doi:10.1007/s00421-005-0014-7

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics*, *44*(1), 17-47.

Luopajärvi, T., Kuorinka, I., Virolainen, M., & Holmberg, M. (1979). Prevalence of tenosynovitis and other injuries of the upper extremities in repetitive work. *Scandinavian journal of work, environment & health*, 48-55.

Potvin, J. R. (2012). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. *Human factors, 54*(2), 175-188.

Troiano, A., Naddeo, F., Sosso, E., Camarota, G., Merletti, R., & Mesin, L. (2008). Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait & Posture, 28*(2), 179-186. doi:https://doi.org/10.1016/j.gaitpost.2008.04.002

Whittaker, R. L., Sonne, M. W., & Potvin, J. R. (2019). Ratings of perceived fatigue predict fatigue induced declines in muscle strength during tasks with different distributions of effort and recovery. *Journal of Electromyography and Kinesiology*.

WSIB. (2017). *"By the numbers: 2017 WSIB statistical report"*. Ontario: Ontario Provincial Government.

Chapter 2. Describing & predicting neuromuscular fatigue during physical work: A Review of the Literature

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1. <u>Neuromuscular Fatigue</u>

Neuromuscular (NM) fatigue has been described in the literature as a temporary decline in force-generating capacity, regardless of whether or not the task is sustained (Enoka & Duchateau, 2008; Frey Law & Avin, 2010). NM fatigue and its decline in force production is transient and reversible, meaning these losses can be reversed with recovery, and are not permanent, as in occurrences of weakness (Williams & Ratel, 2009). Furthermore, task failure is not a necessary criteria for NM fatigue occurrence (Bigland-Ritchie & Woods, 1984); Gardiner suggests NM fatigue should be expanded to include the increases in excitation necessary to maintain submaximal force throughout an exertion (Gardiner, 2011). Nonetheless, most definitions of NM fatigue involve a decrement in force, velocity, or power (Williams & Ratel, 2009).

NM fatigue is a complex biological process that is multi-dimensional nature; thus, its description must take a more multi-faceted approach. The manifestation of NM fatigue is influenced by both central (nervous system) and peripheral (muscular) factors (S. C. Gandevia, 2001), as the failure of force production may develop anywhere along the pathway between the central nervous system (central) and the individual contractile apparatus of muscle fibers (peripheral) (Gardiner, 2011; Kent-Braun, 1999) (Figure 2.1). While the development of NM fatigue cannot be consistently localized to origin or cause, researchers have additionally outlined its onset as a complex interaction between perceptual and physiological factors (Micklewright, Gibson, Gladwell, & Al Salman, 2017).

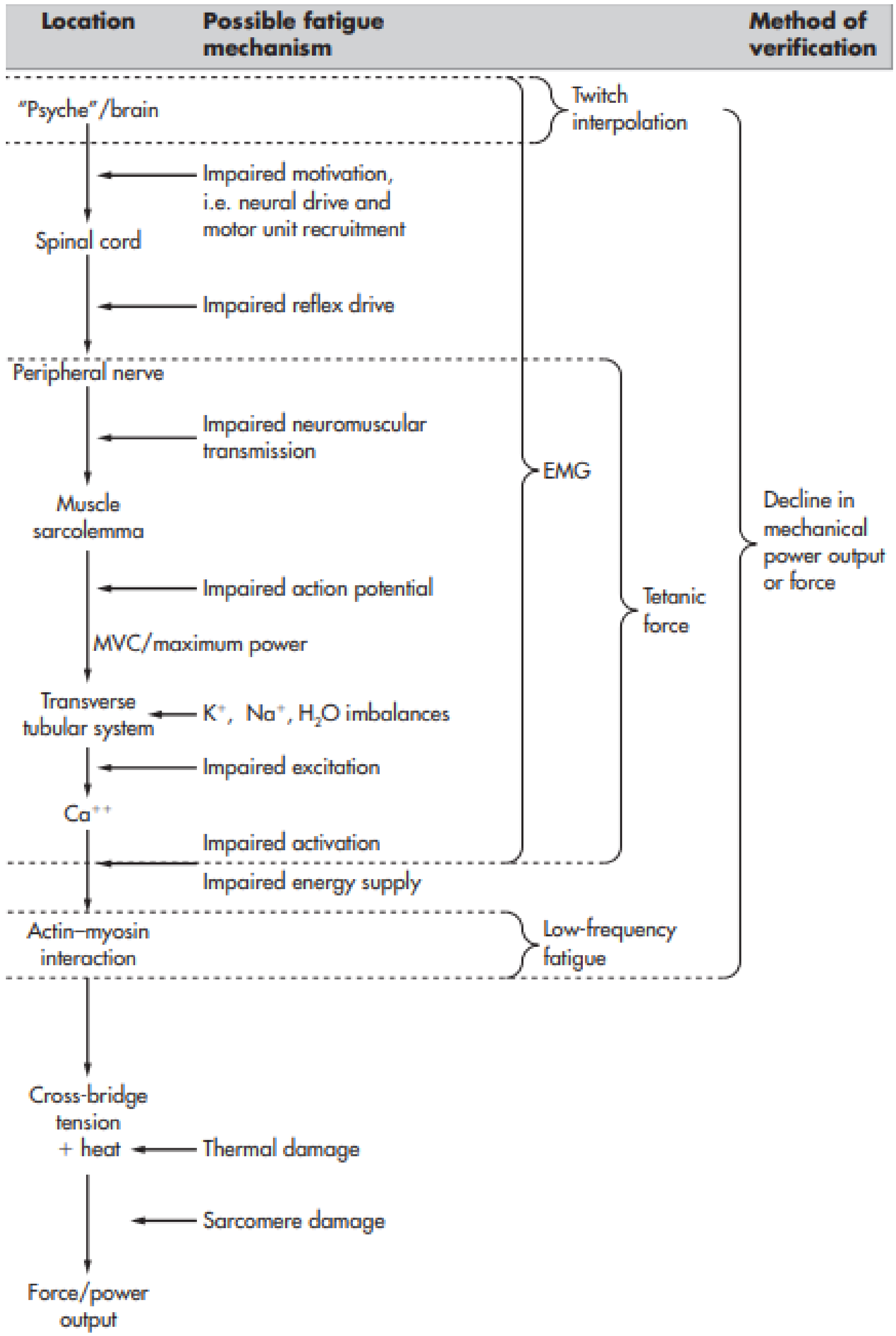

Figure 2.1: Chain-of-command model of NM fatigue (Williams & Ratel, 2009)

1.1. Central Fatigue

Central fatigue involves the neural systems that provide input to the muscle fibers, specifically the motor cortex of the cerebrum, and neural pathways that descend the spinal cord to innervate motor neurons responsible for stimulating muscle fibers for contraction (Figure 2.2) (Merletti & Parker, 2004). The central contribution to neuromuscular fatigue has been characterized by observed decreases in voluntary activation in both maximal and submaximal isometric tasks, attributed to a decline in motor unit firing rates, in addition to an array of contributing mechanisms affecting the neural drive that reaches muscle tissue (S. C. Gandevia, 2001; Gardiner, 2011).

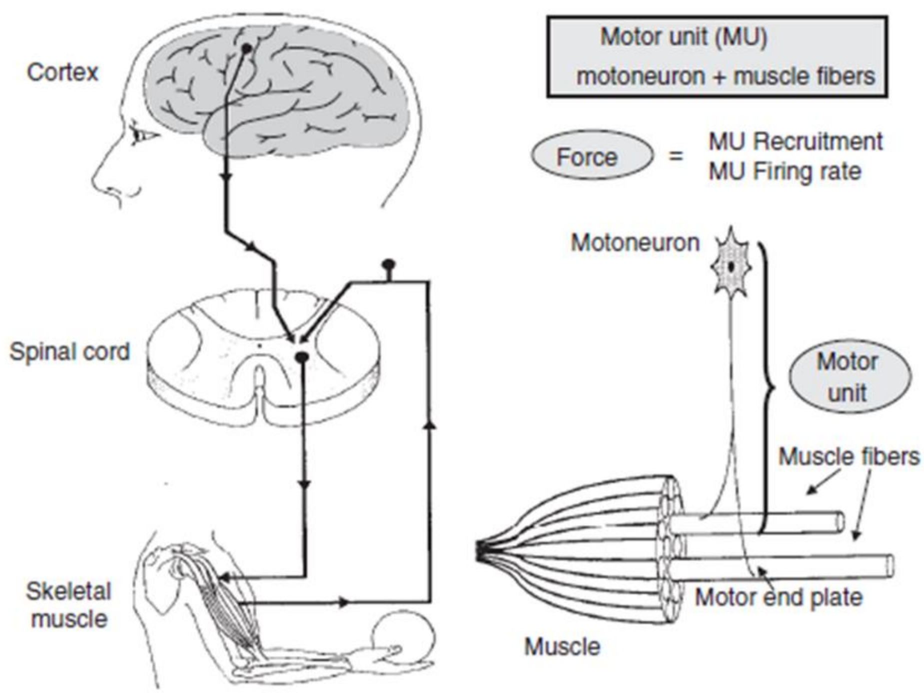

Figure 2.2: Example of a neural pathway that innervates muscle fiber and controls force output (Merletti & Parker, 2004)

A commonly accepted mechanism affecting neural drive during fatigue involves levels of muscle spindle activity, whose discharge has an excitatory influence on motoneurons. The gamma-motorneuron (fusimotor) system, which innervates the intrafusal muscle fibers, has been implicated in its excitatory influence on motoneurons, via studies that have increased gamma motorneuron signal using tendon vibration during contractions; similarly, blocking the signal to intrafusal fibers led to decreases in motoneuron firing rate, indicating the gamma motoneuron system as an important source of motoneuron excitation (Hagbarth, Kunesch, Nordin, Schmidt, & Wallin, 1986). Fatigue onset during prolonged submaximal activity has seen simultaneous decreases in spindle discharge, which influences motoneuron excitation, and thus, neural drive to the extrafusal muscle fiber (Gardiner, 2011).

Motoneuron activity is also regulated from central origins via presynaptic mechanisms. One such mechanism is reciprocal inhibition, which is known to increase during both maximal and submaximal exertions, as evidenced by studies using H-reflexes, which are elicited by stimulus of the peripheral nerve (Gardiner, 2011). Ia afferents then carry the stimulated impulse to the motoneuron via synapse, allowing researchers to indirectly measure motoneuron excitability. For example, in a study assessing reciprocal inhibition of the soleus during a submaximal fatiguing task of the tibialis anterior, depressed H-reflexes were observed in the soleus, indicating reciprocal inhibition of the soleus motor neuron had occurred (Tsuboi, Sato, Egawa, & Miyazaki, 1995).

Influences of neural drive to the muscle have also been attributed to supraspinal origins, that is, the motor cortex. Using techniques such as TMS, researchers have attributed some contribution to neuromuscular fatigue to the cortex, by stimulating the cortex during sustained contractions (S. Gandevia, Allen, Butler, & Taylor, 1996; Taylor, Butler, Allen, & Gandevia, 1996). Two key indicators of supraspinal influence on neural drive are changes in amplitude of the motor evoked potential (MEP), and silent period duration, a period of electrical inactivity at the muscle which increases with cortical inhibition (Gardiner, 2011). Findings revealed increases in MEP amplitude and silent period duration, indicating both excitation and inhibition of the cortex occur simultaneously during sustained exertion. Changes in excitability and inhibition were attributed to the cortex by evoking similar stimulations at the spinal level, which did not show changes in MEP amplitude or silent period duration. Findings were further supported by increases in superimposed muscle twitch response observed during fatigue, indicating suboptimal drive to the muscles specifically from the cortex, as peripheral stimulation also manifested a superimposed contractile response in this fatigued state (S. Gandevia et al., 1996; Taylor et al., 1996).

1.2. Peripheral Fatigue

Peripheral aspects of fatigue describe events that occur beyond the central nervous system, originating outside the spinal cord via the peripheral motor neuron and post-neuromuscular junction/synapse (i.e. motor neurons and innervated muscle fibers). In any event requiring muscle contraction, motor neurons propagate action potentials towards muscle fiber via changes in voltage and release of neurotransmitters in their synapse with muscle fiber. Once activated, muscle fibers require energy via ATP and calcium influx to engage in sarcomere shortening via the pulling mechanism of formed cross-bridges (Merletti & Parker, 2004) (Figure 2.3).

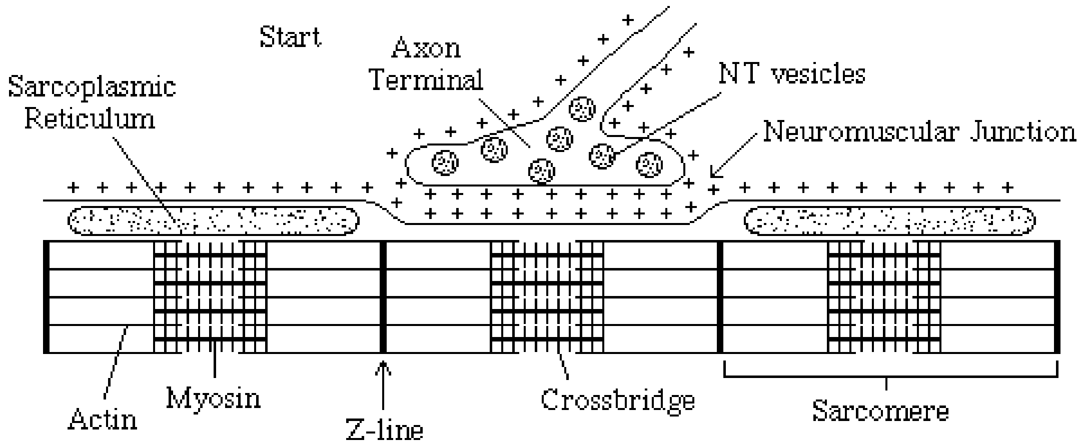

Figure 2.3: Illustration of the neuromuscular synapse between motor neuron & muscle fiber. Sarcomere shortening via ATP and calcium influx occurs due to cross-bridge formation
(Merletti & Parker, 2004)

Peripheral factors of fatigue include inhibitory responses to metabolite accumulations, such as hydrogen ions, reactive oxygen species (ROS), and inorganic phosphates (P_i), which slow the excitation-contraction coupling process that initiates at the neuromuscular junction (Gardiner, 2011; Kent-Braun, 1999). Kinetic changes in cross-bridge formation generate a shift toward a more weakly-bound state, resulting in less force generation, slower contraction speeds, and decreases in power (Gardiner, 2011; Williams & Ratel, 2009).

The neural signal may also fail to be transmitted to the muscle, described as the phenomenon of neuromuscular transmission failure; in addition, potential failure of the muscle response to such neural signal may occur (Gardiner, 2011; Williams &

Ratel, 2009). These changes have been observed in both high and low intensity exertion, and also cause a decline in muscle force output (Kent-Braun, 1999).

A contributing factor to the failure of neuromuscular transmission is the depletion of neurotransmitters released in the synapse; depletion may occur due to decline in available vesicles, as well as lowered vesicle content of the neurotransmitter (Wu & Betz, 1998). In a fatigue study performed on rat diaphragm, indirect stimulation at the motor nerve resulted in pronounced decreases in maximal force when compared to direct stimulation at the muscle itself, indicating fatigue may have been caused at least partially by neurotransmitter depletion (Van Lunteren & Moyer, 1996).

Post-synaptic membrane failure may also occur despite the presence of the neural signal and sufficient neurotransmitter available. A recognized phenomenon that occurs is a desensitization of neurotransmitter receptors during prolonged exposure to neurotransmitters, such as acetyl choline, which is demonstrated in muscle treated with anticholinesterases, which prolong acetyl choline presence in the synapse during observation (Gardiner, 2011). Myofibrillar desensitization to calcium may also occur, regardless of whether calcium concentration levels are sufficient for cross-bridge formation and function (Williams & Ratel, 2009). Failure of the action potential to propagate fully into all branches innervating the muscle fibers may also occur during fatigue (Gardiner, 2011; Williams & Ratel, 2009).

During prolonged submaximal exertion, declines in muscle activation occur despite documented decreases in motor unit firing frequency and increase in recruitment occurring simultaneously. Coupled with the slowing contractile speed of the muscle fibers, as previously discussed, this decline in firing frequency has been labelled as ‘wise’, considering the lower frequencies now required to meet maximal force (Bigland-Ritchie & Woods, 1984). Several physiological mechanisms have been proposed to explain this phenomenon, including motoneuron inhibition.

A popular hypothesis for motoneuron inhibition and its associated changes in firing frequency is centered on the decrease in motoneuron excitability caused by afferent signals coming from the fatigued muscle (Gardiner, 2011). Experiments performed by Bigland-Ritchie and colleagues revealed the inhibitory influence of afferent muscle receptors exposed to the accumulation of metabolic byproducts, as motoneuronal inhibition continued with maintained ischemic conditions of the muscle (BR Bigland-Ritchie, Dawson, Johansson, & Lippold, 1986; J. Woods, Furbush, & Bigland-Ritchie, 1987).

1.3. Subjective Fatigue

Neuromuscular fatigue has also been described in the literature in terms of fatigability, a more normalized description of fatigue levels considering individual variability. Thus, a taxonomy has been proposed for neuromuscular fatigue, associated with two inter-dependent attributes: perceived (subjective) fatigability, and performance (objective) fatigability (Kluger, Krupp, & Enoka, 2013). Both attributes depend on underlying factors, which normalize fatigue to the demands of the task performed.

Perceived fatigability encompasses the individual’s perception of fatigue, and is influenced by the initial state and rate of change of key sensations derived during task performance (Kluger et al., 2013). Afferent feedback provided during exertion or exercise contributes to perceived fatigability, as the need arises to regulate and maintain homeostasis, and resolve disturbances to the psychological state; these changes modulate the performer's integrity while performing the task. It is the modulation of factors, such as blood glucose, core temperature, and psychological attributes of arousal and mood, that affects the individual's ability to generate voluntary activation, and thus, controls the rate of measurable fatigue development, or performance fatigability (Taylor & Gandevia, 2008).

1.4. Objective Fatigue

The attribute of performance fatigability relates the decline of an objective performance measure over a certain period of time (Enoka & Duchateau, 2016). The proposed taxonomy describes this attribute as dependent on two underlying capacities: that of the contractile apparatus, and the capacity of the nervous system to provide activation to the contractile components (Kluger et al., 2013). Thus, performance fatigability is impacted by impairments to contractile function which may also be accompanied by diminishing neural activation/drive originating from the nervous system, manifesting in measurable declines in task performance (Enoka & Duchateau, 2016). It is the interaction of these two attributes of fatigability that limit physical function or performance (Enoka & Duchateau, 2016).

2. **<u>Measures of NM fatigue</u>** — How can fatigue be quantified?

In order for NM fatigue to be described and localized, fatigue research has utilized an array of measures for the purpose of quantifying fatigue and its components. Measures of the levels of force output, muscle activation, tissue oxygenation, and self-reported ratings are commonly used measures of fatigue (S. C. Gandevia, 2001; Kent-Braun, 1999; Williams & Ratel, 2009). These measures have been utilized to describe the sub-optimal changes to normal muscle function that occur with NM fatigue.

2.1. Force Output

As the definition of NM fatigue is characterized by a transient reduction in force output, it becomes apparent that a measurement of muscle force production is the gold-standard for depicting NM fatigue (S. C. Gandevia, 2001). As NM fatigue develops, the muscle is unable to maintain levels of force production, and thus, a decline occurs, as measured by a force transducer or load cell (Halperin, Copithorne, & Behm, 2014).

Changes in muscle force production during NM fatigue have been attributed to both central and peripheral factors (S. C. Gandevia, 2001; Halperin et al., 2014). These changes in force can be due to decreased central drive, or decreased strength of peripheral contraction, despite difficulty in identifying the specific central or peripheral contributions to these force decrements. Obvious fluctuations in force, accompanied by a general decline of force output, may be attributed to central fatigue, as the decreased motor unit firing rates caused by the reduced/inhibited central drive can manifest in force variability with fluctuations around the desired force output (S. C. Gandevia, 2001; Halperin et al., 2014).

Peripheral NM fatigue may also result in a decline in force output, be it due to metabolic waste accumulation, or mechanical fiber damage (Kent-Braun, 1999).

2.2. Electromyography (EMG)

NM fatigue and recovery are commonly assessed using the technique of electromyography (EMG) (Kamen & Gabriel, 2010). Motor control, via modulation of force, can be measured using EMG, as electrical impulses stimulate muscle fibers via neurons descending from the central nervous system. EMG electrodes record the summated electrical activity of many motor units (groups of skeletal muscle fibers innervated by individual motor neurons). Thus, measures of the magnitude, timing, and frequency of electrical activation can be provided, as neurons stimulate innervated muscle fibers for contraction.

Measures of EMG amplitude (peak-to-peak magnitude of signal waves) can depict the level of motor unit activation (Staudenmann, Potvin, Kingma, Stegeman, & van Dieën, 2007). Levels of activation increase or decrease depending on the amount of central drive reaching the muscles (S. C. Gandevia, 2001; Gardiner, 2011). EMG amplitude can be modulated by a mechanism described in Henneman’s size principle, where controlled motor output occurs as a gradual and orderly recruitment of MUs based on increasing size (Henneman, 1979). Increased muscle activation also occurs in part due to increased rate coding, or firing frequency of individual MUs, whose discharge frequency can be altered to increase muscle activation and subsequent contraction (Adrian & Bronk, 1929). The size principle helps explain the documented increases in EMG amplitude that occur with NM fatigue (see Figure 2.4 below); increased neural drive and resultant motor unit recruitment are directed changes during fatigue in attempts to maintain force output, manifesting as an increase in the amplitude of electrical activity (Enoka & Duchateau, 2008).

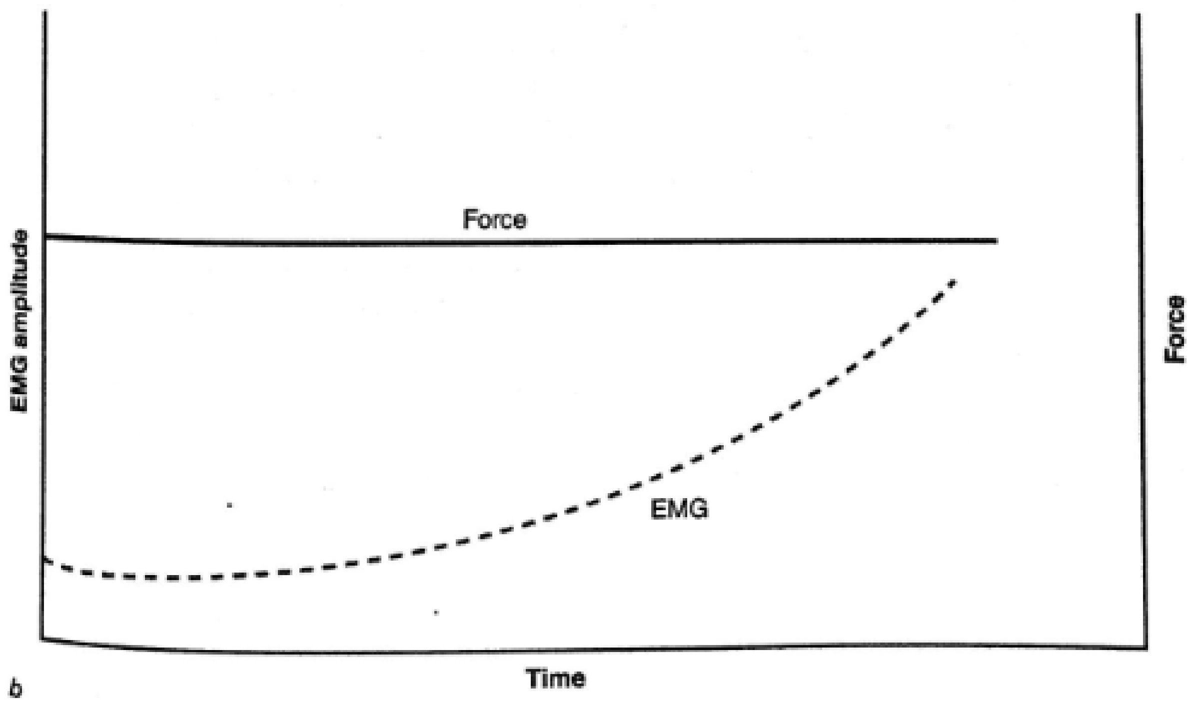

Figure 2.4: EMG amplitude changes during a fatiguing sub-maximal force contraction (Kamen & Gabriel, 2010).

As the electrical potential measured by EMG is a summation of individual motor unit potentials with a large spectrum of constituent frequencies, their mean can be depicted as the mean power frequency (MnPF) obtained by decomposing the spectrum of frequencies (Petrofsky, Glaser, Phillips, Lind, & Williams, 1982). In instances of NM fatigue, a decrease in the MnPF may occur as the mean frequency of collective motor unit action potentials exemplifies a shift to lower frequencies (Mills, 1982; Petrofsky et al., 1982). Explanations for this phenomenon center around the decreased firing rate of motor units with central fatigue, such as a shift towards slower twitch motor units. In addition, the accumulation of metabolites and ions can cause a slowing of conduction velocity compared to resting conditions, which can manifest in a shift towards a lower MnPF (Figure 2.5).

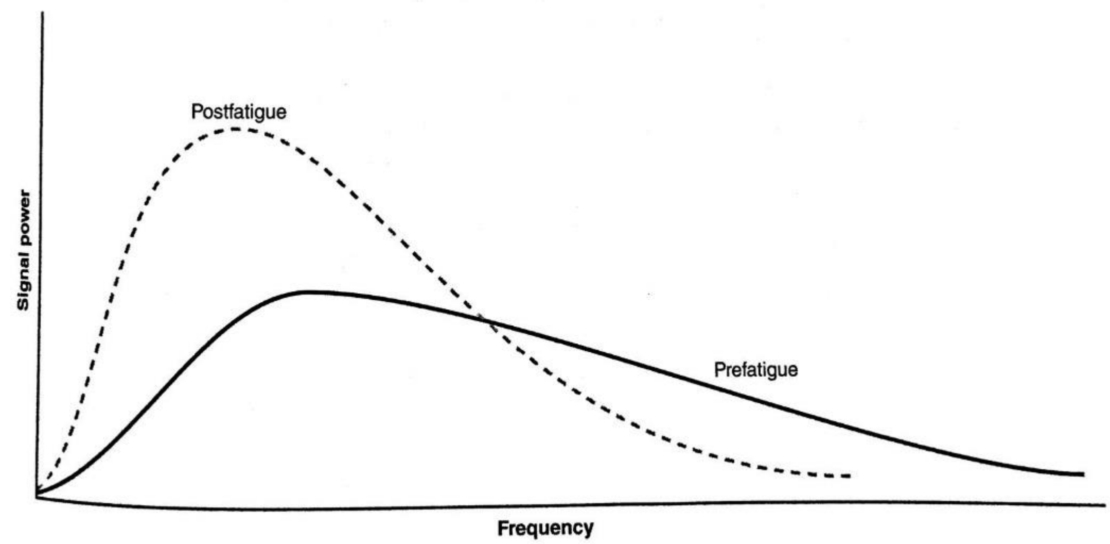

Figure 2.5: EMG MnPF changes during a fatiguing sub-maximal force contraction (Kamen & Gabriel, 2010)

2.3. Tissue Oxygenation (via Near-Infrared Spectroscopy)

Considering the development of NM fatigue involves energy metabolism and oxygen consumption, muscle oxygenation levels are an influencing factor. Conditions of hypoxia - due to poor tissue perfusion - are often accompanied by hypercapnia (buildup of CO2), and high levels of metabolites, which are characteristic of peripheral NM fatigue (Bigland-Ritchie & Woods, 1984; Gardiner, 2011; Kent-Braun, 1999). Levels of tissue oxygenation can be measured by near-infrared-tissue spectroscopy (NIRS), which describes the levels of oxygenated hemoglobin and myoglobin in relation to their deoxygenated counterparts, based on infrared light absorption levels (De Blasi, Cope, Elwell, Safoue, & Ferrari, 1993). Metabolite accumulation in skeletal muscle tissue has a documented role in motoneuron inhibition (central drive), as well as the slowed conduction velocity of muscle excitation, a cardinal characteristic of peripheral NM fatigue (Carregaro, Cunha, Oliveira, Brown, & Bottaro, 2013; Kent-Braun, 1999).

Albeit a more novel technique, the use of NIRS is on the rise given its capacity to determine tissue oxygenation levels, and thus, the development of localized muscle fatigue (Perrey, Thedon, & Bringard, 2010). The development of NM fatigue can be described as a "physiological consequence" of prolonged/repetitive muscle contraction, as effects of insufficient blood flow are further exacerbated by energy consumption and metabolite buildup, due to mechanically increased tissue pressure (Sjøgaard, Kiens, Jørgensen, & Saltin, 1986). Increased intramuscular pressure can impede microcirculation of capillary beds providing oxygen necessary for muscle contraction via adenosine triphosphate production (ATP), along with the necessary disposal of metabolic wastes that accumulate during muscle contraction (Jensen, Sjøgaard, Bornmyr, Arborelius, & Jørgensen, 1995). NIRS has thus been employed to quantify fatigue-induced losses in muscle oxygenation in the ergonomics context, specifically in relation to physical tasks (Perrey et al., 2010). Using NIRS, muscle oxygen saturation levels have been differentiated in terms of task load (Hicks, McGill, & Hughson, 1999), in addition to different contraction modalities, such as in concentric (Mantooth, Mehta, Rhee, & Cavuoto, 2018), sustained, and repetitive contexts (Hunter, Griffith, Schlachter, & Kufahl, 2009). For example, in a study examining the effects of power tool use in different work durations, pacing and work-to-rest ratios affected oxygen saturation levels differently for wrist flexors and extensors (Lin, Maikala, McGorry, & Brunette, 2010).

2.4. Psychophysical (perceived) ratings

As NM fatigue cannot be simply explained by a single mechanism or phenomenon, the combined interpretation of multiple measures provide a more comprehensive picture of the development of such a phenomenon. As discussed in sections 1.1 and 1.3, central and perceptional aspects of fatigue are fundamentally significant to the current understanding of its mechanisms. More specifically, the attribute of perceived fatigability is directly related to the psychological state and level of arousal of the individual, in addition to the perception of incoming sensations as fatigue onset occurs during exertion (Kluger et al., 2013). Thus, psychophysical ratings of fatigue obtained via individual reporting of perceived fatigue levels are commonly utilized to provide unique insight into subjective aspects of NM fatigue.

Psychophysical scales have been employed to quantify NM fatigue in terms of subjectively-perceived intensity of fatigue (Micklewright et al., 2017). Such scales account for the continuously changing nature of perceived fatigue by their capacity to obtain subjective fatigue ratings at any time point during a task. The Borg CR-10 rating scale, a discrete 10-point rating from 0-10, has been used to record individual ratings of perceived exertion (RPE), where 0 indicates no exertion, and 10 describes the highest level of exertion ever experienced (Borg, 1990). This scale has been applied to the context of perceived fatigue, labelling fatigue on a discrete 10-point scale, where ratings can be obtained from an individual verbally or visually (Micklewright et al., 2017). The visual analog scale (VAS) allows individuals to report their perceived fatigue as an intensity level at any point of a continuous scale between no fatigue and highest fatigue level ever experienced. Psychophysically-obtained fatigue metrics have been correlated to more objective measures of fatigue discussed in earlier sections; ratings obtained via the Borg CR-10 scale have shown significant correlation to spectral measures of muscle activation (EMG MnPF) (Hummel et al., 2005), as well as declines in force output (Troiano et al., 2008; S. Woods, Bridge, Nelson, Risse, & Pincivero, 2004).

2.5. Psychological co-variates

As discussed above, most measurements that quantify muscle fatigue rely on established, objective techniques that usually involve some form of performance assessment i.e. force output, endurance time. Levels of performance, however, cannot be explained entirely by central and peripheral fatigue processes alone; levels of emotional arousal (Cooke, Cummings, Hancock, Marras, & Warm, 2010), prior experience (Swart et al., 2009), self-efficacy and knowledge of work end-point (Micklewright, Papadopoulou, Swart, & Noakes, 2010) all play distinct roles in individual performance.

Performance begins at a level that the brain perceives to be sustainable for the length of the bout/shift. This subjectively determined level can vary depending on individual motivation and prior experience, which can directly influence the individual's self-efficacy, or self-confidence in his/her ability to perform the task (Noakes, 2012; Schunk, 1995). Furthermore, psychological constructs of motivation and self-efficacy play a prominent role in the perception of incoming fatigue sensations (Kluger et al., 2013), which make subsequent adjustments to the individual's level of performance.

An individual's emotional arousal levels can also influence performance levels in ergonomics assessments (Noakes, 2012; Szalma, 2014). Factors such as boredom and lack of motivation have demonstrated notable influences on the performance of repetitive, somewhat monotonous tasks (Szalma, 2014). Intrinsic motivation, which entails a self-driven initiative for accomplishment, is known to be influenced by perceived levels of autonomy and competence in a specific work task (Szalma, 2014). Thus, levels of motivation and self-efficacy should be considered alongside measures of LMF during the performance of repetitive tasks, given the established relationship between psychological attributes and the task performance outcomes often used to denote LMF.

3. Neuromuscular Fatigue in Ergonomics

As previously discussed, NM fatigue is described in the literature as arising from central and peripheral changes in physiology, and can be quantified using common physiological measures. The development of NM fatigue in relation to the performance of physical tasks will now be discussed. Fatigue literature has labelled this principle as "task-dependency," which describes the development of NM fatigue as dependent on characteristics of the task performed (Barry & Enoka, 2007; Enoka & Duchateau, 2008). Task dependency has been related to central and peripheral fatigue mechanisms (Yung & Wells, 2017); for example, high intensity tasks have been characterized by peripheral factors, such as contractile failure (Westerblad, Bruton, & Katz, 2010), whereas prolonged submaximal tasks involve central aspects of fatigue, such as neural drive (S. Gandevia, 1998). Two task parameters commonly implemented in both industry and research settings are duty cycle and load/intensity, each with documented influences on NM fatigue.

3.1. Duty Cycle

Duty cycle is defined as the duration of a physical task spent in exertion, in proportion to the total duration of the task (Kilbom, 1994; Yung, Mathiassen, & Wells, 2012) (Eq. 1).

Eq. 1. %Duty Cycle = Time performing exertion during Task / Total Time of Task

In essence, this parameter quantifies repetitive physical tasks by the duration of the task time spent performing work. Considering the primary risk factors for physical injury are excessive force, high repetitions, and poor posture, the parameter of duty cycle falls into the duration-related concept of high repetitions, as duty cycle quantifies the work performed in a repetitive task (Chaffin, Andersson, & Martin, 2006). The longer the proportion of time spent in exertion, the higher the risk of injury; thus, with increasing duty cycle (% of time), risk of injury is positively correlated.

An early, seminal study on the parameter of duty cycle assessed its effects on mean endurance limits and times in a static intermittent (repetitive) elbow flexion task, performed for 60-minutes or until volitional fatigue (reference). The study found mean endurance limits (force as a proportion of maximal voluntary contraction (%MVC)) to decrease in conditions of increasing duty cycle (Björkstén & Jonsson, 1977). This early finding provided insight as to the influence of duty cycle on the capacity to produce force in a physical task. Furthermore, this study disproved an earlier claim suggesting a 15%MVC load as an acceptable limit for a continuous static contraction (with no rest); the study results found this value to significantly overestimate this limit, instead suggesting a load limit as low as a "few percent" of the MVC. Limiting factors of this study and its findings include a small sample size (n=8) and large age range (21-37 years) of participants, thus putting into question the rigorousness of results, amidst other confounders, such as age and task/training experience (Enoka & Duchateau, 2008).

A more recent study assessed the effects of varied duty cycle on direct and indirect measures of NM fatigue, including endurance time, force production, EMG amplitude, MnPF, and self-reported ratings of perceived discomfort **(**RPD**)** (Iridiastadi & Nussbaum, 2006). A static intermittent shoulder abduction task was performed at various duty cycles and contraction intensities, for a duration of 60-minutes or until volitional fatigue. Spectral measures of EMG (MnPF) and endurance time were most sensitive to duty cycle changes, in terms of greater rates of fatigue. Lack of randomization (repeated measures design) and doubts regarding a sufficiently-fatiguing protocol and fatigue criteria/standards were raised as limitations of the study and its design.

3.2. Load/Intensity

Load, or contraction intensity, is another common task parameter that has been examined in relation to NM fatigue (Bigland-Ritchie & Woods, 1984; Frey-Law, Looft, & Heitsman, 2012). Loads are often quantified in the literature as a proportion of a maximal contraction or load (Maximal Acceptable Effort (%MAE) or %MVC), providing normalized values that are implemented in the workplace as load limits, for example.

An early review of findings by Rohmert established an inverse exponential relationship between the magnitude of load held in a sustained isometric contraction, and endurance time, which is the duration of time it can be held for (Figure 2.6) (Rohmert, 1973); endurance time is a common task outcome that is used to quantify fatigue development of a specific task. As the load in the task increases, the endurance time, or duration the load is held, exhibits an exponential decrease. Furthermore, associated reductions in maximal force output occurred in correlation to the load magnitude. Considering occupational tasks are more intermittent (repetitive) in reality, the review makes little mention of the relationship of this characteristic to load and endurance time.

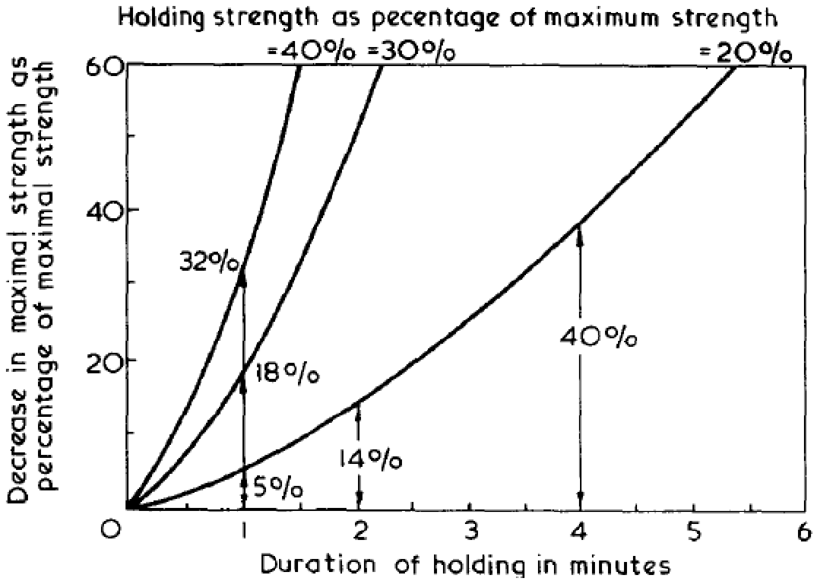

Figure 2.6: Decrease in maximal strength with endurance time during static work (Rohmert, 1973)

A more recent review paper discusses the relationship between load (as a %MVC) and endurance time during intermittent isometric (static) tasks, noting a novel pattern between these two variables (Rashedi & Nussbaum, 2015). As established previously, it is well-documented that NM fatigue generates a reduced capacity to produce force as the task continues; moreover, in intermittent tasks with cycled work and rest components, transient recovery can occur, where the capacity to produce force may exhibit small increases during the rest components that beset the work repetitions. Nonetheless, as the task duration continues, the overall force-producing capacity decreases, until complete recovery occurs. Concerns arise to the generalizability of these findings, considering the data is drawn from empirical studies that are very specific in setting, task, and contraction type.

3.3. Endurance time Studies

The earlier model proposed by Rohmert, as discussed in the previous section, relates the parameter of task load to endurance time, the duration a load can be matched in exertion for (Figure 2.7) (Rohmert, 1973). The model involves an exponential decline in maximal force output over the duration of the task, labelling a 15%MVC load as the fatigue threshold under which contractions can be held continuously without rest. This value was soon contradicted by later models, as loads of even a few %MVC still require some period of rest.

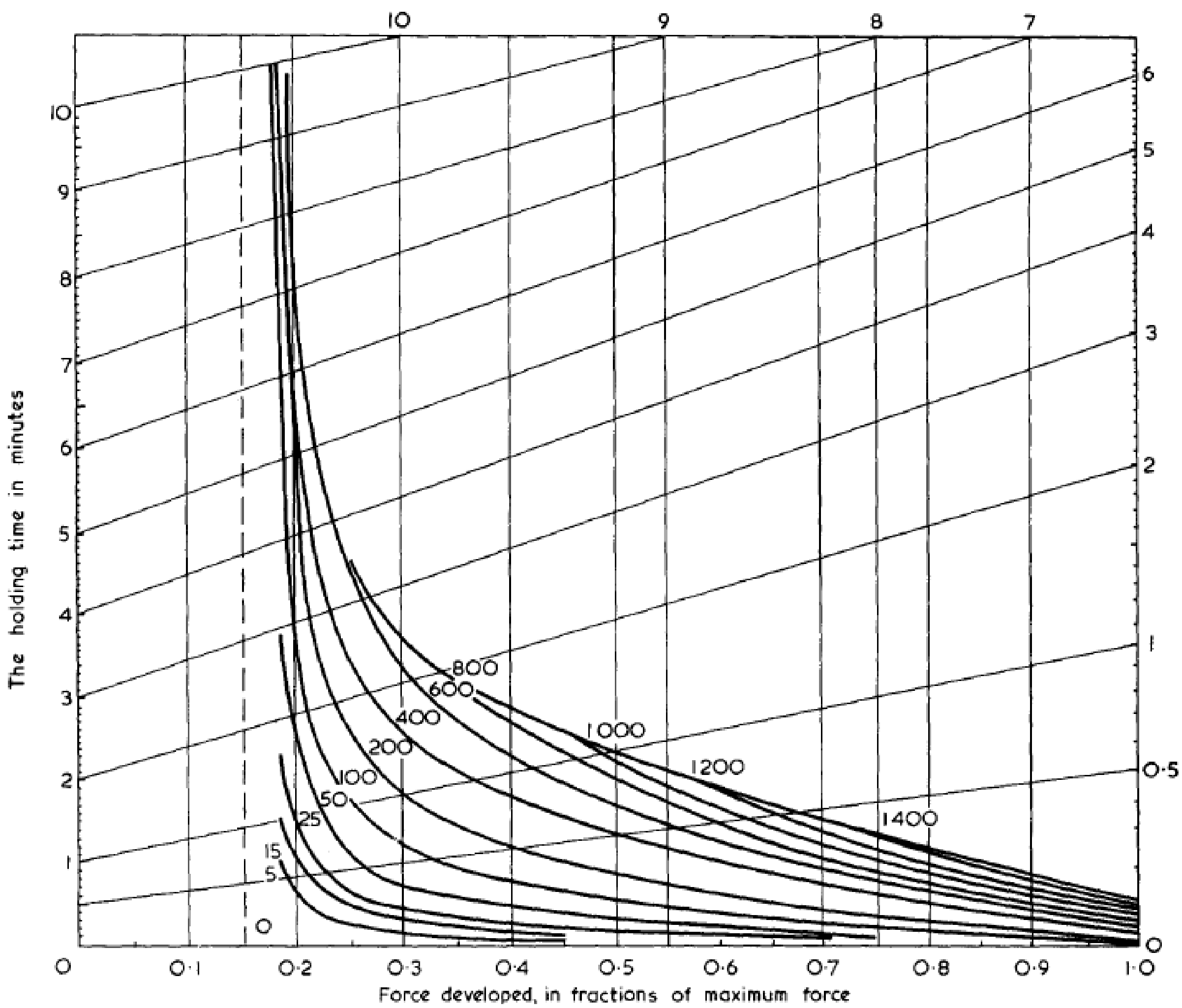

Figure 2.7: Rest allowances (%) for exertions of various force levels and durations (Rohmert, 1973)

In a more recent review, endurance times were compiled for static tasks performed across several body regions as observed experimentally (Frey Law & Avin, 2010). A total of 194 studies were compiled to provide 369 mean endurance time points for isometric tasks performed by a single joint until volitional fatigue. Via meta-analysis, these points were pooled into generalized curves for the ankle, trunk, hand/grip, elbow, knee, and shoulder joints. Joint-specific power and exponential models were developed to predict endurance time for task of specific intensity (%MVC) (Figure 2.8). When compared to the pooled data, the power models were most similar; furthermore, endurance times were found to be significantly different for each joint. Thus, Frey-Law and Avin (2010) conclude a universal model for endurance time across joints may not seem accurate considering the significant variation that exists between joints.

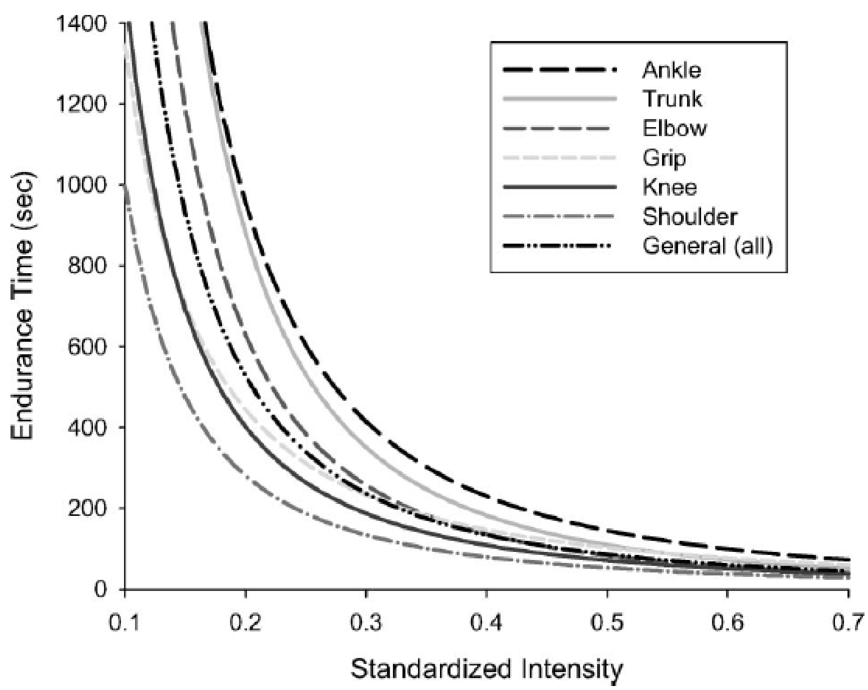

Figure 2.8: Joint-specific power model outputting endurance times for specific intensities (Frey Law & Avin, 2010)

A later study sought to examine whether force variation, a common intervention in the physical workplace, had different effects on a wide array of fatigue measures including endurance time (Yung et al., 2012). Five different conditions of an isometric elbow extension task with identical mean amplitude (15% MVC, 6-second cycle time, and 50% duty cycle) were observed; these conditions included a completely sustained contraction of 15% MVC, as well as varied intermittent contractions ranging from 0-30%MVC, including a sinusoidal force variation. Participants held the sustained contraction condition for the shortest duration of time, while intermittent conditions with amplitude variation allowed for longer endurance times, even without periods of complete rest. For example, the median endurance time for the 0-30%MVC intermittent condition (complete rest periods) exceeded the maximum task duration set by the researchers (60 minutes). Of note, the sinusoidal intermittent condition also exhibited a slower rate of force change compared to the other intermittent conditions.

3.4. Psychophysical studies

The useful insight provided by psychophysical measures, along with its advantageous implementation in experimental and occupational settings, explain the vast number of studies that have analyzed fatigue in this context, in addition to its interaction with physiological manifestations of fatigue. In fact, most occupational standards for physical tasks, as informed by ergonomics guidelines, are designed to not exceed limits acceptable for the 75% of females, which additionally accommodates most males (Waters, Putz-Anderson, Garg, & Fine, 1993).

A thorough review of such psychophysical studies forms the backbone of a predictive model and equation developed by Potvin (2012b). Eight psychophysical studies performed on the upper extremity were included in the analysis, such that provided sufficient training to participants prior to testing, and data on the task timing and frequency for duty cycle to be calculated. Maximum acceptable load/torque/force data were necessary for determining the maximum acceptable effort (MAE) of the specific task. This was determined by respondents after an apportioned period of psychophysical adjustment, where the respondent would determine their individually acceptable load handled over the course of an 8-hour workday. Examples of study tasks include grip tasks, hose insertions, and specific rotation of the forearm. Physiological upper extremity studies were also included for the higher duty cycle range, as only 4 out of the 69 values fell on duty cycles above 0.50. The model outlines psychophysical MAE based on various levels of duty cycle of upper extremity tasks (Potvin, 2012b) (Figure 2.9). Following a negative-exponential curve, the acceptable load decreases as the proportion of work duration increases in the intermittent task. When compared to the empirical study data, RMS difference was 7.2%, with a correlation coefficient of 0.87. However, due to a relative lack of available data for duty cycles above 50% (0.50), the model's predictive value is weaker around the higher part of the curve.

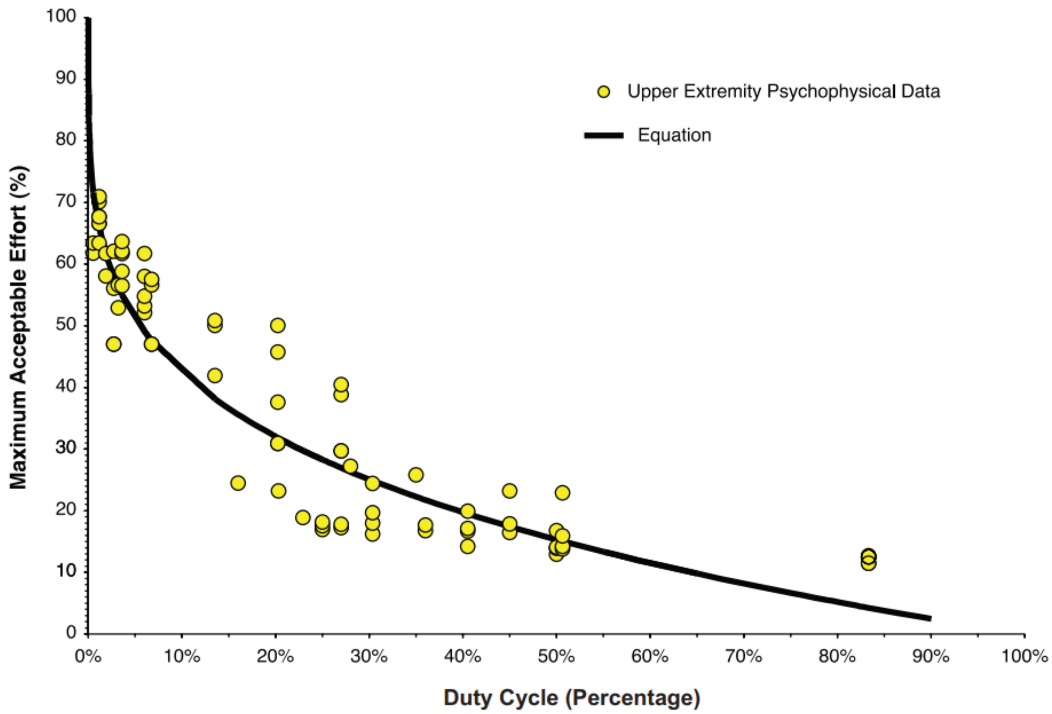

Figure 2.9: Predicted maximal acceptable efforts (% of maximum) of upper extremity tasks per level of duty cycle (Potvin, 2012b)

This psychophysically-informed model was evaluated in a more recent experimental study of a repetitive thumb abduction task, specifically in the duty cycle range of 50% and above (Sonne & Potvin, 2015). Participants performed the task at duty cycles of 50%, 70%, 90%, each at frequencies of 2 and 6 per minute. Results displayed consistent trends with the original model; average MAE values decreased with increasing duty cycle and frequency. In addition, the predictive error (root-mean-square) of the original model decreased once these MAE means were added to the previous data, thus improving the relationship between the model and past studies. Mean MAEs were found to be consistent with physiological studies of high DC (Sonne & Potvin, 2015).

4. Predicting NM Fatigue in Occupational Tasks

Biomechanical modelling of occupational tasks is a commonly employed technique used to quantify and mitigate fatigue-related risks of injury during task performance; these models fall under two distinct approaches, namely, empirical models and theoretical models (Xia & Law, 2008). Empirical models are based on experimental data retrieved from studies performed in a specific context, and can thus be poorly generalizable. Theoretical models predict fatigue development via extrapolation, yet run the risk of oversimplifying the task by failing to include all relevant task-related biomechanical factors and parameters, which may compromise computational efficiency if added. Nonetheless, many validated models exist for ergonomic purposes of predicting NM fatigue.

4.1. 3-Compartment Models

4.1.1. 3-Compartment Model (3CM)

Considering the existing limitations of empirical and theoretical modelling, a novel theoretical model was developed to predict peripheral fatigue of both simple and complex tasks in a "computationally efficient" manner (Frey-Law et al., 2012). The model defines motor units to be in one of three states: resting (M_R), active (M_A), or fatigued (M_F), with each compartment denoting the percentage of total motor units implicated by that state (Figure 2.10). Thus, changes in the collective summation of motor unit activity manifest as the flow of motor units from resting to active to fatigued, then back to resting. Transfer rates between each state are denoted as coefficients of F (fatigue) and R (recovery); motor units flow from resting state to active state via a bi-directional muscle activation-deactivation drive labelled as C(t). Furthermore, recruitment hierarchy (Henneman's size principle) is incorporated via a "last-in-first-out" strategy: slow (S) motor units are recruited first, followed by fast fatigue-resistant (FR), and finally, fast fatigable (FF) motor units; each level of hierarchy consists of its own three-compartment subsystem which differ in transfer rates between the states based on fiber type composition of a muscle. The researchers also went on to demonstrate the model's capacity to predict fatigue at the joint level, where proportion of M_A can depict %MVC, allowing both simple and complex tasks to be modelled. The model has since been validated to predict endurance times for muscles of specific body regions during sustained isometric tasks (Frey-Law et al., 2012)

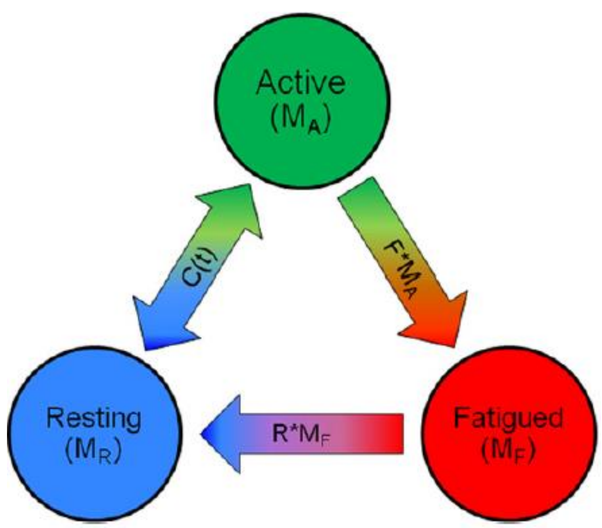

Figure 2.10: 3-compartment model involving the three motor unit states and rates of transfer (Frey-Law et al., 2012)

4.1.2. Modified $3CM_{GMU}$ model (Sonne & Potvin, 2016)

While the 3-compartment (3CM) model proposed by Xia and Frey-Law (2012) has been validated to predict endurance times, it had not yet been validated for complex force histories until a subsequent study performed by Sonne and Potvin (2016). This study sought to validate the 3CM model with empirical data specific to complex force patterns; in addition, the researchers modified the model through the incorporation of several physiological properties related to the recruitment, activation, fatigue, and recovery of graded motor units ($3CM_{GMU}$). Rate of fatigue became a linear function dependent on levels of muscle activation, a factor whose levels were influenced by brain effort level (BE), with these changes reflected in modified fatigue and recovery coefficients ($F_{(i)}$ and $R_{(i)}$). Recruitment and rate coding variables were also modified according to previous models.

A total of nine experimental conditions compiled from five studies were used to compare the performance of the original and modified 3CM models, with seven conditions used to determine the fatigue and recovery coefficients which optimally reduced error between the experimental and modelled data. Participants performed either a cycled hand grip or thumb flexion task held isometrically for either 12 or 15 seconds (two experimental conditions) at a sub-maximal force ranging from 0-45% of MVC, followed by a 2-3 second MVC to observe losses in force. Mean experimental fatigue levels were obtained from two testing conditions to assess performance of the models. The $3CM_{GMU}$ model predicted fatigue levels within 4.1% of MVC for complex force patterns, but performed poorly in predicting endurance times. Results showed the modified model to predict fatigue better than the original model during submaximal tasks of complex force patterns. Moreover, the 3CM models oversimplify motor unit physiology, as a motor unit is assumed to be in one of three states: fully rested, fully active, or fully fatigued.

4.2. Complex motor unit model

Another more recently proposed fatigue model utilized a similar approach in predicting fatigue, describing physiological changes occurring in the responses of individual motor units during prolonged activity (Potvin & Fuglevand, 2017). Using an existing motor unit population model, the authors simulated resting firing rates and isometric forces for a muscle composed of 120 motor units ranging from smaller, low-fatigable to larger, stronger, and more fatigable motor units. Fatigue was simulated both centrally (via firing rate) and peripherally (via force capacity and contraction timing). The authors were interested in potentially differentiating the force contributions and fatigue development of individual MU types across different target forces and contraction types.

Force losses were most pronounced for motor neurons in the upper-middle range (in terms of threshold: MU 60-110), compared to the smallest and largest threshold motor units, as these motor units exhibit greater fatigability than low threshold motor units, as well as longer duration of activity and larger absolute force demands compared to higher threshold motor units (Figure 2.11).

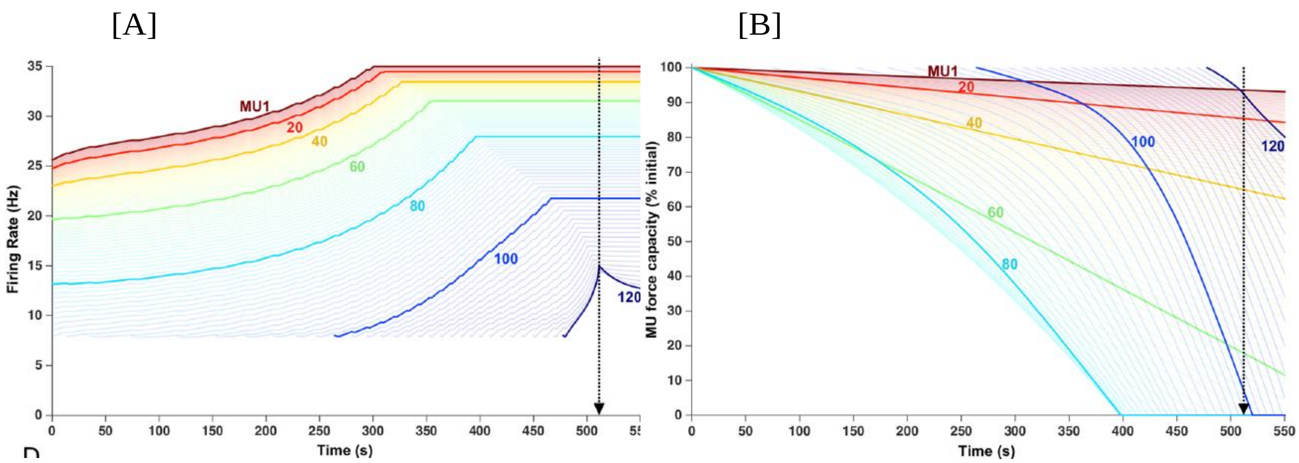

Figure 2.11: Fatigue model output for simulated 20%MVC sustained contraction, denoting [A] firing rate and timing of motor unit recruitment based on threshold, and [B] force losses across the range of motor units (Potvin & Fuglevand, 2017)

While sustained contractions at 15%, 50%, and 85% of MVC attained the same level of overall fatigue, there were notable differences in the composition of motor units fatigued depending on target force, as revealed by the model (Figure 2.12). The low target force contraction induced more fatigue across the motor unit population compared to higher force. Thus, different physiological consequences are implicated by contractions at different target force levels. Finally, endurance times predicted by the model corresponded well with those from pre-existing empirical studies examining different target loads of a sustained isometric contraction, with average and RMS differences amounting to -3.9% and 6.0% of the full range of endurance times.

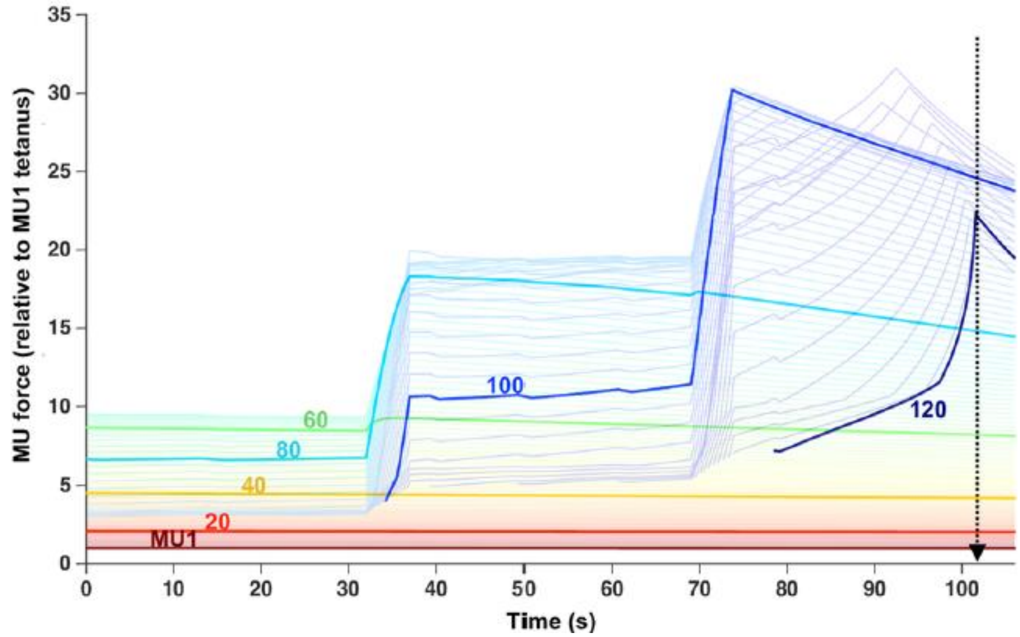

Figure 2.12: Outputs of the fatigue model in a series of progressively higher force plateaus (32-seconds at 20%, 40%, and 60% MVC split by 5-second linear ramps) (Potvin & Fuglevand, 2017)

5. Predicting Acceptable Loads/Duty Cycles in Occupational Tasks

5.1. MAE equation

While numerous models exist to predict muscle fatigue per endurance time and force, even such that extend past this discussion, it becomes fitting to now highlight two predictive formulae that have already been implemented in occupational ergonomics. The psychophysical model proposed by Potvin, as discussed in section 3.4, predicts the maximum acceptable effort (MAE) of intermittent tasks based on said duty cycle level, using psychophysical data compiled from several studies. Potvin developed a mathematical equation (Eq. 2) to predict acceptable load (%MAE) relative to maximum for a given duty cycle:

Eq. 2. $$MAE = 1 - \left[DC - \frac{1}{28{,}800} \right]^{0.24}$$

where MAE depicts the average maximum acceptable effort, with 1.0 representing 100% maximum voluntary effort (MVE). DC represents duty cycle, where 1.0 represents a task with exertion occupying 100% of the task cycle. 28,880 represents the number of seconds in the work period of 8-hours. The best-fit exponent is 0.24, which was determined via a series of regressions to have a correlation coefficient of 0.87, and a root-mean-square difference of 7.2% of MAE (Potvin, 2012a). Since the equation's inception, its applicability to lifting and lowering tasks has been explored (Snook & Ciriello, 1991). Eleven Liberty Mutual psychophysical studies of manual materials handling tasks were assessed, providing 42 lifting/lowering limit values (MAWLs) for which duty cycles were calculated from study data. Calculated duty cycle values were input into the equation to provide MAE values to compare to the empirical values. A similar negative non-linear curve with a correlation of 0.812 and root-mean-square difference of 5.0% MAE was observed. Potvin suggests this bodes well for the equation's potential to be applied to repetitive tasks broader than the context of upper extremity exertions (Potvin, 2012a).

5.2. ACGIH TLV Model

The approach highlighted by Potvin (2012b) was recently utilized by the American College of Governmental Industrial Hygienists (ACGIH®), to form the basis of the official threshold limit values (TLVs) for repetitive upper extremity tasks (ACGIH®, 2016). The TLVs are specified by the ACGIH to apply to the upper extremity, namely the hand/wrist, elbow, and shoulder, and intended for application to cyclical tasks. The TLV equation (Eq. 3) is based on the data from MAE equation, along with newer data from a recent study to support specific fatigue limits for lower exertions below 10% of MAE (duty cycles above 50%):

Eq. 3 $$\%MVC = (100\%) \cdot (-0.143 \ln (DC/100\%) + 0.066)$$

where %MVC indicates percent of maximum strength of the hand/wrist/elbow/shoulder, and DC represents the duty cycle expressed as a percent of task cycle spent in exertion. The equation can also be expressed in terms of DC (Eq. 4); thus, allowing the equation to provide the acceptable force (%MVC) for a given duty cycle, or acceptable DC for a given force (%MVC):

Eq. 4 $$\%DC = (100\%) \cdot e^{((0.066 - (\%MVC/100\%))/0.143)}$$

6. <u>Gaps in Research (i.e. Motivation for Thesis)</u>

Neuromuscular fatigue has been extensively studied through several wide-ranging lenses: from the basic biological processes involved in its development, to the specific modeling of its manifestation in the workplace. Many studies have described the effect of occupational task parameters, such as duty cycle and exertion intensity, on indirect fatigue measures of force output, endurance time, and psychophysical measures, which have combined to shape industry standards in the form of threshold limit values.

However, further research is needed to understand how the human body responds to exposures that are matched with the current threshold limit exposure values. Study 2 of this research thesis aims to assess three workloads with differing DC and load profiles that fall on the ACGIH TLV curve. This study will serve as a valuable validation of our current thresholds, and provide insight into future areas of study that can link the (neuro)physiology of work with occupationally relevant outcomes that can lower the occurrence of work-related injury.

Further investigation and incorporation of more accessible metrics to quantify NM fatigue, including ratings of perceived fatigue (RPF), may also serve a valuable role in helping to characterize the human response to fatiguing workloads. However, this approach has been relatively understudied in comparison to the neurophysiological measures previously discussed, and are often poorly explained or comprehended in laboratory studies evaluating fatigue. Study 1 will evaluate whether measures of RPF can be improved by providing feedback on strength declines.

7. References

ACGIH®. (2016). The American Conference of Governmental Industrial Hygienists. TLVs® and BEIs® based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices.

Adrian, E. D., & Bronk, D. W. (1929). The discharge of impulses in motor nerve fibres. *The Journal of physiology, 67*(2), 9-151.

Barry, B. K., & Enoka, R. M. (2007). The neurobiology of muscle fatigue: 15 years later. *Integrative and comparative biology, 47*(4), 465-473.

Bigland-Ritchie, B., Dawson, N., Johansson, R., & Lippold, O. (1986). Reflex origin for the slowing of motoneurone firing rates in fatigue of human voluntary contractions. *The Journal of physiology, 379*(1), 451-459.

Bigland-Ritchie, B., & Woods, J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & nerve, 7*(9), 691-699.

Björkstén, M., & Jonsson, B. (1977). Endurance limit of force in long-term intermittent static contractions. *Scandinavian journal of work, environment & health*, 23-27.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian journal of work, environment & health*, 55-58.

Carregaro, R., Cunha, R., Oliveira, C. G., Brown, L. E., & Bottaro, M. (2013). Muscle fatigue and metabolic responses following three different antagonist pre-load resistance exercises. *Journal of Electromyography and Kinesiology, 23*(5), 1090-1096.

Chaffin, D., Andersson, G., & Martin, B. (2006). Occupational ergonomics: John Wiley & Sons, New Jersey.

Cooke, N., Cummings, M., Hancock, P., Marras, W., & Warm, J. (2010). *Bored beyond belief: How automation is boring us to distraction.* Paper presented at the Proceedings of the Human Factors and Ergonomics Society 54th Annual Meeting.

De Blasi, R. A., Cope, M., Elwell, C., Safoue, F., & Ferrari, M. (1993). Noninvasive measurement of human forearm oxygen consumption by near infrared spectroscopy. *European journal of applied physiology and occupational physiology, 67*(1), 20-25.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of physiology, 586*(1), 11-23.

Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. *Medicine and science in sports and exercise, 48*(11), 2228.

Frey-Law, L. A., Looft, J. M., & Heitsman, J. (2012). A three-compartment muscle fatigue model accurately predicts joint-specific maximum endurance times for sustained isometric tasks. *Journal of biomechanics, 45*(10), 1803-1808.

Frey Law, L. A., & Avin, K. G. (2010). Endurance time is joint-specific: a modelling and meta-analysis investigation. *Ergonomics, 53*(1), 109-129.

Gandevia, S. (1998). Neural control in human muscle fatigue: changes in muscle afferents, moto neurones and moto cortical drive. *Acta Physiologica Scandinavica, 162*(3), 275-283.

Gandevia, S., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. *The Journal of physiology, 490*(2), 529-536.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological reviews, 81*(4), 1725-1789.

Gardiner, P. (2011). *Advanced neuromuscular exercise physiology*: Human Kinetics.

Hagbarth, K., Kunesch, E., Nordin, M., Schmidt, R., & Wallin, E. (1986). Gamma loop contributing to maximal voluntary contractions in man. *The Journal of physiology, 380*(1), 575-591.

Halperin, I., Copithorne, D., & Behm, D. G. (2014). Unilateral isometric muscle fatigue decreases force production and activation of contralateral knee extensors but not elbow flexors. *Applied Physiology, Nutrition, and Metabolism, 39*(12), 1338-1344.

Henneman, E. (1979). Functional organization of motoneuron pools: the size-principle. *Integration in the nervous system*, 13-25.

Hicks, A., McGill, S., & Hughson, R. L. (1999). Tissue oxygenation by near-infrared spectroscopy and muscle blood flow during isometric contractions of the forearm. *Canadian Journal of Applied Physiology, 24*(3), 216-230.

Hummel, A., Läubli, T., Pozzo, M., Schenk, P., Spillmann, S., & Klipstein, A. (2005). Relationship between perceived exertion and mean power frequency of the EMG signal from the upper trapezius muscle during isometric shoulder elevation. *European journal of applied physiology, 95*(4), 321-326. doi:10.1007/s00421-005-0014-7

Hunter, S. K., Griffith, E. E., Schlachter, K. M., & Kufahl, T. D. (2009). Sex differences in time to task failure and blood flow for an intermittent isometric fatiguing contraction. Muscle & nerve, 39(1), 42-53.

Iridiastadi, H., & Nussbaum, M. A. (2006). Muscular fatigue and endurance during intermittent static efforts: effects of contraction level, duty cycle, and cycle time. *Human factors, 48*(4), 710-720.

Jensen, B., Sjøgaard, G., Bornmyr, S., Arborelius, M., & Jørgensen, K. (1995). Intramuscular laser-Doppler flowmetry in the supraspinatus muscle during isometric contractions. *European journal of applied physiology and occupational physiology, 71*(4), 373-378.

Kamen, G., & Gabriel, D. (2010). *Essentials of electromyography*: Human kinetics.

Kent-Braun, J. A. (1999). Central and peripheral contributions to muscle fatigue in humans during sustained maximal effort. *European journal of applied physiology and occupational physiology, 80*(1), 57-63.

Kilbom, Å. (1994). Assessment of physical exposure in relation to work-related musculoskeletal disorders-what information can be obtained from systematic observations. *Scandinavian journal of work, environment & health*, 30-45.

Kluger, B. M., Krupp, L. B., & Enoka, R. M. (2013). Fatigue and fatigability in neurologic illnesses proposal for a unified taxonomy. *Neurology, 80*(4), 409-416.

Lin, J.-H., Maikala, R. V., McGorry, R., & Brunette, C. (2010). NIRS application in evaluating threaded-fastener driving assembly tasks. *International Journal of Industrial Ergonomics, 40*(2), 146-152.

Mantooth, W. P., Mehta, R. K., Rhee, J., & Cavuoto, L. A. (2018). Task and sex differences in muscle oxygenation during handgrip fatigue development. Ergonomics, 61(12), 1646-1656.

Merletti, R., & Parker, P. A. (2004). *Electromyography: physiology, engineering, and non-invasive applications* (Vol. 11): John Wiley & Sons.

Micklewright, D., Gibson, A. S. C., Gladwell, V., & Al Salman, A. (2017). Development and Validity of the Rating-of-Fatigue Scale. *Sports Medicine, 47*(11), 2375-2393.

Micklewright, D., Papadopoulou, E., Swart, J., & Noakes, T. (2010). Previous experience influences pacing during 20 km time trial cycling. *British journal of sports medicine, 44*(13), 952-960.

Mills, K. (1982). Power spectral analysis of electromyogram and compound muscle action potential during muscle fatigue and recovery. *The Journal of physiology, 326*(1), 401-409.

Noakes, T. D. O. (2012). Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Frontiers in physiology, 3*, 82.

Perrey, S., Thedon, T., & Bringard, A. (2010). Application of near-infrared spectroscopy in preventing work-related musculoskeletal disorders: Brief review. *International Journal of Industrial Ergonomics, 40*(2), 180-184.

Petrofsky, J. S., Glaser, R. M., Phillips, C. A., Lind, A. R., & Williams, C. (1982). Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics, 25*(3), 213-223.

Potvin, J. R. (2012a). An equation to predict maximum acceptable loads for repetitive tasks based on duty cycle: evaluation with lifting and lowering tasks. *Work, 41*(Supplement 1), 397-400.

Potvin, J. R. (2012b). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. *Human factors, 54*(2), 175-188.

Potvin, J. R., & Fuglevand, A. J. (2017). A motor unit-based model of muscle fatigue. *PLoS computational biology, 13*(6), e1005581.

Rashedi, E., & Nussbaum, M. A. (2015). A review of occupationally–relevant models of localised muscle fatigue. *International journal of human factors modelling and simulation, 5*(1), 61-80.

Rohmert, W. (1973). Problems in determining rest allowances: part 1: use of modern methods to evaluate stress and strain in static muscular work. *Applied ergonomics, 4*(2), 91-95.

Schunk, D. H. (1995). Self-efficacy, motivation, and performance. *Journal of applied sport psychology, 7*(2), 112-137.

Sjøgaard, G., Kiens, B., Jørgensen, K., & Saltin, B. (1986). Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. *Acta Physiologica Scandinavica, 128*(3), 475-484.

Snook, S. H., & Ciriello, V. M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics, 34*(9), 1197-1213.

Sonne, M. W., & Potvin, J. R. (2015). A psychophysical study to determine maximum acceptable efforts for a thumb abduction task with high duty cycles. *Ergonomics, 58*(1), 118-127.

Sonne, M. W., & Potvin, J. R. (2016). A modified version of the three-compartment model to predict fatigue during submaximal tasks with complex force-time histories. *Ergonomics, 59*(1), 85-98.

Staudenmann, D., Potvin, J. R., Kingma, I., Stegeman, D. F., & van Dieën, J. H. (2007). Effects of EMG processing on biomechanical models of muscle joint systems: sensitivity of trunk muscle moments, spinal forces, and stability. *Journal of biomechanics, 40*(4), 900-909.

Swart, J., Lamberts, R. P., Lambert, M. I., Lambert, E. V., Woolrich, R. W., Johnston, S., & Noakes, T. D. (2009). Exercising with reserve: exercise regulation by perceived exertion in relation to duration of exercise and knowledge of endpoint. *British journal of sports medicine, 43*(10), 775-781.

Szalma, J. L. (2014). On the application of motivation theory to human factors/ergonomics: Motivational design principles for human–technology interaction. *Human factors, 56*(8), 1453-1471.

Taylor, J. L., Butler, J. E., Allen, G. M., & Gandevia, S. (1996). Changes in motor cortical excitability during human muscle fatigue. *The Journal of physiology, 490*(2), 519-528.

Taylor, J. L., & Gandevia, S. C. (2008). A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *Journal of Applied Physiology, 104*(2), 542-550.

Troiano, A., Naddeo, F., Sosso, E., Camarota, G., Merletti, R., & Mesin, L. (2008). Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait & Posture, 28*(2), 179-186. doi:https://doi.org/10.1016/j.gaitpost.2008.04.002

Tsuboi, T., Sato, T., Egawa, K. i., & Miyazaki, M. (1995). The effect of fatigue caused by electrical induction or voluntary contraction on Ia inhibition in human soleus muscle. *Neuroscience letters, 197*(1), 72-74.

Van Lunteren, E., & Moyer, M. (1996). Effects of DAP on diaphragm force and fatigue, including fatigue due to neurotransmission failure. *Journal of Applied Physiology, 81*(5), 2214-2220.

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics, 36*(7), 749-776.

Westerblad, H., Bruton, J. D., & Katz, A. (2010). Skeletal muscle: energy metabolism, fiber types, fatigue and adaptability. *Experimental cell research, 316*(18), 3093-3099.

Williams, C., & Ratel, S. (2009). *Human muscle fatigue*: Routledge.

Woods, J., Furbush, F., & Bigland-Ritchie, B. (1987). Evidence for a fatigue-induced reflex inhibition of motoneuron firing rates. *Journal of Neurophysiology, 58*(1), 125-137.

Woods, S., Bridge, T., Nelson, D., Risse, K., & Pincivero, D. M. (2004). The effects of rest interval length on ratings of perceived exertion during dynamic knee extension exercise. *Journal of Strength and Conditioning Research, 18*(3), 540-545.

Wu, L.-G., & Betz, W. J. (1998). Kinetics of Synaptic Depression and Vesicle Recycling after Tetanic Stimulation of Frog Motor Nerve Terminals. *Biophysical Journal, 74*(6), 3003-3009. doi:10.1016/S0006-3495(98)78007-5

Xia, T., & Law, L. A. F. (2008). A theoretical approach for modeling peripheral muscle fatigue and recovery. *Journal of biomechanics, 41*(14), 3046-3052.

Yung, M., Mathiassen, S. E., & Wells, R. P. (2012). Variation of force amplitude and its effects on local fatigue. *European journal of applied physiology, 112*(11), 3865-3879.

Yung, M., & Wells, R. P. (2017). Documenting the Temporal Pattern of Fatigue Development. *IISE Transactions on Occupational Ergonomics and Human Factors, 5*(3-4), 115-135.

Chapter 3.

Improving ratings of perceived fatigue relative to objective measures of localized muscle fatigue using a feedback-based familiarization protocol

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1. Introduction

Work-related musculoskeletal disorders of the upper extremity account for 22% of all lost-time injury claims in Ontario (WSIB, 2017). Occupational musculoskeletal overexertion injuries are precipitated by an acute or chronic work task demand that exceeds tissue capacity, and have historically been the leading injury event in the past decade, accounting for 19% of claims in 2017 (WSIB, 2017). Prolonged, repetitive upper extremity work can lead to the development of localized muscle fatigue, which is associated with musculoskeletal overexertion injuries and diminishing performance (Gates & Dingwell, 2010; Kumar, 2001). Thus, the proactive assessment of work tasks to mitigate the accumulation of neuromuscular fatigue is an important requirement in workplace assessments and design.

Localized muscle fatigue (LMF) is typically defined and quantified as a decline in muscle force production capability (Williams & Ratel, 2009). Other modalities can also be used as indicators for LMF, including the analysis of electromyographic (EMG) signals in both the amplitude and frequency domains (Mills, 1982; Petrofsky et al., 1982). With the development of LMF being a complex, multi-dimensional process, it is also recommended to consider the psychological component, in concert with muscle-specific manifestations of force and activation, for a more holistic description of LMF (S. C. Gandevia, 2001).

Psychophysical ratings of perceived fatigue (RPF) can provide unique insight into the subjective components of neuromuscular fatigue (Micklewright et al., 2017). RPF has been utilized in several studies, administered primarily via a modified Borg CR-10 scale (Borg, 1990), and has correlated well to the more traditionally-used fatigue metrics of muscle activation (i.e. EMG amplitude [aEMG] and mean power frequency [MnPF])

(Hummel et al., 2005) and reduction in strength (Troiano et al., 2008). RPF scores have further demonstrated a significant relationship with force reduction during complex work-recovery profiles of intermittent thumb flexion efforts, providing instantaneous estimates of localized fatigue (Whittaker, Sonne, et al., 2019). Using this psychophysical approach, the individual can use their perception of his/her own fatigue to provide an additional and non-invasive approach for assessing NM fatigue in the workplace, and in the laboratory. (Noro & Imada, 1991; Yeung, Genaidy, Karwowski, & Leung, 2002).

Despite the potential utility of RPF in both occupational laboratory settings, the provision of RPF scale familiarization is inconsistent in the literature. While scales used to obtain RPF scores, such as the Borg CR-10 scale, encompass discrete points anchored by minimum (e.g. 0 - *no fatigue at all*) and maximum (e.g. 10 – *maximum fatigue*) values (Borg, 1990; Micklewright et al., 2017), individuals unfamiliar with the scale may not be calibrated to these values conceptually without prior scale familiarization (Sood, Nussbaum, & Hager, 2007).

As such, the purpose of this study was to determine whether a period of familiarization to the RPF scale can improve the accuracy of these subjective ratings in relation to measures of strength and muscle activation. This familiarization consisted of regular online feedback, pertaining to a reduction in muscle strength, as individuals progressed through a fatiguing isometric elbow flexion protocol. It was hypothesized that the error (average and root-mean-square) between RPF and aEMG, MnPF, and MVC would decrease for individuals that underwent this RPF familiarization period, relative to a control group that received no such feedback on their instantaneous levels of muscle fatigue.

2. <u>Methods</u>

2.1. Participants

Twenty participants (10 M and 10 F) were recruited from a convenience sample at the university. Each participant was randomly assigned to one of two groups: the control (no feedback) group or the experimental (feedback) group. Each group consisted of equivalent numbers of males and females (Table 3.1). Exclusion criteria included history of acute or chronic upper extremity pain, injury, or surgery within one year prior to the data collection. Participants provided written and verbal consent before their commencement in the study, and were asked to follow similar dietary and caffeine intake before each session, while refraining from upper extremity resistance exercise to ensure adequate recovery between sessions. All portions of this study were approved by the university's research ethics board.

Table 3.1: Mean values for participant demographics (standard deviation)

Group	Age (years)	Height (cm)	Weight (kg)
Feedback (n=10)	21.1 (1.5)	166.4 (12.1)	66.0 (14.1)
Males (n=5)	21.6 (2.1)	176.6 (6.2)	77.6 (9.8)
Females (n=5)	20.6 (0.5)	156.2 (5.4)	54.4 (3.2)
Control (n=10)	21.4 (1.3)	172.6 (10.2)	77.1 (15.9
Males (n=5)	21.6 (1.5)	181.8 (1.6)	87.7 (15.5)
Females (n=5)	21.2 (1.3)	163.3 (4.3)	66.5 (6.9)

2.2 Instrumentation & Data Acquisition

2.2.1 Surface electromyography (sEMG)

Surface electromyography (sEMG) was used to collect muscle activity of the biceps brachii. Disposable bipolar Ag/AgCl surface electrodes with foam adhesive hydrogel (disc-shaped, 3 cm radius) (Meditrace 130, Kendall, Mansfield, MA, USA) were placed on the skin overlying the muscle after shaving with a disposable razor and sanitizing with an isopropyl alcohol swab. Electrodes were placed on the muscle belly at an inter-electrode distance of 6 cm, as based upon previously established standards (Stegeman & Hermens, 2007). sEMG was recorded using a Bortec AMT-8 surface electromyography (sEMG) system (Bortec, Calgary, AB, Canada), and the signal was amplified (AMT-8, Bortec, Calgary, AB, Canada) and sampled at 2000 Hz using a 16-bit A/D conversion system (ODAUIII, Northern Digital Inc., Waterloo, ON, Canada). Muscle activity was normalized to maximum voluntary excitation (MVE), elicited during three repetitions of an isometric maximum voluntary contraction (MVCs) for elbow flexion and extension in the same posture used during the experiment. Signal bias was removed by subtracting the average voltage obtained during a resting/quiet trial.

2.2.2 Dynamometry

All force measurements were conducted using a six-degree of freedom PY6-500 transducer (Bertec, Columbus, OH, USA) sampled at 1000 Hz. The transducer was mounted to a rigid vertical piece of 80/20 slotted rail, and affixed to the participant using a padded cuff placed at the mid-point of the forearm. Force and sEMG data were collected continuously and synchronously using customized LabVIEW software (National Instruments, Austin, TX, USA) on a PC-compatible computer.

2.2.3 Ratings of Perceived Fatigue (RPF)

Ratings of perceived fatigue (RPF) were obtained visually using a modified Visual Analogue Scale (VAS) (Micklewright et al., 2017). The scale was provided to participants as a continuous sliding linear scale on customized LabView software. Using a mouse, participants dragged the slider to indicate their perceived level of fatigue at any point between no perceived fatigue and maximal level of fatigue. Previous research has found no clinically relevant differences between subjective measures obtained in a digital format in comparison to traditional, paper-based VAS assessment methods (Delgado et al., 2018).

2.2.4 Psychological Assessments

2.2.4.1 Intrinsic Motivation

Motivation for task performance was assessed post-fatigue protocol completion/termination using three subscales from the Intrinsic Motivation Inventory (IMI): the interest and enjoyment subscale (7 items), perceived competence subscale (6 items) and effort/importance subscale (5 items) (Ryan, 1982). Each item is rated using a 7-point Likert-type scale, ranging from 1 (*not at all true*) to 7 (*very true*). An example item from the interest and enjoyment subscale is: "I enjoyed doing this activity very much." An example item from the effort/importance subscale asked participants to respond to this statement: "It was important to me to do well at this task." All subscales met conventional standards of internal consistency (alpha > 0.70).

2.2.4.2 Task Self-Efficacy

During the second and third sessions, self-efficacy for protocol completion, relative to baseline (first session), was assessed verbally using a modified version of the TSE scale (11 items) (Bandura, 2006). Immediately after the first cycle and middle cycle (based on total cycles completed in the 1st session), participants were asked, *"From 0, meaning not confident, to 10, meaning totally confident, how confident are you in your ability to go longer than last time?"*

2.3 Experimental Procedures & Protocol

2.3.1 Design

Both the control and feedback groups performed an intermittent, isometric elbow flexion fatigue protocol in three separate sessions. Each session was separated by at least 3 days, with efforts undertaken to test at equivalent times of day to control for diurnal variability (Chtourou et al., 2011). Both groups performed an identical protocol during the first session (day 1) to provide baseline measures. In the second session (day 2), participants in the feedback group received online feedback pertaining to their decline in strength upon subsequent MVC exertions, throughout the entire fatigue protocol. In the final session (day 3), all participants conducted an identical fatigue protocol as in the baseline (day 1), to test for any retention effects. In the above protocol, participants in the control group performed identical fatigue protocols for three consecutive sessions (Figure 3.1). Each experimental session entailed experimental setup, baseline measures, a fatigue protocol, and recovery protocol.

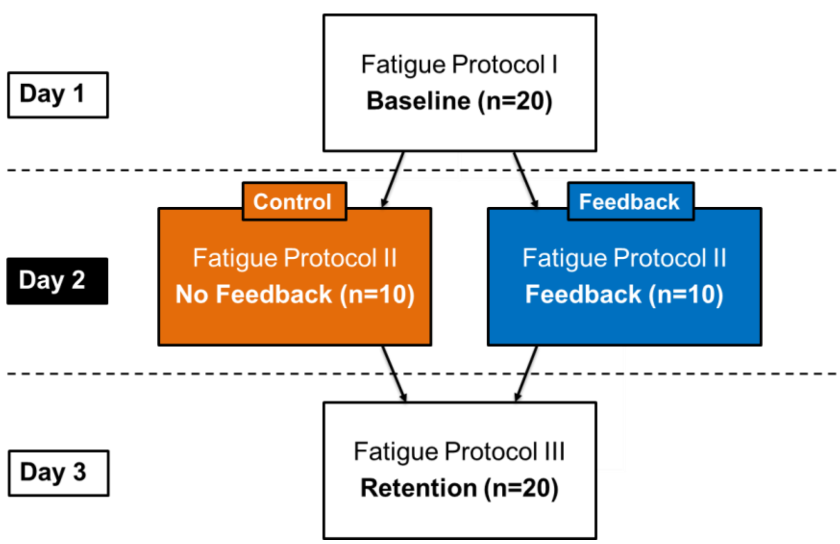

Figure 3.1: Pre-test post-test repeated measures design of study, with control group in *orange*, and feedback group in *blue*

2.3.2 Setup

Surface electrodes were placed after the skin was abraded and cleaned with a disposable razor and alcohol swabs. Participants were then seated facing a height-adjustable table that supported the dominant arm at 90° of shoulder and elbow flexion. From a supinated forearm position, participants performed isometric elbow flexion against a padded cuff chained to the force transducer and affixed to the middle of the forearm (Figure 3.2). Using visual feedback presented on a computer monitor, participants were informed of the timing and contraction level (relative to maximum) that characterized the fatigue protocol.

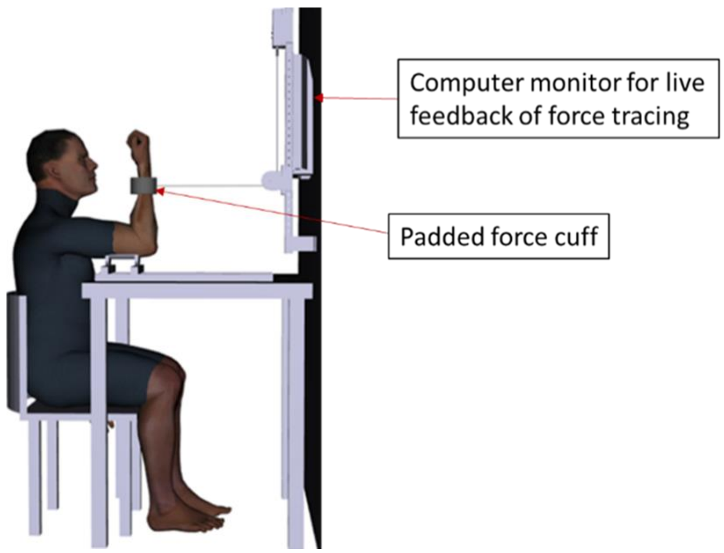

Figure 3.2: Experimental set-up outlining participant position, 6-DOF force transducer, and computer monitor for online force tracing

2.3.3 Baseline

Baseline strength and peak EMG amplitude of the biceps brachii were obtained via 3 separate maximal voluntary contraction (MVC) tests. Participants were instructed to perform maximal supinated elbow flexion (targeting biceps) against the force transducer with a one-minute rest period separating each MVC. In addition, three reference contractions were conducted at the same relative intensity of the force plateaus in the fatigue protocol (i.e. 50% of MVC) to provide a baseline measure of mean power frequency (MnPF) and EMG amplitude. Lastly, baseline rating of perceived fatigue and exertion were obtained from the participant.

2.3.4 **Fatigue Protocol**:

The fatigue protocol involved an intermittent elbow flexion task performed at a duty cycle of 50% and relative contraction intensity of 50%MVC (Figure 3.3). Performing a repetitive task at these duty cycle and relative MVC levels was expected to lead to a significant manifestation of muscle fatigue (ACGIH®, 2016; Potvin, 2012b). Repetitive efforts were completed in 5-minute cycles, with 4 minutes of exertion followed by a 1-minute resting period where RPF and strength (MVC test) measures were obtained. Work cycles were performed until volitional fatigue, or until 60-minutes (12 cycles) had elapsed. During day 2, the experimental group was provided with visual online feedback pertaining to their strength decline, relative to baseline MVC, following each MVC test performed between cycles (every 5-minutes) (Figure 3.4).

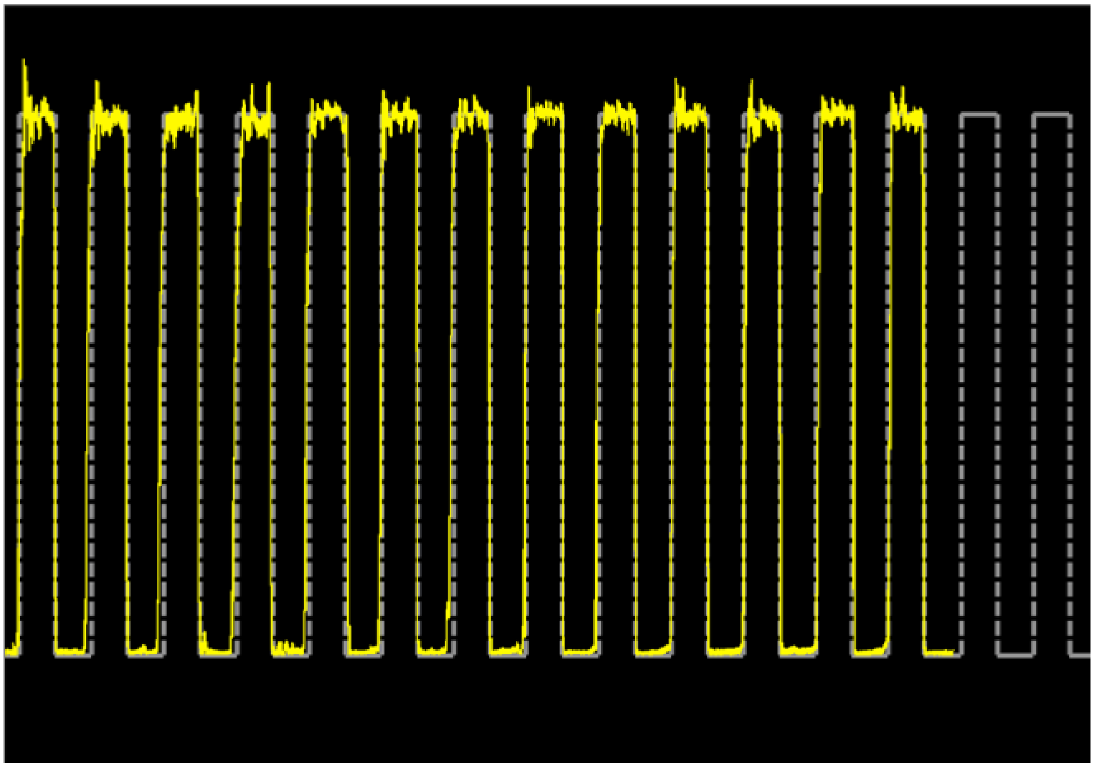

Figure 3.3: The online presentation of the force tracing profile. Participants were instructed to match their force output (represented by scrolling yellow line) with the force template (dotted grey line) scaled to 50% of baseline elbow flexion MVC.

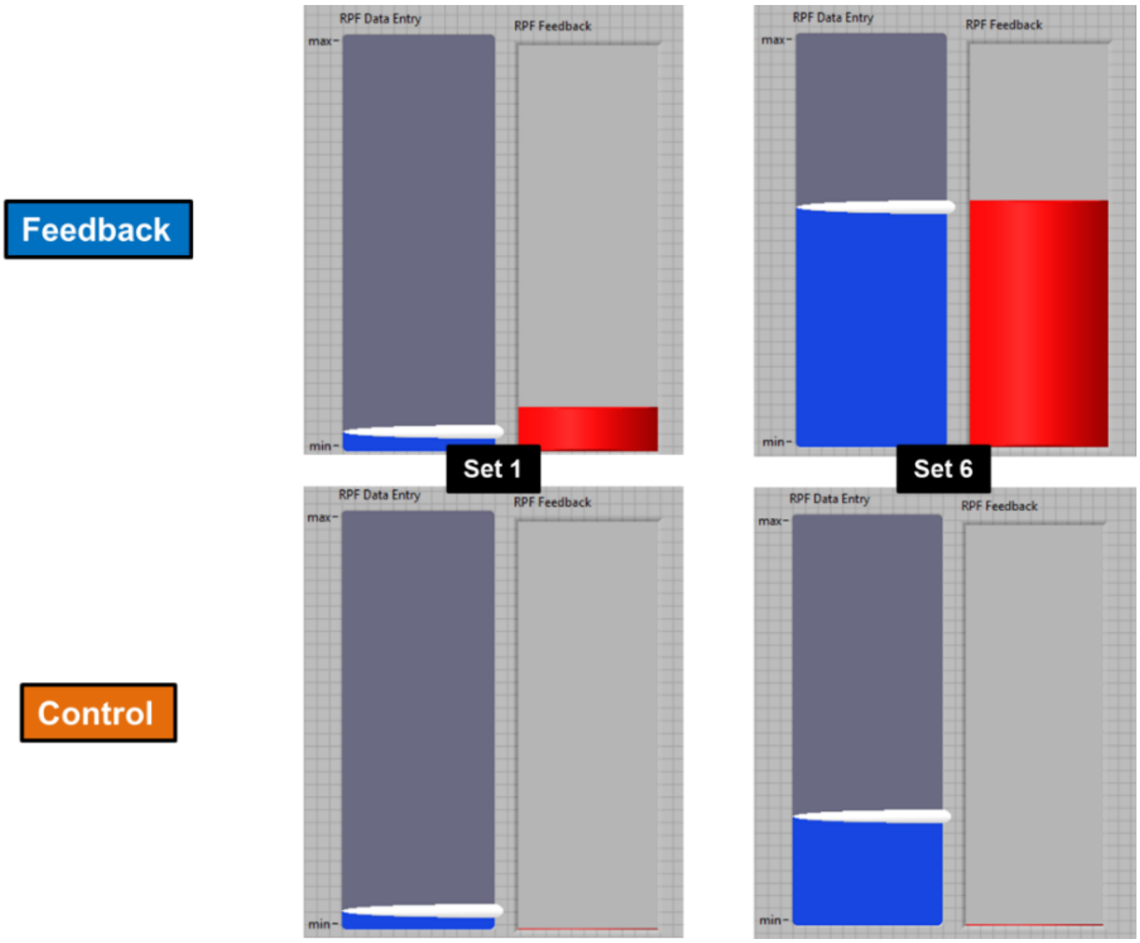

Figure 3.4: Following each cycle, RPF was rated by all participants using the blue modified visual analog scale slider. This was immediately followed by an MVC exertion. During day 2, the feedback group (top 2 images) received information (via the red gauge) on how much their MVC had declined from baseline. For example, a 10% decrease in MVC would be indicated to the participant as shown by the *red* bar of the top left image, compared to a 60% decrease in MVC in the top right image. The control group (bottom images) did not receive any such feedback on their MVC decline at any time points.

2.4 Data Analysis

sEMG signals were rectified using a root-mean-square (RMS) window of 0.5 seconds. RMS amplitude and MnPF, computed from a fast fourier transform, were taken from a 1-second window during the final plateau of each cycle. aEMG amplitude was normalized to peak RMS activation obtained at baseline. Each MnPF value was normalized to baseline

MnPF, which was computed as the average MnPF of the three reference contractions recorded while rested. All force signals were smoothed using a 1-second moving average and normalized to peak elbow flexion strength obtained during baseline MVC trials. RPF ratings were also expressed relative to baseline ratings. All fatigue measures were rubber-banded in the time domain (time-normalized) via 2^{nd} order polynomials, as employed in previous research to normalize fatigue measures with individual variability in performance times (La Delfa, Sutherland, & Potvin, 2014). As MnPF and MVC values would be expected to decrease under fatiguing conditions, each of these variables were multiplied by -1, such that a decrease in MnPF or MVC with fatigue would be expressed as a 'fatigue unit' that increased from 0 (rested). Therefore, all variables were normalized to baseline and shared a common directionality with fatigue, which allowed for more appropriate error calculations with normalized RPF.

2.5 Statistical Analysis

The dependent variables for this study were the average (i.e. constant) error and root mean square error (RMSE) between normalized RPF and: 1) strength (MVC), 2) aEMG, and 3) MnPF. A 2 (group) x 3 (day) x 3 (time – start, middle, end) repeated measures mixed MANOVA was used to assess differences in average error for RPF-MVC, RPF-aEMG and RPF-MnPF dependent variables. Differences in RMSE were assessed via another repeated measures mixed MANOVA following a 2 (group) x 3 (day) design. Significant score differences of the IMI subscales (interest and enjoyment (IE), perceived competence (PC), and effort/importance (EI)) were determined via a 2 (group) x 3 (day) RM MANOVA design. A separate univariate ANOVA was used to assess differences in TSE scores (2 [group] x 2 [time – start & midway] x 3 [day]).Univariate ANOVAs were conducted for significant dependent variables from each MANOVA, with Tukey's post-hoc comparisons then conducted on significant interactions and main effects. All statistical tests were conducted at an α level of $p < 0.05$. Partial-eta-squared effect sizes were computed, with values greater than 0.06 and 0.14 considered medium and large, respectively (Field, 2013).

3. Results

A significant 3-way MANOVA interaction was found for RPF-MVC, RPF-aEMG, and RPF-MnPF average error ($F = 2.761$, $p < 0.01$, $\eta^2 = 0.135$). For RMSE, a significant 2-way (group x day) interaction was also found for the above three variables ($F = 2.739$, $p < 0.05$, $\eta^2 = 0.195$).

3.1. Maximum Voluntary Contraction vs. RPF

Upon subsequent univariate testing, a significant 3-way interaction was found for RPF-MVC average error ($F = 9.060$, $p < 0.005$, $\eta^2 = 0.335$). Average error between RPF ratings and strength (MVC) declines varied significantly between control and feedback groups across both time and day (Figure 3.5). The feedback group had 67% less error between RPF and MVC at the end of day 2, and 97% less average error between these measures at the end of day 3.

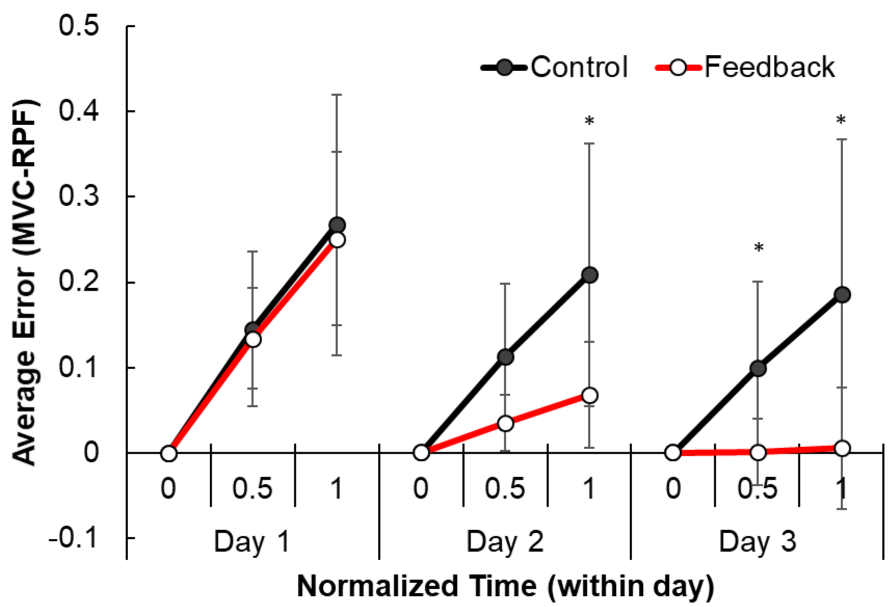

Figure 3.5: Average error for RPF-MVC across days for control (*black*) and feedback (*red*) groups. (*) indicates significant difference between control and feedback group (p<0.05). Error bars indicate standard deviation.

A significant 2-way interaction was observed for RMSE between RPF and MVC ($F= 5.388$, $p < 0.01$, $\eta^2 = 0.230$). RMSE between RPF and MVC showed significant difference across days for the control and feedback groups (Figure 3.6). RMSE for the feedback group was 65% and 72% lower than the control group for days 2 and 3, respectively.

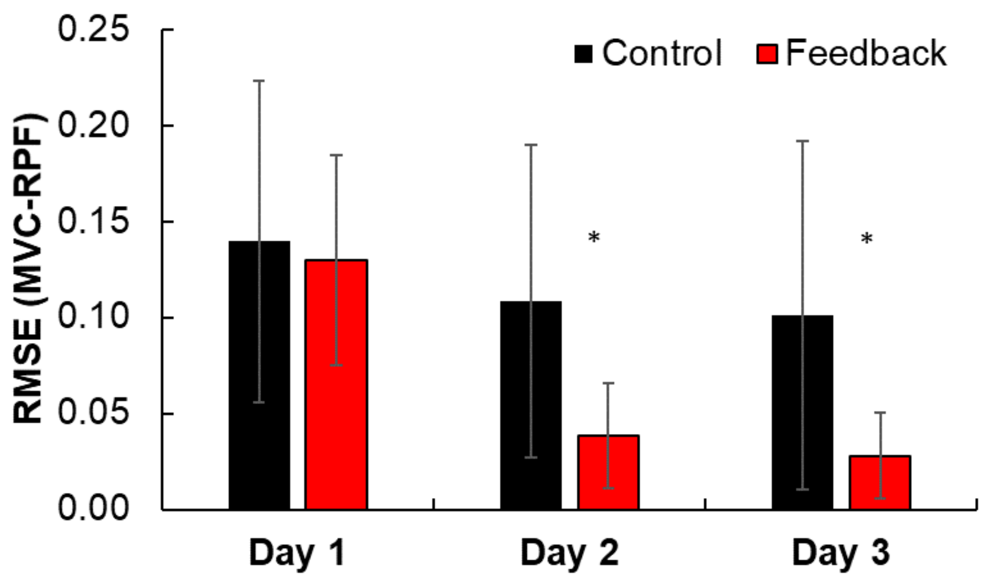

Figure 3.6: RMSE for RPF-MVC across days for control (*black*) and feedback (*red*) groups. (*) indicates significant difference between control and feedback groups ($p<0.05$). Error bars indicate standard deviation.

3.2. MnPF vs RPF

A significant 3-way interaction was observed for average error between RPF and MnPF ($F = 6.172$, $p < 0.05$, $\eta^2 = 0.255$) (Figure 3.7). Average error (RPF-MnPF) was 51% lower for the feedback group at the end of the second session (day 2) and 71% lower at the completion of the third session (day 3).

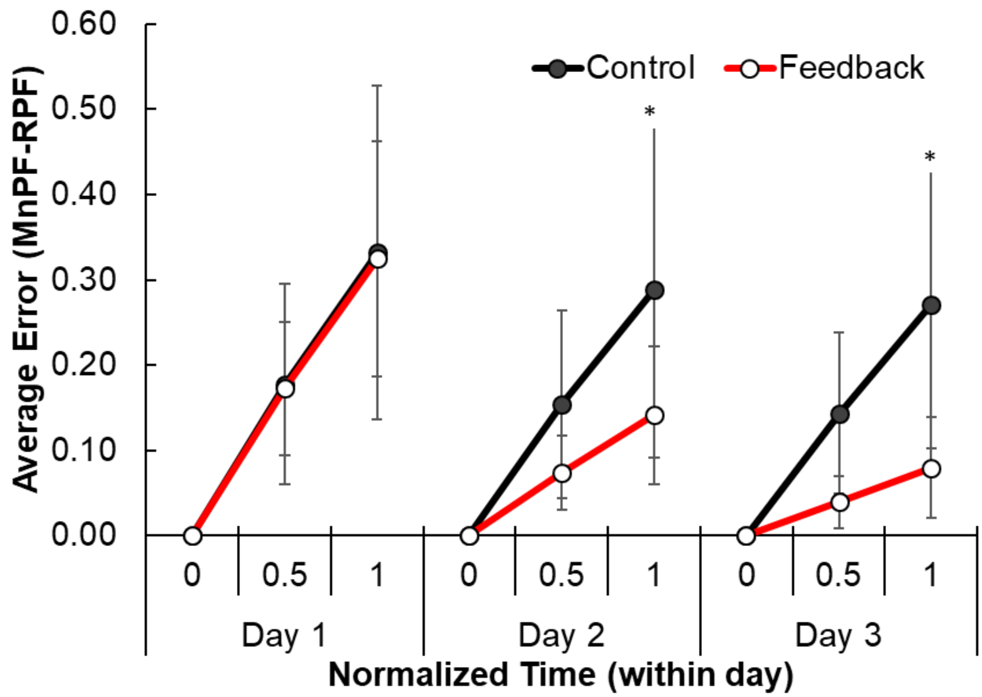

Figure 3.7: Average error for RPF-MnPF across days for control (*black*) and feedback (*red*) groups. (*) indicates significant difference between control and feedback groups ($p<0.05$). Error bars indicate standard deviation from the mean.

There was a significant 2-way interaction between group and days for RMSE ($F = 5.534$, $p < 0.01$, $\eta^2 = 0.235$). RPF-MnPF RMSE values for the feedback group were 50% and 69% lower than the control group on days 2 and 3, respectively (Figure 3.8).

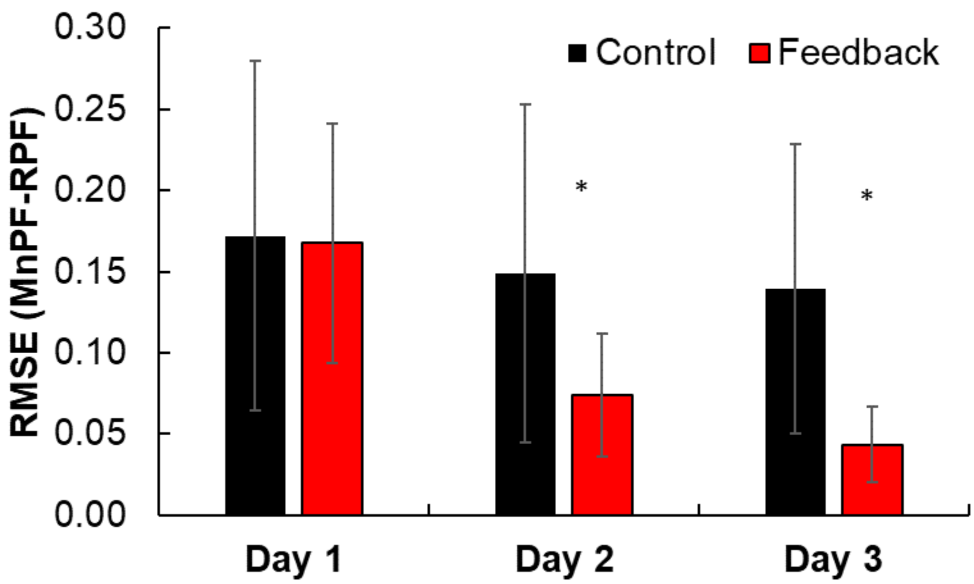

Figure 3.8: RMSE for RPF-MnPF across days for control (*black*) and feedback (*red*) groups. (*) indicates significant difference between control and feedback groups ($p < 0.05$). Error bars indicate standard deviation.

3.3. aEMG vs RPF

Univariate ANOVAs for average error (Figure 3.9) and RMSE (Figure 3.10) between aEMG and RPF did not return any significant effects or interactions.

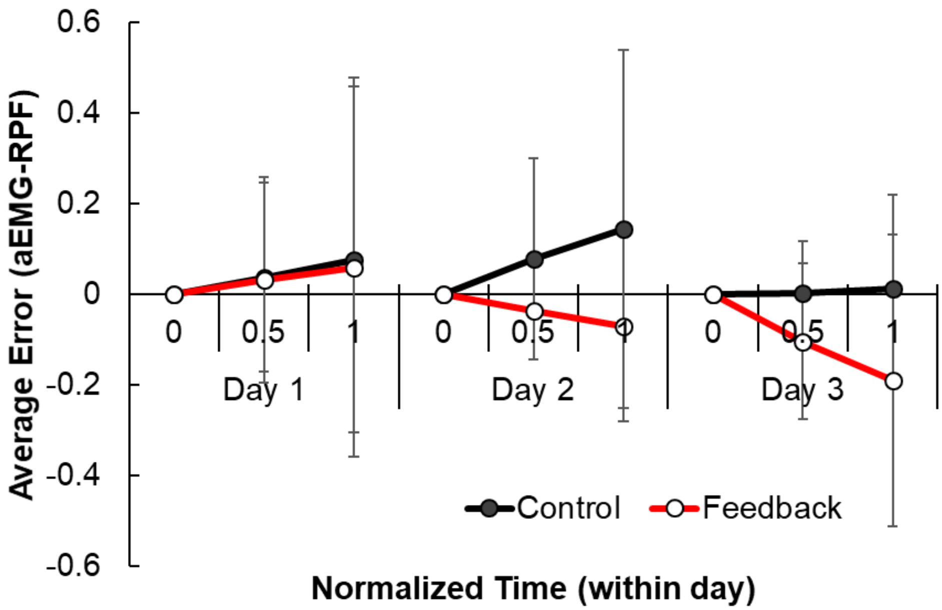

Figure 3.9: Average error for RPF-aEMG across days for control (*black*) and feedback (*red*) groups. Error bars indicate standard deviation.

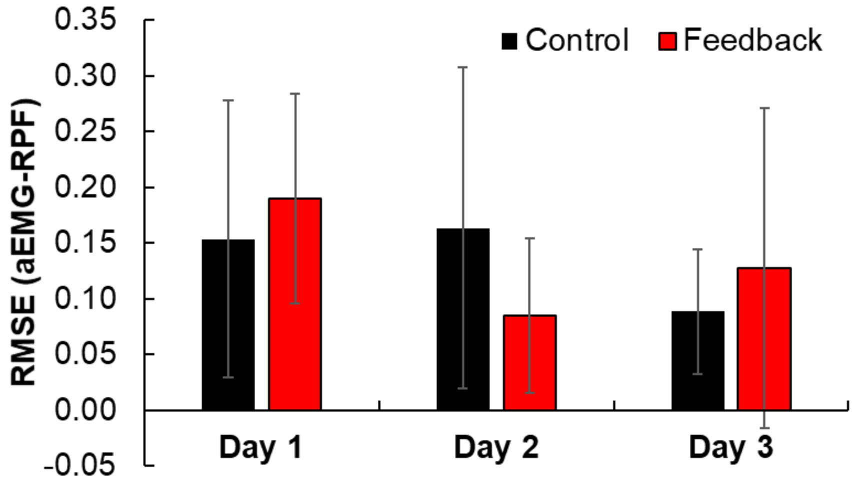

Figure 3.10: RMSE for RPF-aEMG across days for control (*black*) and feedback (*red*) groups. Error bars indicate standard deviation.

3.4. Psychological Assessments

The MANOVA did not return any significant effects or interactions for all IMI subscales and TSE scores between the groups across days (Table 3.2).

Table 3.2: Mean (standard deviation) scores & F-values for significant differences between groups

	Control	Feedback	F	p
Endurance Time - 1 (min)	31.5 (10.8)	31.5 (15.8)	1.506	0.235
Endurance Time - 2 (min)	33.5 (13.7)	42.5 (14.0)		
Endurance Time - 3 (min)	30.0 (11.1)	36.0 (17.0)		
IMI - Interest & Enjoyment - 1	4.54 (1.5)	4.81 (1.6)	0.282	0.756
IMI - Interest & Enjoyment - 2	4.31 (1.5)	4.60 (1.5)		
IMI - Interest & Enjoyment - 3	4.32 (1.5)	4.37 (1.6)		
IMI - Perceived Competence - 1	4.55 (0.8)	4.77 (1.5)	1.660	0.204
IMI - Perceived Competence - 2	4.15 (1.4)	4.72 (1.5)		
IMI - Perceived Competence - 3	4.87 (1.2)	4.48 (2.1)		
IMI - Effort/Importance - 1	6.30 (0.8)	6.28 (0.7)	0.024	0.977
IMI - Effort/Importance - 2	6.22 (1.0)	6.16 (0.7)		
IMI - Effort/Importance - 3	6.42 (0.9)	6.34 (0.6)		
TSE - Day 2 Start	5.0 (3.1)	5.6 (2.3)	0.013	0.910
TSE - Day 2 Midway	4.5 (3.4)	5.1 (1.9)		
TSE - Day 3 Start	5.5 (2.7)	5.8 (2.0)	0.013	0.910
TSE - Day 3 Midway	4.5 (3.2)	4.70 (2.2)		

4. Discussion

This study sought to explore the effect of targeted performance feedback on the accuracy of self-reported ratings of perceived fatigue (RPF), relative to currently accepted indicators of localized muscle fatigue. Specifically, we hypothesized the error (average and RMS) would decrease between RPF and MVC, aEMG, and MnPF, in the experimental group, after receiving this feedback on the second day. Consistent with our hypotheses, average error and RMSE, between RPF and measures of strength (MVC) and muscle MnPF, decreased for participants in the feedback group; average and RMSE values were significantly lower for the feedback group when compared to control group error values. These improvements in error also occurred in the absence of any changes in motivation, task self-efficacy or endurance time. Thus, this study shows how effective a period of RPF familiarization can be in terms of its predictive utility as a psychophysical fatigue measure.

Previous studies have not established a consistent relationship between subjective ratings of fatigue and indicators of LMF in the myoelectric domain (i.e. EMG RMS or MnPF). While subjective perceptions of exertion and upper trapezius MnPF were closely related during an isometric shoulder elevation fatigue protocol (Hummel et al., 2005), these measures were incongruent during a study that assessed upper trapezius median frequency and the subjective perceptions of fatigue by violinists performing practice sessions (Chan et al., 2000). Another study failed to find a correlation between EMG estimates and subjective perceptions of cervical muscle fatigue during maximal voluntary contractions, despite subjective assessments returning higher reliability across days compared to EMG estimates (Strimpakos, Georgios, Eleni, Vasilios, & Jacqueline, 2005). Despite a lack of consistency in these findings, a secondary analysis of this dataset shows no significant differences in the slope of MVC decline and EMG MnPF between days, indicating their overall reliability as indicators of LMF progression (La Delfa et al., 2019).

Incongruent with our hypotheses, however, was the lack of improvements in error (average and RMSE) between RPF and aEMG. While Borg CR-10 ratings of subjective fatigue have been significantly related to changes in RMS EMG during isometric fatigue of the upper trapezius muscle (Troiano et al., 2008), several theories exist as to why the trends of these measures did not match as consistently as expected. Since the EMG-force relationship can be non-linear (Kamen & Gabriel, 2010), and strength-specific feedback was provided to participants in the feedback group, it may be possible that the provision of EMG-specific feedback may have impacted the error between RPF and EMG amplitude differently. Furthermore, a known adaptation to muscle fatigue is the increase in synergist recruitment to compensate for agonist fatigue (Enoka, 1995). Such is the case with the brachioradialis during periods of elbow muscle fatigue (Belhaj-Saif, Fourment, & Maton, 1996). Decreased co-activation of antagonists can also occur during agonist fatigue, as decreased neural drive to the unfatigued antagonist was reported during fatigue of the agonist at the elbow joint (Kennedy, McNeil, Gandevia, & Taylor, 2013). The lack of EMG-specific feedback and diversity of activation strategies may help explain why RPF was not as aligned with aEMG as it did with the other indicators of LMF in this evaluation

Participants in the feedback group rated their muscle fatigue more accurately, relative to their actual strength decline, compared to their counterparts in the control group. Of note, improvements in accuracy continued to the retention day 3, where feedback cues were not provided (RMSE of RPF-MVC was 72% lower for the feedback group). This is an important finding considering the intuitive and non-invasive nature of RPF as a tool to assess LMF. Thus, RPF assessments can be easily implemented in laboratory and occupational settings – especially considering myoelectric and force measures may carry practical and methodological limitations. The necessary costs and expertise to employ such fatigue measures may limit usability in the field. These findings, along with data demonstrating the strong relationship of RPF and force declines during repetitive work with varied work-rest profiles, should validate concerns regarding the subjective nature of RPF ratings, thus confirming RPF as a viable metric in diverse settings (Whittaker, Sonne, et al., 2019).

In laboratory evaluations, these results would suggest experimenters interested in using RPF as an indicator for LMF should include a familiarization session on a separate day, which may not be feasible in some cases where time and/or equipment for familiarization is limited. There may be differences in the readiness of individuals to respond to familiarization, perhaps causing some people to require a longer bout to be familiarized, considering it still remains a subjective estimate of perceived fatigue. For the purposes of this study, RPF was considered in isolation from potential psychological confounders such as training experience and/or resistance training history. However, differences in levels of intrinsic motivation and task self-efficacy were minimal between groups. This was an important finding, as these psychological elements have been shown to influence task performance (Noakes, 2012; Schunk, 1995; Wilmore, 1968).

Future studies could involve the implementation of a transfer task as a third session to confirm whether the effect of familiarization is elbow flexion specific, or whether a similar period of RPF training using biceps LMF can be transferable to LMF elsewhere in the body. The latter scenario would allow for robust implementation outside of the laboratory, and make a valuable non-invasive measure of LMF more accessible in ergonomics field evaluations. Future research should also explore the effect of training background/experience on RPF accuracy. When asked to rate perceived effort and perceived risk of injury during lifting tasks, physiotherapists who were familiar with evaluating task demands showed high reliability for ratings across days (Yeung et al., 2002). Furthermore, their subjective ratings showed high validity when correlated to parameters of the NIOSH lifting equation. Should experience play a role in perceived fatigue ratings, it would be of best interest to either control for this variable, or alternatively, explore its impact on RPF ratings.

5. Conclusion

In conclusion, the present study has provided novel evidence that a period of familiarization can improve the accuracy of ratings of perceived fatigue in relation to measures of strength (MVC) and certain myoelectric manifestations of LMF. These results, along with previous literature that highlights the reliability and validity of RPF, should encourage researchers to utilize this approach with the provision of a familiarization session to provide enhanced and more robust estimates of LMF.

6. **References**

ACGIH®. (2016). The American Conference of Governmental Industrial Hygienists. TLVs® and BEIs® based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices.

Bandura, A. (2006). Guide for constructing self-efficacy scales. *Self-efficacy beliefs of adolescents, 5*(1), 307-337.

Belhaj-Saif, A., Fourment, A., & Maton, B. (1996). Adaptation of the precentral cortical command to elbow muscle fatigue. *Experimental brain research, 111*(3), 405-416.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian journal of work, environment & health*, 55-58.

Chan, R. F., Chow, C.-y., Lee, G. P., To, L.-k., Tsang, X. Y., Yeung, S. S., & Yeung, E. W. (2000). Self-perceived exertion level and objective evaluation of neuromuscular fatigue in a training session of orchestral violin players. *Applied ergonomics, 31*(4), 335-341.

Chtourou, H., Zarrouk, N., Chaouachi, A., Dogui, M., Behm, D. G., Chamari, K., . . . Souissi, N. (2011). Diurnal variation in Wingate-test performance and associated electromyographic parameters. *Chronobiology international, 28*(8), 706-713.

Delgado, D. A., Lambert, B. S., Boutris, N., McCulloch, P. C., Robbins, A. B., Moreno, M. R., & Harris, J. D. (2018). Validation of digital visual analog scale pain scoring with a traditional paper-based visual analog scale in adults. *Journal of the American Academy of Orthopaedic Surgeons. Global research & reviews, 2*(3).

Enoka, R. M. (1995). Mechanisms of muscle fatigue: central factors and task dependency. *Journal of Electromyography and Kinesiology, 5*(3), 141-149.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*: sage.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological reviews, 81*(4), 1725-1789.

Gates, D. H., & Dingwell, J. B. (2010). Muscle fatigue does not lead to increased instability of upper extremity repetitive movements. *Journal of biomechanics, 43*(5), 913-919.

Hummel, A., Läubli, T., Pozzo, M., Schenk, P., Spillmann, S., & Klipstein, A. (2005). Relationship between perceived exertion and mean power frequency of the EMG signal from the upper trapezius muscle during isometric shoulder elevation. *European journal of applied physiology, 95*(4), 321-326. doi:10.1007/s00421-005-0014-7

Kamen, G., & Gabriel, D. (2010). *Essentials of electromyography*: Human kinetics.

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2013). Firing of antagonist small-diameter muscle afferents reduces voluntary activation and torque of elbow flexors. *The Journal of physiology, 591*(14), 3591-3604.

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics, 44*(1), 17-47.

La Delfa, N. J., Sutherland, C. A., & Potvin, J. R. (2014). EMG processing to interpret a neural tension-limiting mechanism with fatigue. *Muscle & nerve, 50*(3), 384-392.

La Delfa, N.J., Wakeely, F., Abdel-Malek, D., Foley, R.G., Graham, J.D. Experimental repeatability of an upper extremity muscle fatigue protocol. Proceedings from the XXVII Congress of the International Society of Biomechanics. August 2019.

Micklewright, D., Gibson, A. S. C., Gladwell, V., & Al Salman, A. (2017). Development and Validity of the Rating-of-Fatigue Scale. *Sports Medicine, 47*(11), 2375-2393.

Mills, K. (1982). Power spectral analysis of electromyogram and compound muscle action potential during muscle fatigue and recovery. *The Journal of physiology, 326*(1), 401-409.

Noakes, T. D. O. (2012). Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Frontiers in physiology, 3*, 82.

Noro, K., & Imada, A. S. (1991). *Participatory ergonomics*: Taylor & Francis.

Petrofsky, J. S., Glaser, R. M., Phillips, C. A., Lind, A. R., & Williams, C. (1982). Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics, 25*(3), 213-223.

Potvin, J. R. (2012). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. *Human factors, 54*(2), 175-188.

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of personality and social psychology, 43*(3), 450.

Schunk, D. H. (1995). Self-efficacy, motivation, and performance. *Journal of applied sport psychology, 7*(2), 112-137.

Sood, D., Nussbaum, M. A., & Hager, K. (2007). Fatigue during prolonged intermittent overhead work: reliability of measures and effects of working height. *Ergonomics, 50*(4), 497-513.

Stegeman, D., & Hermens, H. (2007). Standards for surface electromyography: The European project Surface EMG for non-invasive assessment of muscles (SENIAM). *Enschede: Roessingh Research and Development*, 108-112.

Strimpakos, N., Georgios, G., Eleni, K., Vasilios, K., & Jacqueline, O. (2005). Issues in relation to the repeatability of and correlation between EMG and Borg scale assessments of neck muscle fatigue. *Journal of Electromyography and Kinesiology, 15*(5), 452-465.

Troiano, A., Naddeo, F., Sosso, E., Camarota, G., Merletti, R., & Mesin, L. (2008). Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait & Posture, 28*(2), 179-186. doi:https://doi.org/10.1016/j.gaitpost.2008.04.002

Whittaker, R. L., Sonne, M. W., & Potvin, J. R. (2019). Ratings of perceived fatigue predict fatigue induced declines in muscle strength during tasks with different distributions of effort and recovery. *Journal of Electromyography and Kinesiology*.

Williams, C., & Ratel, S. (2009). *Human muscle fatigue*: Routledge.

Wilmore, J. H. (1968). Influence of motivation on physical work capacity and performance. *Journal of Applied Physiology, 24*(4), 459-463.

WSIB. (2017). *"By the numbers: 2017 WSIB statistical report"*. Ontario: Ontario Provincial Government.

Yeung, S. S., Genaidy, A. M., Karwowski, W., & Leung, P. (2002). Reliability and validity of self-reported assessment of exposure and outcome variables for manual lifting tasks: a preliminary investigation. *Applied ergonomics, 33*(5), 463-469.

Chapter 4:

Exploring localized muscle fatigue responses at repetitive workloads along current upper limb ergonomics threshold limit values

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Word Count: ~6,300

1. **Introduction**

With musculoskeletal disorders (MSDs) of the upper extremity accounting for 22% of work-related lost time injury claims in Ontario (WSIB, 2017), several efforts have been undertaken to understand their etiology and work towards their prevention. High amounts of force, poor posture, and excessive repetition/duration are traditionally considered key risk factors for MSDs. Prolonged, repetitive upper extremity work can lead to the development of localized muscle fatigue (LMF), which has been associated with numerous negative outcomes including reduced performance (Gates & Dingwell, 2008) and the development of MSDs (Armstrong et al., 1993; Kumar, 2001).

LMF has been studied extensively with respect to several occupationally-relevant task parameters and ergonomics risk factors. Excessive load, high repetition, and increased task duration have consistently demonstrated greater LMF development during physical work. For example, the influence of high force/load has long shown a strong relationship with notable increases in fatigue responses, as well as lower endurance times (Björkstén & Jonsson, 1977; Rohmert, 1973). Excessive task repetition has also demonstrated reduced endurance times in addition to accumulation of LMF and perceived discomfort (Côté, Feldman, Mathieu, & Levin, 2008; Moore & Wells, 2005). Cycle times of longer duration have shown significantly greater accumulation of LMF in studies of the upper arm (Dickerson, Meszaros, Cudlip, Chopp-Hurley, & Langenderfer, 2015; Rashedi & Nussbaum, 2016). Similarly, high duty cycles, which expresses the proportion of task duration spent in effort, have been demonstrated to produce substantial amounts of LMF in repetitive work of the upper extremity (Iridiastadi & Nussbaum, 2006; Sonne & Potvin, 2015).

Given the myriad of task parameters to be considered in workplace tasks, efforts undertaken to establish robust limits for repetitive work are challenged by the diversity of task conditions encountered. Methods such as the Strain Index (Steven Moore & Garg, 1995)and the Rapid Upper Limb Assessment (RULA) (McAtamney & Corlett, 1993) are popular ergonomics approaches that factor high repetition and excessive load in their calculation of MSD risk. Psychophysical methodologies have also served as a valuable approach in the estimation of acceptable upper extremity repetitive work limits. In these psychophysical approaches, highly trained individuals rely on their perceptions to estimate the maximum effort or load they can sustain during a variety of loading and repetition scenarios, without accruing undue levels of strain or fatigue. Potvin (2012b) developed an equation to characterize the relationship between duty cycle and maximal acceptable effort (MAE), which represented the average psychophysically-based acceptable loads divided by their corresponding single-effort maximum strengths. The MAE equation was based on 69 upper extremity tasks from 8 psychophysical studies, and has since been validated by recent lifting and lowering study data (Potvin, 2012a) and psychophysical studies at high duty cycles (Sonne & Potvin, 2015).

The psychophysically-based equation from Potvin (2012b) was also used as the basis for the official threshold limit value (TLV) established by the American College of Governmental Industrial Hygienists (ACGIH®) for cyclical upper limb localized work (ACGIH®, 2016). The resulting equation developed by the ACGIH® was similar to the MAE equation, but refitted in the 50-90% duty cycle ranges, such that the equation was not forced to 0% MVC at 100% duty cycle. This TLV can be used to estimate the acceptable percent duty cycle for a given relative load (%MVC), or inversely, the acceptable %MVC for a given duty cycle. Assumptions of the TLV include performance of a static, cyclic task at constant intensity over the course of an 8-hour workday.

The ACGIH® also states that "as much as half of the population working at, or just below, the TLV may experience some performance decrements or discomfort", but the magnitude of these decrements or LMF is currently unknown. Exploring the LMF response at workloads along the TLV can provide insight on whether certain regions of the TLV curve should be preferred when designing repetitive upper extremity work, or whether the logarithmic relationship between MAE and DC is balanced from a LMF perspective. As such, the purpose of this study is to examine differences in objective and subjective LMF responses when an intermittent isometric upper extremity task is performed at differing workloads along the ACGIH® TLV. We hypothesized that there would be no differences in outcome measures across the three threshold limit combinations we evaluated, with minimal manifestations of localized fatigue occurring across all measures in the 1-hour timeframe of the experiment.

2. <u>Methods</u>

2.1. Participants

Sixteen participants (8 M and 8 F) were recruited from the university's student population (Table 4.1). Exclusion criteria included history of acute or chronic upper extremity pain, injury, or surgery within one year prior to the data collection. Prior to commencement of the study, written and verbal consent were obtained, and participants were asked to follow similar dietary and caffeine intake before each session and refrain from upper extremity resistance exercise to ensure adequate recovery between sessions.

Table 4.1: Mean participant demographics (standard deviation)

Sex	Age (years)	Height (cm)	Weight (kg)
Females (n=8)	21.4 (1.85)	158.0 (5.8)	59.9 (4.0)
Males (n=8)	21.1 (1.89)	177.6 (6.5)	77.2 (9.5)

2.2. Instrumentation & Data Acquisition

2.2.1. Surface electromyography (sEMG)

Surface electromyography (sEMG) was used to record the muscle activity from the biceps brachii, triceps brachii, and brachioradialis of the dominant arm. Disposable bipolar Ag/AgCl surface electrodes with foam adhesive hydrogel (disc-shaped, 3 cm radius) (Meditrace 130, Kendall, Mansfield, MA, USA) were placed on the skin overlying the muscle after shaving with a disposable razor and sanitizing with an isopropyl alcohol swab. Electrodes were placed on the muscle bellies at an inter-electrode distance of 6 cm, as based upon previously established standards (Stegeman & Hermens, 2007). sEMG was recorded using CED 1401 interface (Cambridge Electronic Design 167 Ltd., Cambridge, UK)*;* the signal was amplified (AMT-8, Bortec, Calgary, AB, Canada) and sampled at 2000 Hz using a 16-bit A/D conversion system (ODAUIII, Northern Digital Inc., Waterloo, ON, Canada). EMG amplitude was normalized to maximum voluntary excitation (MVE), elicited during a battery of maximum isometric voluntary contractions (MVCs) of elbow flexion and extension. Each MVIC was repeated, with the highest obtained signal in all trials used as the maximum reference. Resting signal DC bias was measured in a resting EMG trial and subtracted from all EMG signals.

2.2.2. Dynamometry

All force measurements were obtained using a six-degree of freedom transducer (PY6-500, Bertec, Columbus, OH, USA) sampled at 1000 Hz. The force transducer was mounted to a rigid vertical piece of 80/20 slotted rail, and affixed to the participant using a padded cuff placed around the midpoint of the forearm, between the olecranon and ulnar styloid, to ensure a consistent relative moment arm between and within participants. Force and sEMG data were collected continuously and synchronously using customized LabVIEW software (National Instruments, Austin, TX, USA) on a PC-compatible computer.

2.2.3. Near-Infrared Spectroscopy (NIRS)

Levels of tissue oxygenation (tissue saturation index, TSI) were recorded using near-infrared spectroscopy (NIRS), consisting of a light emitter and sensor (Oxymon, Artinis Medical Systems, Einsteinweg, Netherlands) placed on the muscle belly of the biceps brachii. Using the Oxysoft 3.0.95 software (Artinis Medical Systems, Netherlands) levels of infrared light absorption were sampled at 50 Hz, calculating the tissue saturation index of the biceps brachii in real-time, as the ratio of oxygenated hemoglobin to total hemoglobin.

2.2.4. Psychophysical and Psychological Assessments:

Ratings of perceived fatigue (RPF) were obtained visually using a modified Visual Analogue Scale (VAS) (Micklewright et al., 2017; Abdel-Malek et al., in preparation). The scale was provided to participants as a continuous sliding linear scale on customized LabView software. Using a mouse, participants dragged the slider to indicate their perceived level of fatigue at any point between no fatigue and highest level of fatigue experienced (Abdel-Malek et al., in preparation).

Motivation for task performance was assessed post-fatigue protocol completion using three subscales from the Intrinsic Motivation Scale: the interest and enjoyment subscale (7 items), perceived competence subscale (6 items) and effort/importance subscale (5 items) (Ryan, 1982). Each item is rated using a 7-point Likert-type scale, ranging from 1 (*not at all true*) to 7 (*very true*). An example item from the interest and enjoyment subscale is: “I enjoyed doing this activity very much.” An example item from the effort/importance subscale asked participants to respond to this statement: “It was important to me to do well at this task.” All subscales met conventional standards of internal consistency (alpha > 0.70).

Following each cycle of the fatigue protocol, participants were asked to rate their perceived level of physical exertion using Borg’s CR-10 scale, ranging from 0 (*nothing at all*) to 10 (*absolute maximum*) (Borg, 1962). Participants were also asked to rate the state of their general mood on a 10-point Likert-type scale ranging from +5 (*very good*) to -5 (*very bad*) (Hardy & Rejeski, 1989) following each cycle.

2.3. Experimental Procedures & Protocol

2.3.1. Design

Following a repeated measures design, each participant performed three separate sessions of an intermittent elbow flexion task in a fatiguing protocol. Each session was performed at a different combination of DC and relative load (see section 2.3.2 below). Session order was counterbalanced using a Latin square, with each session separated by at least 3 days of rest. Prior to the experimental sessions, participants first performed a familiarization session to gain familiarity with the task and RPF scale (Abdel-Malek et al., in prep). The familiarization session consisted of six 4-minute cycles of intermittent isometric elbow flexion at a duty cycle of 50% and intensity of 50% of maximum voluntary contraction (MVC). During the 1-minute rest period that followed each work cycle, participants provided a rating of perceived fatigue, and a measure of strength decline via a MVC test. Strength decline (as a % of baseline MVC) was provided to participants as familiarization to the RPF scale. Previous research has demonstrated that RPF familiarization provided in this format can improve the accuracy of RPF ratings during an intermittent isometric elbow flexion fatigue protocol relative to objective measures of localized muscle fatigue (LMF) (Abdel-Malek et al., in prep). Each experimental session entailed set-up, baseline measures, a fatigue protocol, and recovery period.

2.3.2. TLV Workloads

The workload for each session of the fatiguing protocol was derived from a separate TLV along the ACGIH® curve, with different levels of duty cycle and relative load (Figure 4.1). The low DC condition involved a 20% duty cycle at an intensity of 29.6% MVC. The medium DC protocol was characterized by a 40% duty cycle and a 19.7% MVC intensity. A duty cycle of 60% and intensity of 13.9%MVC characterized the fatigue protocol for the high DC condition.

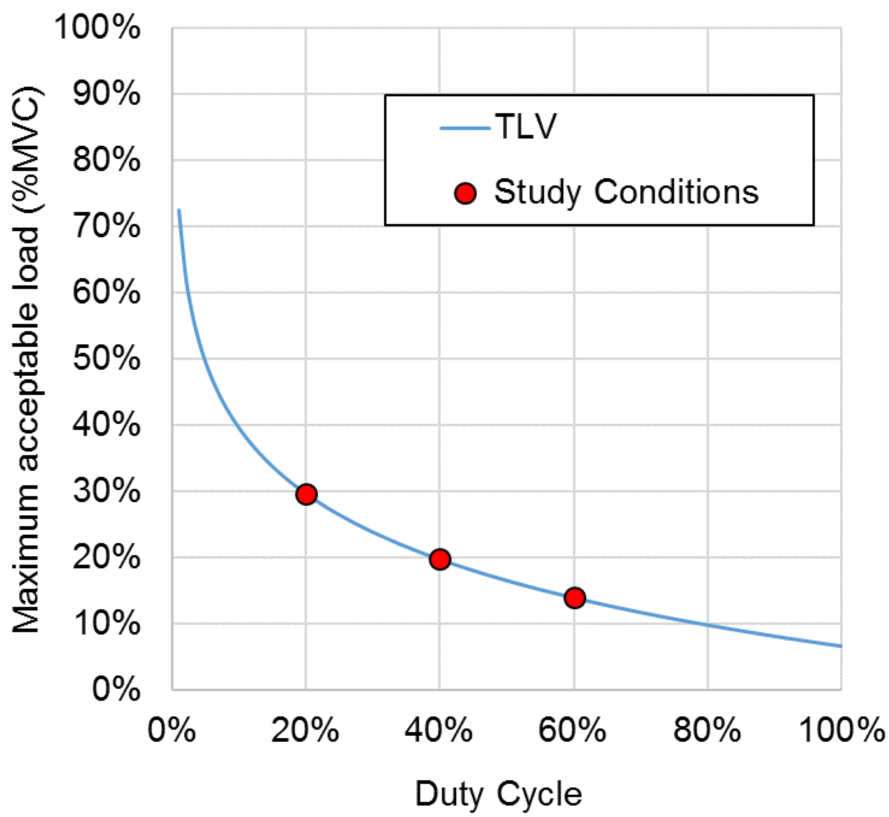

Figure 4.1: Workloads representing the three study conditions (red circles) are shown relative to the ACGIH TLV curve. This curve establishes acceptable maximum relative loads as a function of duty cycle.

2.3.3. Experimental Protocol

Following skin preparation, surface electrodes were affixed overlying the three muscle bellies, with the NIRS sensor affixed on the muscle belly of the biceps brachii adjacent to the placed electrodes. Participants were then seated facing a height-adjustable table that supported the dominant arm at 90° of shoulder and elbow flexion. From a supinated forearm position, participants performed isometric elbow flexion against a padded cuff chained to the 6 DOF transducer and affixed to the middle of the forearm. Using online visual feedback presented on a computer monitor, participants were required to ‘trace’ a template by exerting tension against the padded cuff (Figure 4.2).

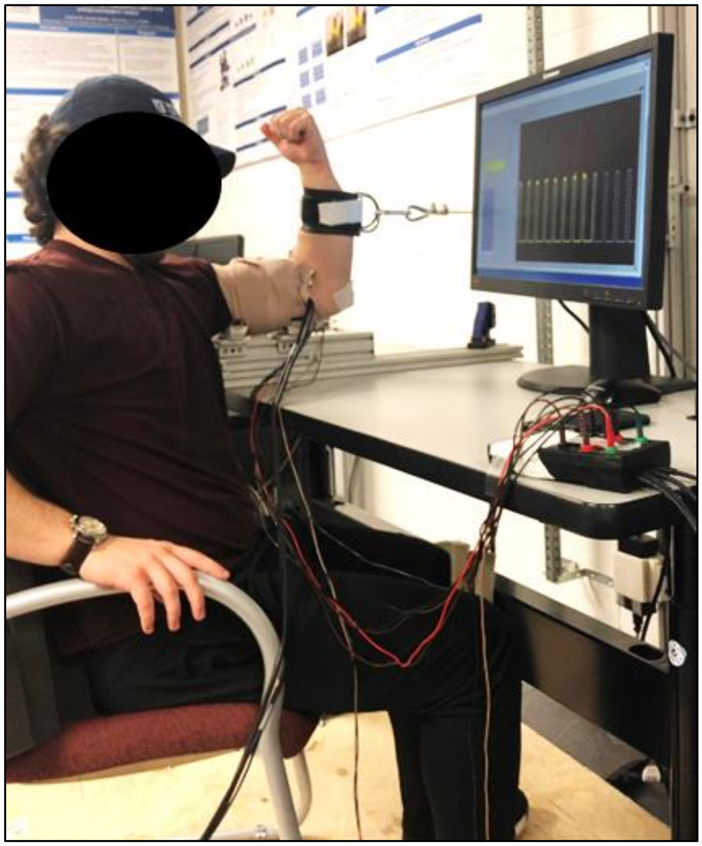

Figure 4.2: Experimental set-up. Participants were seated in front of a computer monitor, which provided online information on their force output relative to a template representative of the DC/TLV workload being conducted in that session.

Baseline strength and peak amplitude of the biceps brachii, brachioradialis, and triceps brachii were obtained via separate maximal voluntary contraction (MVC) tests. Participants were instructed to perform maximal supinated elbow flexion (biceps), maximal neutral elbow flexion (brachioradialis) and maximal supinated elbow extension (triceps) against the 6 DOF transducer. Participants completed a minimum of three MVC trials per muscle in order to obtain three values within 5% maximal strength, with a one-minute rest period separating each trial. In addition, as MnPF is dependent on level of muscle activation, three reference contractions were conducted at the relative force level required during that particular session (i.e. 29.7%, 19.6% or 13.9% MVC) to provide a baseline (i.e. rested) measure of MnPF. Lastly, baseline ratings of perceived fatigue and exertion were obtained from the participant.

For the fatigue protocol, participants were asked to perform intermittent elbow flexion efforts by tracing the online tracing profile. Contractions were performed in 5-minute cycles (Figure 4.3), with 4 minutes of exertion followed by a 1-minute resting period where RPF, RPE, and FS measures were obtained. MVC trials were performed after every third work cycle in order to obtain measures of strength decline at an interval that minimized fatigue incurred due to maximal exertions (B Bigland-Ritchie, Furbush, & Woods, 1986). These work cycles were performed until volitional fatigue, or until 60-minutes (12 cycles) had elapsed.

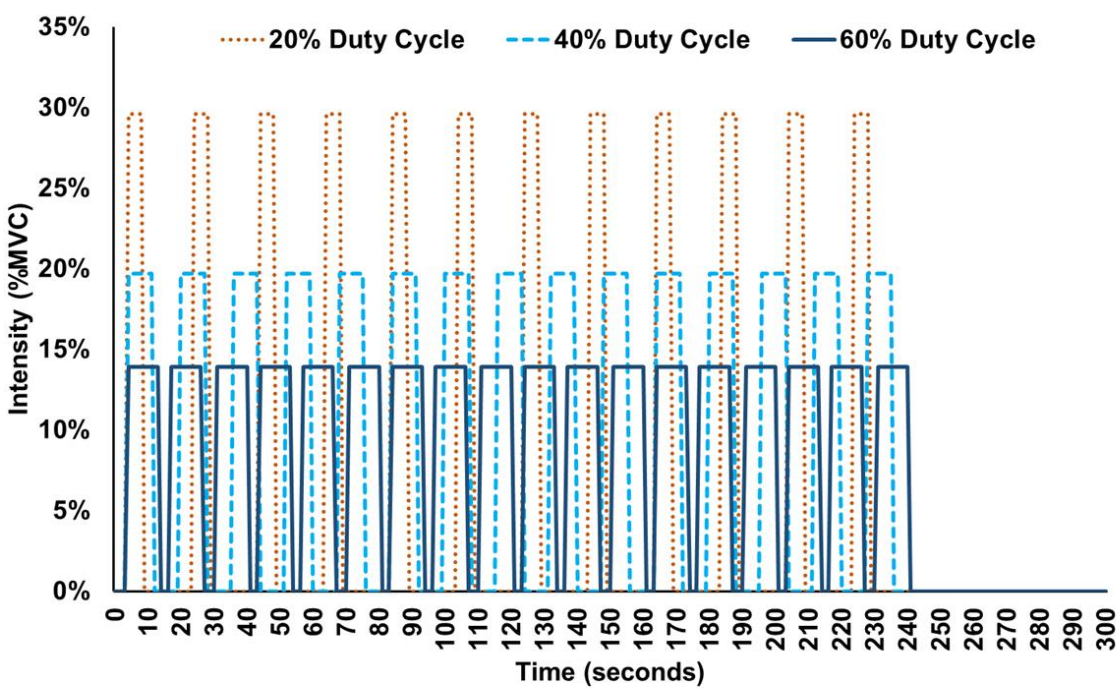

Figure 4.3: Force exertion profiles for the three separate TLV workloads overlaid on each other. The low DC workload is outlined in *red (dotted lines),* medium DC outlined in *light blue (dashed line)*, and the high DC in *dark blue (solid line).* The rest period between cycles is represented by no force exertion between 240-300 seconds. Note: This rest time was included in the calculation of DC.

2.4. Data Analysis

sEMG signals from the biceps were rectified using a root-mean-square (RMS) window of 0.5 seconds. RMS amplitudes recorded during a 1-second window of the final contraction of each cycle were normalized to peak activation obtained at baseline. A Fast Fourier Transform (FFT) was used to compute the MnPF of the sEMG signal during a 1-second window from the last plateau of every cycle performed. Each MnPF value was normalized to baseline MnPF, which was computed as the average MnPF of the three reference contractions recorded at baseline. All force signals were smoothed using a 1-second moving average and normalized to peak elbow flexion strength obtained during baseline MVC trials. RPF and RPE ratings were also expressed relative to baseline ratings. Tissue saturation index (TSI) was recorded during the same 1-second window of the final contraction of each cycle, and normalized relative to the reference contraction at baseline. **Thesis Note: We experienced complications in the analysis of NIRS TSI, and therefore do not have any data available at this point.*

2.5. Statistical Analysis

The dependent measures of aEMG, MnPF, MVC, RPF, RPE, and FS were considered in a 3 (Condition) x 5 (Time – cycles 0 (baseline), 3, 6, 9, 12) x 2 (Sex) repeated measures mixed MANOVA. A second RM MANOVA was used to evaluate significant score differences in the IMI subscales (interest and enjoyment (IE), perceived competence (PC), and effort/importance (EI)) within a 3 (Condition) x 2 (Sex) design. Univariate repeated measures ANOVAs were conducted for significant dependent variables from the MANOVA, with Tukey's post-hoc comparisons then conducted for significant differences. Statistical tests were conducted at an α level of $p < 0.05$. Partial-eta-squared effect sizes were computed, with values greater than 0.06 and 0.14 considered medium and large, respectively (Field, 2013).

3. <u>Results</u>

3.1. aEMG

A significant condition by time interaction was found for aEMG ($F = 6.270$, $p < 0.00001$, $\eta p^2 = 0.309$)) (Figure 4.4). In general, a trend of increasing aEMG with lower duty cycles was found. After baseline, aEMG differed significantly for all duty cycle conditions. The lowest aEMG amplitudes were observed in the high duty cycle condition, where it was 58% and 43% lower than the low and medium duty cycle conditions, respectively.

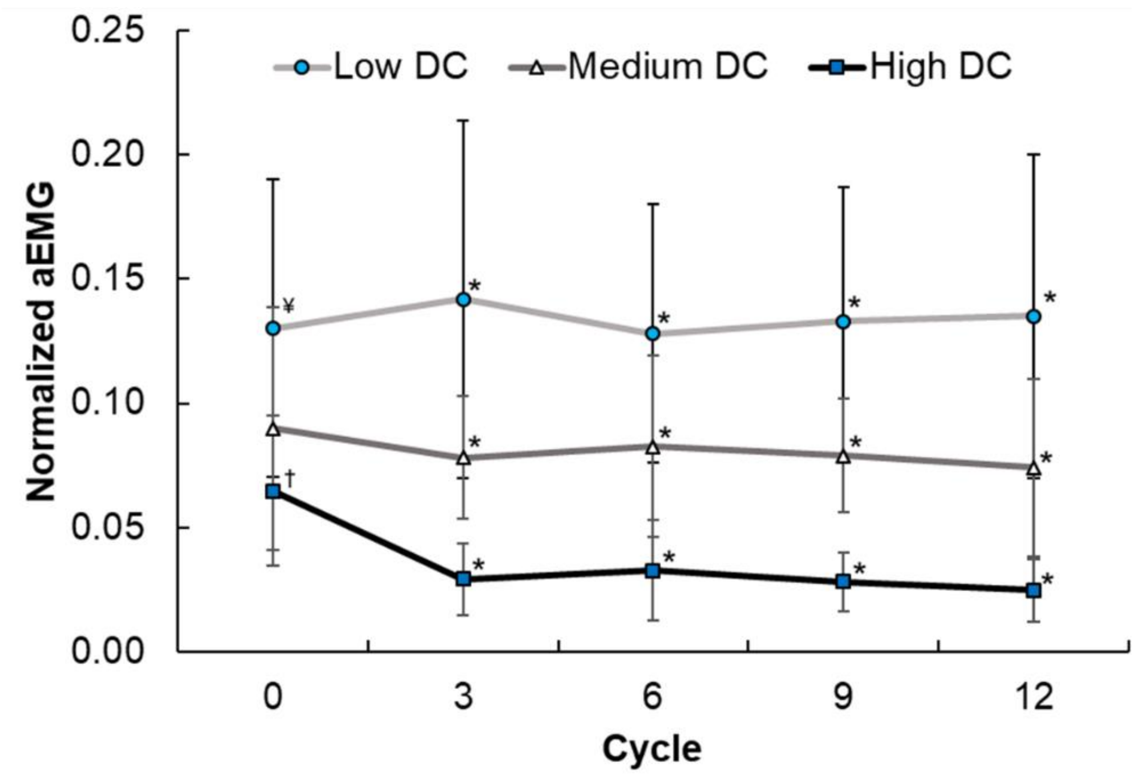

Figure 4.4: Normalized aEMG across cycles for each workload. Significant difference from Low DC denoted as (†), significant difference from High DC (¥), significant difference from both DCs (*). Error bars indicate standard deviation from the mean.

3.2. MnPF

A significant interaction was found between condition and time for MnPF ($F= 6.626$, $p < 0.001$, $\eta p^2= 0.321$) (Figure 4.5). MnPF for the high DC condition was significantly lower than the low duty cycle condition across all cycles after baseline, steadily decreasing from 8% lower values at cycle 3, with 16% lower values at protocol completion. All 3 duty cycle conditions differed significantly at the final cycle, with medium and high duty cycle conditions exhibiting 9% and 16% lower values of MnPF.

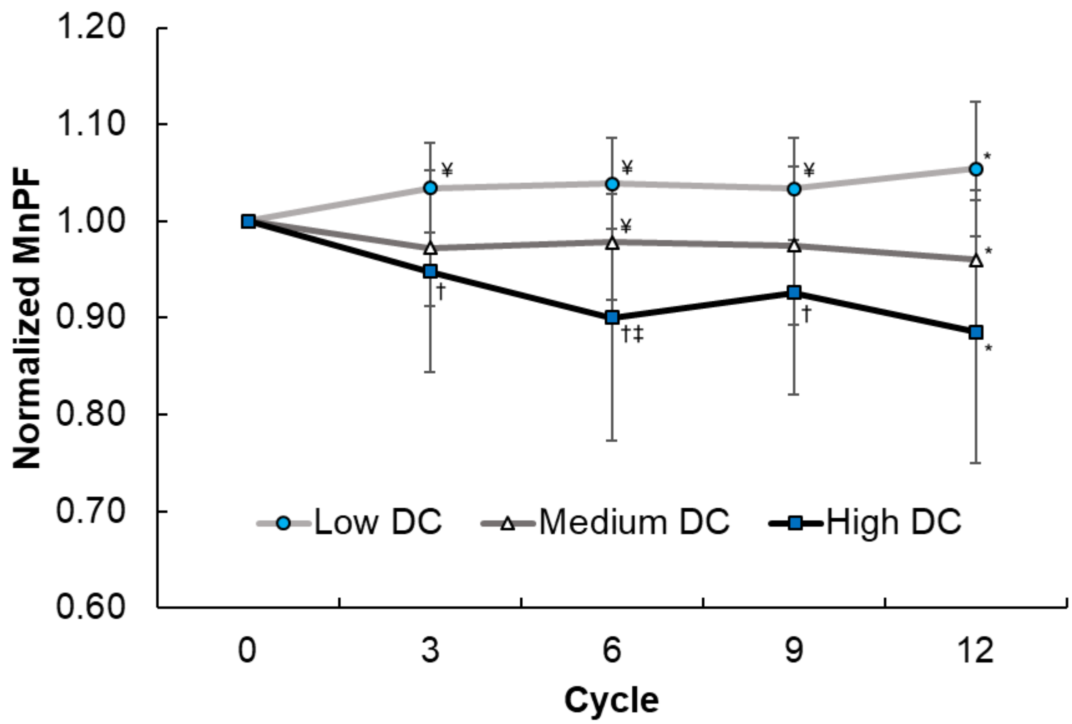

Figure 4.5: Normalized MnPF across cycles for each workload. Significant difference from Low DC denoted as (†), significant difference from Med DC (‡), significant difference from High DC (¥), significant difference from both DCs (*). Error bars indicate standard deviation from the mean.

3.3. MVC

A significant main effect for MVC values was found between conditions ($F= 4.277$, $p < 0.05$, $\eta p^2= 0.234$) (Figure 4.6). The high DC condition resulted in a 4% and 5% larger decline in strength compared to the medium and low duty cycle conditions, respectively, across the entire time duration.

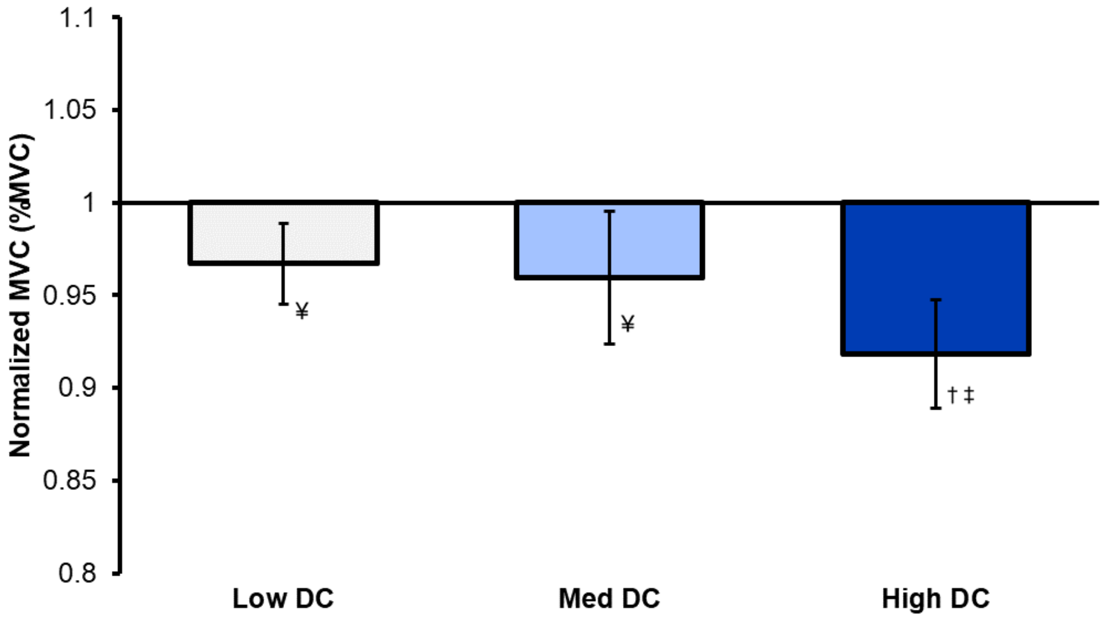

Figure 4.6: Normalized strength decline (%MVC) for each workload. Significant difference from Low DC denoted as (†), significant difference from Med DC (‡), significant difference from High DC (¥). Error bars indicate standard deviation.

3.4. Psychological Assessments

3.4.1. **IMI**

Scores from the perceived competence subscale returned a significant main effect for workload condition ($F = 8.774$, $p < 0.01$, $\eta p^2 = 0.403$). Perceived competence scores obtained after completing the low duty cycle workload were 13% and 14% higher than scores obtained post-medium and post-high duty cycle workloads, respectively.

3.4.2. **RPE**

RPE values demonstrated a significant interaction for condition by time ($F = 2.55$, $p < 0.05$, $\eta p^2 = 0.133$). RPE for the high duty cycle condition was 36% higher than the medium duty cycle condition, and 30% higher than the low duty cycle condition at cycle 9.

4. Discussion

Using an array of neuromuscular and psychophysical fatigue measures, we sought to validate current duty cycle and exertion intensity-based threshold limit values for upper extremity repetitive work. We hypothesized that the full complement of outcome measures studied (i.e. aEMG, MnPF, MVC, RPF, RPE) would not show meaningful differences, as all conditions fell along the acceptable curve of the ACGIH® TLV. However, fatigue response variables in both the myoelectric and strength domains revealed consistent decrements for the high DC conditions relative to the low and medium DC conditions, indicating the workloads set according to different levels of the ACGIH® TLV curve may not result in equivalent fatigue responses.

Myoelectric-based indicators of fatigue, in both the amplitude and frequency domains, indicated differing neuromuscular fatigue responses across the three workload conditions. As was expected, the high DC condition consistently exhibited the lowest EMG amplitudes compared to the other duty cycles (40-58% lower), as the level of contraction (%MVC) was inversely proportional to duty cycle. However, other than an initial decline between baseline and cycle 3 for the high DC group, the difference between DC conditions remained consistent across the progression of fatigue. Typically, localized muscle fatigue is associated with increases in EMG amplitude during sub-maximal isometric contractions (Petrofsky et al., 1982), but this was generally not observed in the current study. One possible explanation for this finding was that individuals were not fatiguing their muscles to the point of exhaustion, and therefore the protocol was not demanding enough to elicit the typical muscle fatigue response in the amplitude domain. Further analysis of agonist and antagonist co-contraction may also explain the preservation of EMG amplitude throughout the fatigue protocol, as numerous muscle activation strategies may have been employed to share the constant sub-maximal load (Belhaj-Saif et al., 1996; Enoka, 1995; Kennedy et al., 2013).

Despite the consistent muscle activation throughout the fatigue protocols, analysis of muscle MnPF revealed interesting difference between DC conditions, which coincided with the observed decline in MVC. The high DC workload also showed the largest overall decline in MnPF compared to baseline (11% decline), while low and medium DC workloads showed a 5% increase, and 4% decline, respectively. An 11% decline in MnPF would be considered substantial, as this exceeds the conventional threshold of a 9% reduction often considered in muscle fatigue evaluations (Öberg, Sandsjö, & Kadefors, 1991; Whittaker, La Delfa, & Dickerson, 2019). While a shift to lower frequencies may indicate fatigue-related slowing of conduction velocity, increases in MnPF could be explained by motor unit substitution of lower-threshold motor units with higher action potential conduction velocities. More sustained contractions have exhibited faster declines in MnPF compared to more intermittent elbow extension tasks, perhaps due to better metabolite removal during prolonged rest periods (Byström & Kilbom, 1990; Yung et al., 2012). MnPF values were consistently lower than the low DC workload, with the final MnPF value of each workload showing significant differences (8% difference between each workload). Other research has found high DC to yield more rapid fatigue development than high load (low DC) for myoelectric measures of RMS amplitude and MnPF measures (Iridiastadi & Nussbaum, 2006).

The consistency of myoelectric measures has been questioned, given their poor sensitivity during low-intensity conditions (Arendt-Nielsen, Mills, & Forster, 1989; Hagberg, 1981; Jørgensen, Fallentin, Krogh-Lund, & Jensen, 1988). Synergist recruitment (brachioradialis) may have occurred throughout the task to compensate for agonist fatigue, a mechanism previously reported during elbow fatigue (Belhaj-Saif et al., 1996; Enoka, 1995). Similarly, neural drive to the antagonist and resultant co-activation may have decreased during fatigue of the biceps, as reported by Kennedy and colleagues (Kennedy et al., 2013). While changes in muscle temperature are known to influence patterns of EMG amplitude (Gamet, Duchene, Garapon-Bar, & Goubel, 1993), the period of warm-up prior to the protocol (strength tests and reference contractions) should have aided in achieving a steady-state muscle temperature, although minimal changes in temperature may have occurred. Changes in MnPF during static work have been partially attributed to slowed muscle fiber conduction velocity as intramuscular metabolites buildup (Arendt-Nielsen & Mills, 1988), intermittent work entails rest periods where metabolites are more effectively eliminated. Longer contraction periods, however, such as during the high DC workload, may be associated with such mechanisms, along with changes in motor unit recruitment strategies (i.e. firing rate) during fatigue onset (Iridiastadi & Nussbaum, 2006).

Contrary to our hypothesis, the high DC workload exhibited the greatest overall decline in MVC (strength), with a 4-5% larger decline than the medium and low DC conditions. This finding complements previous data that have demonstrated higher strength declines during more sustained static contractions than those of intermittent efforts (Yung et al., 2012). Similarly, in intermittent isometric dumbbell lifts, efforts of higher duty cycle had lower endurance times compared to contractions of shorter duration, supporting findings of this current study regarding the highly-fatiguing high DC workload. Less sustained contractions may allow for more substitution of motor units compared to longer-held contractions (Falla & Farina, 2007; Potvin & Fuglevand, 2017); in addition, longer contractions may mitigate appropriate metabolite disposal that builds up in the area as intramuscular pressure can limit blood flow (Sahlin, Tonkonogi, & Söderlund, 1998). These mechanisms may help explain the reduced force decline associated with the low and medium duty cycle contractions.

Interestingly, changes in RPF and affect (via FS) revealed no significant differences across workloads. However, RPE measures were significantly higher during the high DC workload. RPF measures have shown strong correlation to fatigue accumulation, as denoted by force declines, during intermittent efforts of distal thumb flexion (Whittaker, Sonne, et al., 2019). While DC levels were not directly manipulated, RPF ratings correlated well with MVC measures in conditions of complex, differing work-recovery profiles. The relationship between subjective ratings and objective fatigue accumulation has also been established by previous research. For example, ratings of perceived discomfort were significantly affected by higher load and higher duty cycle parameters during an intermittent shoulder abduction task (Iridiastadi & Nussbaum, 2006). Shorter cycle times of an intermittent isometric index finger abduction task led to lower rates of increase in ratings of perceived discomfort, as well (Rashedi & Nussbaum, 2016). The lack of this finding in the current study was interesting, given the relationship observed between RPF with both decline in MVC and EMG MnPF in a nearly identical protocol (Abdel-Malek et al., in prep). The most likely explanation is that the workloads examined in these studies were not demanding enough to produce localized muscle fatigue that was detectable perceptually. This specificity of RPF accuracy as a function of LMF would be an interesting direction for future research, to determine at what levels of fatigue individuals are more aptly able to perceive muscle fatigue locally. While measures of perceived exertion may not have the appropriate sensitivity to assess muscle fatigue accumulation, they do provide insight into the perceived challenge of an activity (Micklewright et al., 2017; Whittaker, Sonne, et al., 2019). In this case, individuals perceived the high DC workload to be more challenging than the lower duty cycle workloads. A similar trend in intrinsic motivation was found with regards to perceived competence (via IMI), as the high DC workload exhibited the lowest scores of perceived competence post-task. The negative relationship between levels of intrinsic motivation and perceived effort, as established per the social cognitive theory, may explain this finding at the high DC workload (Bandura, 1986; Schunk, 1995); furthermore, participant knowledge of task end-point may have mitigated these differences in motivation and perceived effort for workloads at the end of each session (Noakes, 2012; Szalma, 2014).

Mean contraction level (MCL), which denotes maximal voluntary effort (MVE) as the product of load (%MVC) and DC, has also been utilized to compare and contrast tasks with differing workloads (Corcos, Jiang, Wilding, & Gottlieb, 2002). Accordingly, the low

(20%DC, 29.6%MVC), medium (40% DC, 19.7%MVC), and high (60% DC, 13.9%MVC) DC workloads correspond to MCLs of 6, 8, and 9 percent of MVE, respectively. While Rohmert's model for rest allowances deemed a 15% MVE contraction acceptable without rest periods (Rohmert, 1973), subsequent models and guidelines have labelled tasks of 10-17%MVE as an acceptable range (Bergamasco, Girola, & Colombini, 1998; Björkstén & Jonsson, 1977; Iridiastadi & Nussbaum, 2006). Nevertheless, the high DC condition (MCL = 9% MVE) still manifested notable fatigue-related declines in force and MnPF.

In a similar protocol performed at an exertion intensity of 50% (well above the ACGIH® TLV), a substantial fatigue response was observed across several fatigue indicators similar to this protocol, including strength and EMG metrics (Wakeely et al., in prep), corroborating reports of substantial localized fatigue during protocols of intermittent work at 50% intensity for the biceps brachii (Corcos et al., 2002), and quadriceps/soleus (B Bigland-Ritchie et al., 1986). Therefore, this evaluation serves as an important validation for psychophysically based threshold limit values for repetitive work. While all individuals finished the entire protocol, reporting relatively low levels of RPF and RPE throughout, it is important to keep in mind that these TLVs are based on an 8-hour work day. Considering the declines observed in MVC and MnPF, it may be difficult to sustain such workloads over the expected time period. Additionally, this protocol entailed a very isolated task, which may have also contributed to the observed fatigue responses. Future research should repeat this methodology using more complex and varied repetitive tasks, which allow for additional localized muscle recovery and sustained performance (Sonne, Hodder, Wells, & Potvin, 2015; Yung et al., 2012).

Despite the above considerations, the declines in MVC and MnPF demonstrate that not all TLV limits, defined by the psychophysical relationship between maximum acceptable effort and duty cycle, may necessarily be equivalent in avoiding excessive LMF. The high DC condition resulted in relatively more LMF accumulation according to declines in MVC and MnPF, metrics that have been considered and employed as reliable indicators of LMF development (S. C. Gandevia, 2001). These findings have important implications for ergonomists/engineers designing and/or evaluating repetitive upper extremity work. When considering parameters of duty cycle and load/intensity, reducing duty cycle, and therefore increasing recovery time, may be a more potent mechanism in the avoidance of LMF accumulation in comparison to reducing effort/intensity.

The current results also suggest that the psychophysically-based maximum acceptable effort (MAE) equation (Potvin, 2012), which was used as a basis for the ACGIH TLV, may provide a more realistic threshold limit for higher DC exertions. The MAE equation proposes lower limits of load for higher DC work (Potvin, 2012b) (Figure 4.7). In general, there is a paucity of psychophysical data in the high DC range, making acceptable load estimations in this range slightly more tenuous. However, Sonne & Potvin (2015) collected psychophysical data from high DC efforts (e.g. 50, 70 & 90%) in a thumb abduction task, which further supported the MAE equation's validity at high duty cycle ranges. Conversely, the ACGIH® TLV seems to overestimate appropriate work at DC of 1.00, as efforts as low as 5% MVC have caused fatigue after only one hour of sustained contraction (Jørgensen et al., 1988; Sjøgaard et al., 1986).

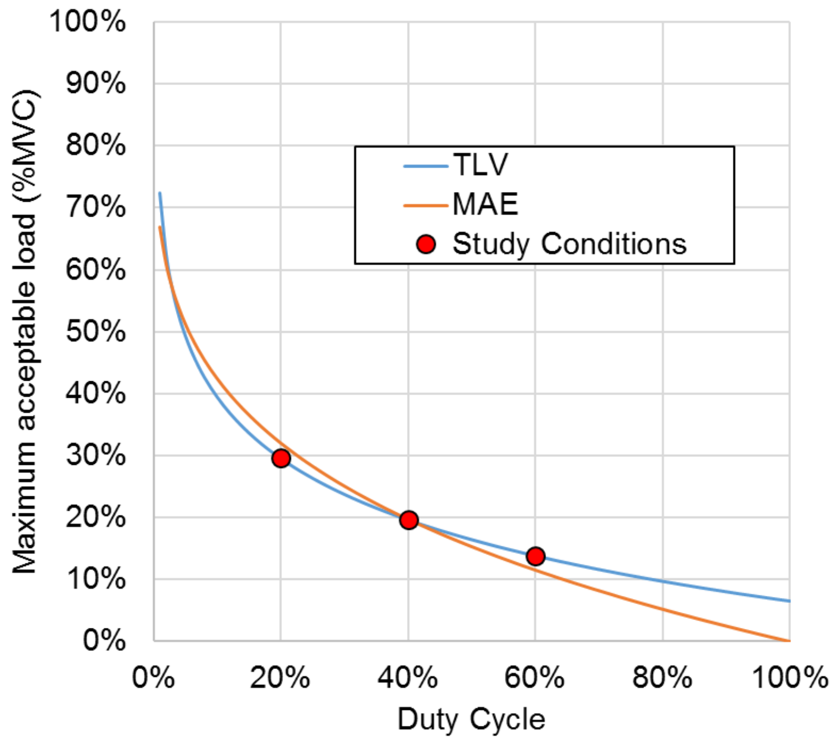

Figure 4.7: Comparison between the curves derived from the ACGIH® TLV (blue) and MAE (orange) equations. At duty cycles above ~40%, the MAE curve (Potvin, 2012) is forced towards 0% MVC at 100% duty cycle; whereas the TLV curve remains relatively high for very high duty cycles.

4.1. Limitations/future research

As with many laboratory assessments of physical work and muscle fatigue, session duration may limit the scope of such assessments. While these workloads are characteristic of acceptable thresholds to an 8-hour workday, 1-hour sessions may not have sufficiently induced fatigue, in addition to a potential ceiling effect (protocol limit of 60 minutes) that may have occurred for comparisons between conditions. The measures employed may not have fully captured the development of fatigue during a 1-hour window, a prevalent limitation in laboratory assessments of occupational tasks (Santos et al., 2016). An important distinction should be made regarding significant differences of fatigue measures; a clinically significant change in a fatigue measure may not correspond to a statistically significant difference, and vice versa. This is often combated by showing agreement across several muscle fatigue indicators, as was this case in this study. As the sample for this study involved younger participants assessed in laboratory setting, future research should involve some form of field assessments of the worker population. Age-related differences can influence the assessment of fatigue, as differences in muscle fiber composition have been proposed to explain the phenomenon of fatigue resistance in older adults performing sustained low-load isometric tasks (Adamo, Khodaee, Barringer, Johnson, & Martin, 2009; Avin & Frey Law, 2011; Cavuoto & Nussbaum, 2014). The effects of these workloads should be assessed for other joints of the upper limb, in addition to more dynamic or complex efforts that may be more representative of workplace tasks.

5. Conclusion

This study explored the localized muscle fatigue response at acceptable workloads along the ACGIH® TLV curve, and has demonstrated that measures of muscle activation (MnPF), strength (%MVC), and subjective effort (RPE) produced a more pronounced fatigue response at high (i.e. 60%) duty cycle levels. Upper-extremity tasks may be best designed to avoid contractions at higher duty cycles, which may result in higher risks of fatigue-related injury.

6. References

ACGIH®. (2016). The American Conference of Governmental Industrial Hygienists. TLVs® and BEIs® based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices.

Adamo, D., Khodaee, M., Barringer, S., Johnson, P., & Martin, B. (2009). Low mean level sustained and intermittent grip exertions: Influence of age on fatigue and recovery. *Ergonomics, 52*(10), 1287-1297.

Arendt-Nielsen, L., & Mills, K. R. (1988). Muscle fibre conduction velocity, mean power frequency, mean EMG voltage and force during submaximal fatiguing contractions of human quadriceps. *European journal of applied physiology and occupational physiology, 58*(1-2), 20-25.

Arendt-Nielsen, L., Mills, K. R., & Forster, A. (1989). Changes in muscle fiber conduction velocity, mean power frequency, and mean EMG voltage during prolonged submaximal contractions. *Muscle & nerve, 12*(6), 493-497.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, A., . . . Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian journal of work, environment & health*, 73-84.

Avin, K. G., & Frey Law, L. A. (2011). Age-related differences in muscle fatigue vary by contraction type: a meta-analysis. *Physical therapy, 91*(8), 1153-1165.

Bandura, A. (1986). Social foundations of thought and action. *Englewood Cliffs, NJ, 1986*.

Belhaj-Saif, A., Fourment, A., & Maton, B. (1996). Adaptation of the precentral cortical command to elbow muscle fatigue. *Experimental brain research, 111*(3), 405-416.

Bergamasco, R., Girola, C., & Colombini, D. (1998). Guidelines for designing jobs featuring repetitive tasks. *Ergonomics, 41*(9), 1364-1383.

Bigland-Ritchie, B., Furbush, F., & Woods, J. (1986). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. *Journal of Applied Physiology, 61*(2), 421-429.

Björkstén, M., & Jonsson, B. (1977). Endurance limit of force in long-term intermittent static contractions. *Scandinavian journal of work, environment & health*, 23-27.

Borg, G. (1962). Physical performance and perceived exertion.

Byström, S., & Kilbom, Å. (1990). Physiological response in the forearm during and after isometric intermittent handgrip. *European journal of applied physiology and occupational physiology, 60*(6), 457-466.

Cavuoto, L. A., & Nussbaum, M. A. (2014). The influences of obesity and age on functional performance during intermittent upper extremity tasks. *Journal of Occupational and Environmental Hygiene, 11*(9), 583-590.

Corcos, D. M., Jiang, H.-Y., Wilding, J., & Gottlieb, G. L. (2002). Fatigue induced changes in phasic muscle activation patterns for fast elbow flexion movements. *Experimental brain research, 142*(1), 1-12.

Côté, J. N., Feldman, A. G., Mathieu, P. A., & Levin, M. F. (2008). Effects of fatigue on intermuscular coordination during repetitive hammering. *Motor control*, 12(2), 79-92.

Dickerson, C. R., Meszaros, K. A., Cudlip, A. C., Chopp-Hurley, J. N., & Langenderfer, J. E. (2015). The influence of cycle time on shoulder fatigue responses for a fixed total overhead workload. *Journal of biomechanics, 48*(11), 2911-2918.

Enoka, R. M. (1995). Mechanisms of muscle fatigue: central factors and task dependency. *Journal of Electromyography and Kinesiology, 5*(3), 141-149.

Falla, D., & Farina, D. (2007). Periodic increases in force during sustained contraction reduce fatigue and facilitate spatial redistribution of trapezius muscle activity. *Experimental brain research, 182*(1), 99-107.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*: sage.

Gamet, D., Duchene, J., Garapon-Bar, C., & Goubel, F. (1993). Surface electromyogram power spectrum in human quadriceps muscle during incremental exercise. *Journal of Applied Physiology, 74*(6), 2704-2710.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological reviews, 81*(4), 1725-1789.

Gates, D. H., & Dingwell, J. B. (2008). The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. *Experimental brain research, 187*(4), 573-585.

Hagberg, M. (1981). Electromyographic signs of shoulder muscular fatigue in two elevated arm positions. *American journal of physical medicine, 60*(3), 111-121.

Hardy, C. J., & Rejeski, W. J. (1989). Not what, but how one feels: the measurement of affect during exercise. *Journal of Sport and Exercise Psychology, 11*(3), 304-317.

Iridiastadi, H., & Nussbaum, M. A. (2006). Muscular fatigue and endurance during intermittent static efforts: effects of contraction level, duty cycle, and cycle time. *Human factors, 48*(4), 710-720.

Jørgensen, K., Fallentin, N., Krogh-Lund, C., & Jensen, B. (1988). Electromyography and fatigue during prolonged, low-level static contractions. *European journal of applied physiology and occupational physiology, 57*(3), 316-321.

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2013). Firing of antagonist small-diameter muscle afferents reduces voluntary activation and torque of elbow flexors. *The Journal of physiology, 591*(14), 3591-3604.

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics, 44*(1), 17-47.

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied ergonomics, 24*(2), 91-99.

Micklewright, D., Gibson, A. S. C., Gladwell, V., & Al Salman, A. (2017). Development and Validity of the Rating-of-Fatigue Scale. *Sports Medicine, 47*(11), 2375-2393.

Moore, A., & Wells, R. (2005). Effect of cycle time and duty cycle on psychophysically determined acceptable levels in a highly repetitive task. *Ergonomics*, 48(7), 859-873.

Noakes, T. D. O. (2012). Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Frontiers in physiology, 3*, 82.

Öberg, T., Sandsjö, L., & Kadefors, R. (1991). Variability of the EMG mean power frequency: a study on the trapezius muscle. *Journal of Electromyography and Kinesiology, 1*(4), 237-243.

Petrofsky, J. S., Glaser, R. M., Phillips, C. A., Lind, A. R., & Williams, C. (1982). Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics, 25*(3), 213-223.

Potvin, J. R. (2012a). An equation to predict maximum acceptable loads for repetitive tasks based on duty cycle: evaluation with lifting and lowering tasks. *Work, 41*(Supplement 1), 397-400.

Potvin, J. R. (2012b). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. *Human factors, 54*(2), 175-188.

Potvin, J. R., & Fuglevand, A. J. (2017). A motor unit-based model of muscle fatigue. *PLoS computational biology, 13*(6), e1005581.

Rashedi, E., & Nussbaum, M. A. (2016). Cycle time influences the development of muscle fatigue at low to moderate levels of intermittent muscle contraction. *Journal of Electromyography and Kinesiology, 28,* 37-45.

Rohmert, W. (1973). Problems in determining rest allowances: part 1: use of modern methods to evaluate stress and strain in static muscular work. *Applied ergonomics, 4*(2), 91-95.

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of personality and social psychology, 43*(3), 450.

Sahlin, K., Tonkonogi, M., & Söderlund, K. (1998). Energy supply and muscle fatigue in humans. *Acta Physiologica Scandinavica, 162*(3), 261-266.

Santos, J., Baptista, J. S., Monteiro, P. R. R., Miguel, A. S., Santos, R., & Vaz, M. A. (2016). The influence of task design on upper limb muscles fatigue during low-load repetitive work: A systematic review. *International Journal of Industrial Ergonomics, 52,* 78-91.

Schunk, D. H. (1995). Self-efficacy, motivation, and performance. *Journal of applied sport psychology, 7*(2), 112-137.

Sjøgaard, G., Kiens, B., Jørgensen, K., & Saltin, B. (1986). Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. *Acta Physiologica Scandinavica, 128*(3), 475-484.

Sonne, M. W., Hodder, J. N., Wells, R., & Potvin, J. R. (2015). Force time-history affects fatigue accumulation during repetitive handgrip tasks. *Journal of Electromyography and Kinesiology, 25*(1), 130-135.

Sonne, M. W., & Potvin, J. R. (2015). A psychophysical study to determine maximum acceptable efforts for a thumb abduction task with high duty cycles. *Ergonomics, 58*(1), 118-127.

Steven Moore, J., & Garg, A. (1995). The strain index: a proposed method to analyze jobs for risk of distal upper extremity disorders. *American Industrial Hygiene Association Journal, 56*(5), 443-458.

Szalma, J. L. (2014). On the application of motivation theory to human factors/ergonomics: Motivational design principles for human–technology interaction. *Human factors, 56*(8), 1453-1471.

Whittaker, R. L., La Delfa, N. J., & Dickerson, C. R. (2019). Algorithmically detectable directional changes in upper extremity motion indicate substantial myoelectric shoulder muscle fatigue during a repetitive manual task. *Ergonomics, 62*(3), 431-443.

Whittaker, R. L., Sonne, M. W., & Potvin, J. R. (2019). Ratings of perceived fatigue predict fatigue induced declines in muscle strength during tasks with different distributions of effort and recovery. *Journal of Electromyography and Kinesiology*.

WSIB. (2017). *"By the numbers: 2017 WSIB statistical report"*. Ontario: Ontario Provincial Government.

Yung, M., Mathiassen, S. E., & Wells, R. P. (2012). Variation of force amplitude and its effects on local fatigue. *European journal of applied physiology, 112*(11), 3865-3879.

Chapter 5. General Discussion & Conclusions

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This chapter will synthesize and summarize the main contributions and conclusions from the totality of this research. After revisiting the purpose and rationale of this thesis, key findings will and the overall contributions of this research to this field of study will be highlighted. This chapter will conclude by proposing practical recommendations pertaining to current ergonomics guidelines, and will discuss future directions of research in this line of inquiry.

1. Purpose & Rationale

As with most ergonomics evaluations, this thesis was motivated by the problematic incidence of upper extremity MSDs and injuries in the workplace, with 22% of lost-time claims in 2016 attributed to the upper extremity (WSIB, 2017). Ergonomics literature has long identified high repetitions, excessive force, and poor postures as key risk factor for MSDs in the workplace (Genaidy, Al-Shedi, & Shell, 1993). Overexertion in any of these domains coincides with development of localized muscle fatigue (LMF) in individuals whose capacities to sustain workplace demands are exceeded (Björkstén & Jonsson, 1977; Iridiastadi & Nussbaum, 2006; Sonne & Potvin, 2015). Avoiding instances of excessive LMF development requires a proper description of what is appropriate, from both worker capacity and task demand standpoints. Thus, the overarching purpose of this thesis was to gain a better understanding of LMF development (worker capacities & task demands), across several objective and subjective measures, during repetitive upper extremity tasks.

Quantifying LMF development requires a holistic and methodical experimental approach, as its development can be manifested differently across neuromechanics, psychophysical and physiological domains. Compared to other more traditional indicators of fatigue (e.g. myoelectric and measures of force decline), ratings of perceived fatigue

(RPF) have been relatively understudied, but have the potential to provide important insight into the psychophysical element of LMF development (Micklewright et al., 2017; Whittaker, Sonne, et al., 2019). Previous use of RPF scales in both laboratory and occupational settings have not consistently provided scale familiarization to individuals who are asked to assess their subjective level of fatigue. As such, administering RPF as a fatigue assessment method was not being optimized, as individuals using the scale were likely unsure as to what they were rating. Thus, the purpose of study 1 was to explore whether scale familiarization, through a deliberate period of performance feedback, would improve the accuracy and predictive utility of RPF ratings relative to other gold standard LMF assessment techniques.

Specific occupationally-relevant task parameters are commonly linked to fatigue development, and therefore have been the focus of experimental evaluation. For example, researchers have confirmed the effects of high load (Björkstén & Jonsson, 1977; Rohmert, 1973), and high duty cycle (DC) levels (Björkstén & Jonsson, 1977; Iridiastadi & Nussbaum, 2006; Sonne & Potvin, 2015) on excessive LMF development. In response to this predictable relationship between increasing task demand and muscle fatigue, thresholds have been established to guide ergonomists and engineers in the design of acceptable workloads for repetitive upper extremity tasks. Inputs of repetition/duration (i.e. duty cycle) and relative effort (%MVC) are used to predict maximal acceptable efforts (MAEs) of repetitive upper extremity work using a model of previous psychophysical data (Potvin, 2012b). Current threshold limit values (TLVs) for repetitive upper extremity work are based on Potvin's MAE equation to provide acceptable levels of DC and load in an upper extremity task (ACGIH®, 2016). Study 2 assessed the neuromechanical and psychophysical LMF responses in individuals performing three separate workloads of a repetitive upper extremity task at current ergonomics workload thresholds (i.e. ACGIH® TLV). While numerous studies have examined the isolated and interactive effects of varying DC and task exertion effort on LMF measures (Björkstén & Jonsson, 1977; Corcos et al., 2002; Iridiastadi & Nussbaum, 2006; Sonne & Potvin, 2015), this is the first study, to the best of our knowledge, examining LMF responses anchored to actual threshold limits being used in industry today. Therefore, the results of this study provide both basic insight into the multi-faceted nature of localized muscle fatigue, but also provides an important validation for the ergonomics limits currently being used by ergonomists in the field today.

2. Key Findings

2.1. Study 1

In chapter 3, the study exploring the effects of scale familiarization on the accuracy of RPF ratings was presented. In order to assess improvements in RPF accuracy, the error between RPF and classic measures of LMF were contrasted, specifically in relation to strength decline (MVC), aEMG, and MnPF.

Both average and root-mean-square error (RMSE) showed significant decreases after RPF familiarization was provided, between RPF and MVC. Compared to the control group, ratings provided by the feedback group showed 67% less average error on day 2, and 97% less average error on day 3, where feedback cues were no longer provided. Similar improvements in error were mirrored via 65% and 72% lower RMSE values for the feedback group on days 2 and 3, respectively. Furthermore, error between RPF and MnPF showed similar improvements for the feedback group: average error and RMSE were 71% and 69% lower than the control group at the end of session 3, respectively. After familiarization, RPF provided by the feedback group were significantly improved relative to MnPF changes as LMF developed. Additional psychologically-based analyses demonstrated non-significant differences in intrinsic motivation and task self-efficacy for both groups. Thus, it can be assumed individuals in both groups demonstrated similar levels of intrinsic motivation and self-efficacy, regardless of scale familiarization.

The goal of this study was to determine whether RPF scale familiarization could improve the accuracy of RPF measures during a repetitive upper extremity task, considering a standardized familiarization protocol is not consistently provided in studies measuring LMF. Considering these findings, the results suggest that providing a period of RPF familiarization can significantly improve utilization of this method in assessments of LMF. This is particularly important given the practicality and non-invasive nature of subjective scales, which lends particularly well to evaluations of muscle fatigue outside of a controlled laboratory setting.

2.2. Study 2

The second study of this thesis, as highlighted in Chapter 4, utilized a wide assortment of objective and subjective experimental techniques to assess how LMF responses differed at separate workloads along the current ACGIH® TLV curve. Measures of aEMG, MnPF, MVC, and RPF were utilized to portray the LMF response, and differentiate these workloads. Note: Levels of muscle oxygenation were also recorded using NIRS, but these analyses are still in progress.

Several differences were observed in the manifestation of LMF between the three workload conditions, which countered our hypothesis that no differences would be observed. In the myoelectric domain, MnPF was significantly affected by workload, as the high DC condition demonstrated the largest overall decline in MnPF from baseline. The significant decrease in MnPF was interesting, considering the aEMG values during the high DC workload were 58% and 43% lower than the low and medium DC conditions, respectively. This suggests that the lack of recovery time during the High DC condition was a key factor in the more pronounced manifestation of LMF. In other words, the muscle activating at a higher relative effort for a shorter duration was not as fatiguing as the muscle activating at a lower level for a longer duration.

The central finding, that the High DC condition was the most taxing from a LMF perspective, is also corroborated by other indicators of muscle fatigue. The high DC workload manifested the greatest decline in strength from baseline; 4-5% greater than declines seen in the medium and low DC conditions. Despite being insignificant in our statistical analyses, RPF was highest during the last quarter of the high DC protocol, with ratings 3-4% higher than the low and medium DC conditions. RPE values also demonstrated a similar trend between workloads, as perceived exertion during the high DC condition was rated 30-36% higher than the low and medium DC conditions.

When considering the LMF responses observed across all subjective and objective experimental measurements, a TLV workload with a higher duty cycle appears to be more taxing to the neuromuscular system. This provides important insight into how repetitive work tasks can be designed, and suggests potential modification to the higher DC portion of the ACGIH® TLV curve, to values more in line with the MAE curve proposed by Potvin (2012).

3. General Limitations & Future Directions

While physiological mechanisms have been proposed to explain why high DC levels induce the most LMF, levels of blood flow and oxygenation could be explored during repetitive work in the high DC range, considering the contribution of sex differences to intramuscular pressure (Hunter & Enoka, 2001). Other joints of the upper limb should also be observed in repetitive work, should different trends in DC levels and LMF development be seen at the wrist, shoulder, fingers, etc.

Furthermore, myoelectric measures of muscle activation during LMF can rely on different recruitment and firing rate strategies associated with fiber type composition, a characteristic that varies greatly with age and sex (Adamo et al., 2009; Avin & Frey Law, 2011; Cavuoto & Nussbaum, 2014; Hunter & Enoka, 2001), and could affect the fatigability of some individuals compared to others. While the sample observed in these studies involved younger adults, middle-aged adults can exhibit fatigue resistance due to different fiber type compositions. Furthermore, as a preliminary laboratory assessment of physical work, an isolated isometric task was examined, which may not be representative of more dynamic and varied tasks typically seen in occupational settings. Future ergonomic studies in this line of inquiry should explore more dynamic tasks, perhaps in a field-setting, performed by a sample closer in age to the working population.

4. Final Recommendations

The combined findings from these thesis studies provide important new insights that can be applied by researchers and practitioners interested in mitigating the development of upper extremity muscle fatigue in the workplace. Prior RPF scale familiarization should be provided to individuals asked to assess their fatigue level, whether in laboratory or occupational settings.

In terms of currently implemented TLVs for acceptable DC and load of repetitive upper extremity tasks (ACGIH®, 2016), different LMF responses were seen in individuals performing repetitive upper extremity work at different thresholds along the TLV curve. More specifically, the acceptable combination of high DC and low load exhibited the greatest fatigue in terms of myoelectric and strength decrement metrics. Thus, it may be prudent to avoid designing/performing work at the higher end of the DC spectrum whenever possible, even if below or close to the threshold provided by the ACGIH®. While the TLV model mathematically predicts acceptable combinations of DC and loads based on previous empirical data, the lack of data in the high DC range (above 50%) forced the model to use "refitted" data that may have overestimated TLVs in this range. Updating current TLV guidelines may be necessary, as even a 60% duty cycle appears to produce a significant LMF response in just one hour of work. For higher duty cycle tasks, the MAE equation proposed by Potvin (2012) may serve as a more conservative threshold for the prevention of LMF during repetitive upper limb tasks.

5. References

ACGIH®. (2016). The American Conference of Governmental Industrial Hygienists. TLVs® and BEIs® based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices.

Adamo, D., Khodaee, M., Barringer, S., Johnson, P., & Martin, B. (2009). Low mean level sustained and intermittent grip exertions: Influence of age on fatigue and recovery. *Ergonomics, 52*(10), 1287-1297.

Adrian, E. D., & Bronk, D. W. (1929). The discharge of impulses in motor nerve fibres. *The Journal of physiology, 67*(2), 9-151.

Arendt-Nielsen, L., & Mills, K. R. (1988). Muscle fibre conduction velocity, mean power frequency, mean EMG voltage and force during submaximal fatiguing contractions of human quadriceps. *European journal of applied physiology and occupational physiology, 58*(1-2), 20-25.

Arendt-Nielsen, L., Mills, K. R., & Forster, A. (1989). Changes in muscle fiber conduction velocity, mean power frequency, and mean EMG voltage during prolonged submaximal contractions. *Muscle & nerve, 12*(6), 493-497.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, A., . . . Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian journal of work, environment & health*, 73-84.

Avin, K. G., & Frey Law, L. A. (2011). Age-related differences in muscle fatigue vary by contraction type: a meta-analysis. *Physical therapy, 91*(8), 1153-1165.

Bandura, A. (1986). Social foundations of thought and action. *Englewood Cliffs, NJ, 1986*.

Bandura, A. (2006). Guide for constructing self-efficacy scales. *Self-efficacy beliefs of adolescents, 5*(1), 307-337.

Barry, B. K., & Enoka, R. M. (2007). The neurobiology of muscle fatigue: 15 years later. *Integrative and comparative biology, 47*(4), 465-473.

Belhaj-Saif, A., Fourment, A., & Maton, B. (1996). Adaptation of the precentral cortical command to elbow muscle fatigue. *Experimental brain research, 111*(3), 405-416.

Bergamasco, R., Girola, C., & Colombini, D. (1998). Guidelines for designing jobs featuring repetitive tasks. *Ergonomics, 41*(9), 1364-1383.

Bigland-Ritchie, B., Dawson, N., Johansson, R., & Lippold, O. (1986). Reflex origin for the slowing of motoneurone firing rates in fatigue of human voluntary contractions. *The Journal of physiology*, *379*(1), 451-459.

Bigland-Ritchie, B., Furbush, F., & Woods, J. (1986). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. *Journal of Applied Physiology*, *61*(2), 421-429.

Bigland-Ritchie, B., & Woods, J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & nerve, 7*(9), 691-699.

Björkstén, M., & Jonsson, B. (1977). Endurance limit of force in long-term intermittent static contractions. *Scandinavian journal of work, environment & health*, 23-27.

Borg, G. (1962). Physical performance and perceived exertion.

Borg, G. (1990). Psychophysical scaling with applications in physical work and the perception of exertion. *Scandinavian journal of work, environment & health*, 55-58.

Byström, S., & Kilbom, Å. (1990). Physiological response in the forearm during and after isometric intermittent handgrip. *European journal of applied physiology and occupational physiology, 60*(6), 457-466.

Carregaro, R., Cunha, R., Oliveira, C. G., Brown, L. E., & Bottaro, M. (2013). Muscle fatigue and metabolic responses following three different antagonist pre-load resistance exercises. *Journal of Electromyography and Kinesiology, 23*(5), 1090-1096.

Cavuoto, L. A., & Nussbaum, M. A. (2014). The influences of obesity and age on functional performance during intermittent upper extremity tasks. *Journal of Occupational and Environmental Hygiene, 11*(9), 583-590.

Chaffin, D., Andersson, G., & Martin, B. (2006). Occupational ergonomics: John Wiley & Sons, New Jersey.

Chan, R. F., Chow, C.-y., Lee, G. P., To, L.-k., Tsang, X. Y., Yeung, S. S., & Yeung, E. W. (2000). Self-perceived exertion level and objective evaluation of neuromuscular fatigue in a training session of orchestral violin players. *Applied ergonomics, 31*(4), 335-341.

Chtourou, H., Zarrouk, N., Chaouachi, A., Dogui, M., Behm, D. G., Chamari, K., . . . Souissi, N. (2011). Diurnal variation in Wingate-test performance and associated electromyographic parameters. *Chronobiology international, 28*(8), 706-713.

Cooke, N., Cummings, M., Hancock, P., Marras, W., & Warm, J. (2010). *Bored beyond belief: How automation is boring us to distraction.* Paper presented at the Proceedings of the Human Factors and Ergonomics Society 54th Annual Meeting.

Corcos, D. M., Jiang, H.-Y., Wilding, J., & Gottlieb, G. L. (2002). Fatigue induced changes in phasic muscle activation patterns for fast elbow flexion movements. *Experimental brain research, 142*(1), 1-12.

Côté, J. N., Feldman, A. G., Mathieu, P. A., & Levin, M. F. (2008). Effects of fatigue on intermuscular coordination during repetitive hammering. *Motor control, 12*(2), 79-92.

De Blasi, R. A., Cope, M., Elwell, C., Safoue, F., & Ferrari, M. (1993). Noninvasive measurement of human forearm oxygen consumption by near infrared spectroscopy. *European journal of applied physiology and occupational physiology, 67*(1), 20-25.

Delgado, D. A., Lambert, B. S., Boutris, N., McCulloch, P. C., Robbins, A. B., Moreno, M. R., & Harris, J. D. (2018). Validation of digital visual analog scale pain scoring with a traditional paper-based visual analog scale in adults. *Journal of the American Academy of Orthopaedic Surgeons. Global research & reviews, 2*(3).

Dickerson, C. R., Meszaros, K. A., Cudlip, A. C., Chopp-Hurley, J. N., & Langenderfer, J. E. (2015). The influence of cycle time on shoulder fatigue responses for a fixed total overhead workload. *Journal of biomechanics, 48*(11), 2911-2918.

Enoka, R. M. (1995). Mechanisms of muscle fatigue: central factors and task dependency. *Journal of Electromyography and Kinesiology, 5*(3), 141-149.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of physiology, 586*(1), 11-23.

Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. *Medicine and science in sports and exercise, 48*(11), 2228.

Falla, D., & Farina, D. (2007). Periodic increases in force during sustained contraction reduce fatigue and facilitate spatial redistribution of trapezius muscle activity. *Experimental brain research, 182*(1), 99-107.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*: sage.

Frey-Law, L. A., Looft, J. M., & Heitsman, J. (2012). A three-compartment muscle fatigue model accurately predicts joint-specific maximum endurance times for sustained isometric tasks. *Journal of biomechanics, 45*(10), 1803-1808.

Frey Law, L. A., & Avin, K. G. (2010). Endurance time is joint-specific: a modelling and meta-analysis investigation. *Ergonomics, 53*(1), 109-129.

Gamet, D., Duchene, J., Garapon-Bar, C., & Goubel, F. (1993). Surface electromyogram power spectrum in human quadriceps muscle during incremental exercise. *Journal of Applied Physiology, 74*(6), 2704-2710.

Gandevia, S. (1998). Neural control in human muscle fatigue: changes in muscle afferents, moto neurones and moto cortical drive. *Acta Physiologica Scandinavica, 162*(3), 275-283.

Gandevia, S., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. *The Journal of physiology, 490*(2), 529-536.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological reviews, 81*(4), 1725-1789.

Gardiner, P. (2011). *Advanced neuromuscular exercise physiology*: Human Kinetics.

Gates, D. H., & Dingwell, J. B. (2008). The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. *Experimental brain research, 187*(4), 573-585.

Gates, D. H., & Dingwell, J. B. (2010). Muscle fatigue does not lead to increased instability of upper extremity repetitive movements. *Journal of biomechanics, 43*(5), 913-919.

Genaidy, A., Al-Shedi, A., & Shell, R. (1993). Ergonomic risk assessment: preliminary guidelines for analysis of repetition, force and posture. *Journal of human ergology, 22*(1), 45-55.

Hagbarth, K., Kunesch, E., Nordin, M., Schmidt, R., & Wallin, E. (1986). Gamma loop contributing to maximal voluntary contractions in man. *The Journal of physiology, 380*(1), 575-591.

Hagberg, M. (1981). Electromyographic signs of shoulder muscular fatigue in two elevated arm positions. *American journal of physical medicine, 60*(3), 111-121.

Halperin, I., Copithorne, D., & Behm, D. G. (2014). Unilateral isometric muscle fatigue decreases force production and activation of contralateral knee extensors but not elbow flexors. *Applied Physiology, Nutrition, and Metabolism, 39*(12), 1338-1344.

Hardy, C. J., & Rejeski, W. J. (1989). Not what, but how one feels: the measurement of affect during exercise. *Journal of Sport and Exercise Psychology, 11*(3), 304-317.

Henneman, E. (1979). Functional organization of motoneuron pools: the size-principle. *Integration in the nervous system*, 13-25.

Hicks, A., McGill, S., & Hughson, R. L. (1999). Tissue oxygenation by near-infrared spectroscopy and muscle blood flow during isometric contractions of the forearm. *Canadian Journal of Applied Physiology, 24*(3), 216-230.

Hummel, A., Läubli, T., Pozzo, M., Schenk, P., Spillmann, S., & Klipstein, A. (2005). Relationship between perceived exertion and mean power frequency of the EMG signal from the upper trapezius muscle during isometric shoulder elevation. *European journal of applied physiology, 95*(4), 321-326. doi:10.1007/s00421-005-0014-7

Hunter, S. K., & Enoka, R. M. (2001). Sex differences in the fatigability of arm muscles depends on absolute force during isometric contractions. *Journal of Applied Physiology, 91*(6), 2686-2694.

Hunter, S. K., Griffith, E. E., Schlachter, K. M., & Kufahl, T. D. (2009). Sex differences in time to task failure and blood flow for an intermittent isometric fatiguing contraction. *Muscle & nerve, 39*(1), 42-53.

Iridiastadi, H., & Nussbaum, M. A. (2006). Muscular fatigue and endurance during intermittent static efforts: effects of contraction level, duty cycle, and cycle time. *Human factors, 48*(4), 710-720.

Jensen, B., Sjøgaard, G., Bornmyr, S., Arborelius, M., & Jørgensen, K. (1995). Intramuscular laser-Doppler flowmetry in the supraspinatus muscle during isometric contractions. *European journal of applied physiology and occupational physiology, 71*(4), 373-378.

Jørgensen, K., Fallentin, N., Krogh-Lund, C., & Jensen, B. (1988). Electromyography and fatigue during prolonged, low-level static contractions. *European journal of applied physiology and occupational physiology, 57*(3), 316-321.

Kamen, G., & Gabriel, D. (2010). *Essentials of electromyography*: Human kinetics.

Kennedy, D. S., McNeil, C. J., Gandevia, S. C., & Taylor, J. L. (2013). Firing of antagonist small-diameter muscle afferents reduces voluntary activation and torque of elbow flexors. *The Journal of physiology, 591*(14), 3591-3604.

Kent-Braun, J. A. (1999). Central and peripheral contributions to muscle fatigue in humans during sustained maximal effort. *European journal of applied physiology and occupational physiology, 80*(1), 57-63.

Kilbom, Å. (1994). Assessment of physical exposure in relation to work-related musculoskeletal disorders-what information can be obtained from systematic observations. *Scandinavian journal of work, environment & health*, 30-45.

Kluger, B. M., Krupp, L. B., & Enoka, R. M. (2013). Fatigue and fatigability in neurologic illnesses proposal for a unified taxonomy. *Neurology, 80*(4), 409-416.

Kumar, S. (2001). Theories of musculoskeletal injury causation. *Ergonomics, 44*(1), 17-47.

La Delfa, N. J., Sutherland, C. A., & Potvin, J. R. (2014). EMG processing to interpret a neural tension-limiting mechanism with fatigue. *Muscle & nerve, 50*(3), 384-392.

Lin, J.-H., Maikala, R. V., McGorry, R., & Brunette, C. (2010). NIRS application in evaluating threaded-fastener driving assembly tasks. *International Journal of Industrial Ergonomics, 40*(2), 146-152.

Luopajärvi, T., Kuorinka, I., Virolainen, M., & Holmberg, M. (1979). Prevalence of tenosynovitis and other injuries of the upper extremities in repetitive work. *Scandinavian journal of work, environment & health*, 48-55.

Mantooth, W. P., Mehta, R. K., Rhee, J., & Cavuoto, L. A. (2018). Task and sex differences in muscle oxygenation during handgrip fatigue development. *Ergonomics, 61*(12), 1646-1656.

McAtamney, L., & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied ergonomics, 24*(2), 91-99.

Merletti, R., & Parker, P. A. (2004). *Electromyography: physiology, engineering, and non-invasive applications* (Vol. 11): John Wiley & Sons.

Micklewright, D., Gibson, A. S. C., Gladwell, V., & Al Salman, A. (2017). Development and Validity of the Rating-of-Fatigue Scale. *Sports Medicine, 47*(11), 2375-2393.

Micklewright, D., Papadopoulou, E., Swart, J., & Noakes, T. (2010). Previous experience influences pacing during 20 km time trial cycling. *British journal of sports medicine, 44*(13), 952-960.

Mills, K. (1982). Power spectral analysis of electromyogram and compound muscle action potential during muscle fatigue and recovery. *The Journal of physiology, 326*(1), 401-409.

Moore, A., & Wells, R. (2005). Effect of cycle time and duty cycle on psychophysically determined acceptable levels in a highly repetitive task. *Ergonomics, 48*(7), 859-873.

Noakes, T. D. O. (2012). Fatigue is a brain-derived emotion that regulates the exercise behavior to ensure the protection of whole body homeostasis. *Frontiers in physiology, 3*, 82.

Noro, K., & Imada, A. S. (1991). *Participatory ergonomics*: Taylor & Francis.

Öberg, T., Sandsjö, L., & Kadefors, R. (1991). Variability of the EMG mean power frequency: a study on the trapezius muscle. *Journal of Electromyography and Kinesiology, 1*(4), 237-243.

Perrey, S., Thedon, T., & Bringard, A. (2010). Application of near-infrared spectroscopy in preventing work-related musculoskeletal disorders: Brief review. *International Journal of Industrial Ergonomics, 40*(2), 180-184.

Petrofsky, J. S., Glaser, R. M., Phillips, C. A., Lind, A. R., & Williams, C. (1982). Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics, 25*(3), 213-223.

Potvin, J. R. (2012a). An equation to predict maximum acceptable loads for repetitive tasks based on duty cycle: evaluation with lifting and lowering tasks. *Work, 41*(Supplement 1), 397-400.

Potvin, J. R. (2012b). Predicting maximum acceptable efforts for repetitive tasks: an equation based on duty cycle. *Human factors, 54*(2), 175-188.

Potvin, J. R., & Fuglevand, A. J. (2017). A motor unit-based model of muscle fatigue. *PLoS computational biology, 13*(6), e1005581.

Rashedi, E., & Nussbaum, M. A. (2015). A review of occupationally–relevant models of localised muscle fatigue. *International journal of human factors modelling and simulation, 5*(1), 61-80.

Rashedi, E., & Nussbaum, M. A. (2016). Cycle time influences the development of muscle fatigue at low to moderate levels of intermittent muscle contraction. *Journal of Electromyography and Kinesiology, 28*, 37-45.

Rohmert, W. (1973). Problems in determining rest allowances: part 1: use of modern methods to evaluate stress and strain in static muscular work. *Applied ergonomics*, *4*(2), 91-95.

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of personality and social psychology, 43*(3), 450.

Sahlin, K., Tonkonogi, M., & Söderlund, K. (1998). Energy supply and muscle fatigue in humans. *Acta Physiologica Scandinavica, 162*(3), 261-266.

Santos, J., Baptista, J. S., Monteiro, P. R. R., Miguel, A. S., Santos, R., & Vaz, M. A. (2016). The influence of task design on upper limb muscles fatigue during low-load repetitive work: A systematic review. *International Journal of Industrial Ergonomics, 52*, 78-91.

Schunk, D. H. (1995). Self-efficacy, motivation, and performance. *Journal of applied sport psychology, 7*(2), 112-137.

Sjøgaard, G., Kiens, B., Jørgensen, K., & Saltin, B. (1986). Intramuscular pressure, EMG and blood flow during low-level prolonged static contraction in man. *Acta Physiologica Scandinavica, 128*(3), 475-484.

Snook, S. H., & Ciriello, V. M. (1991). The design of manual handling tasks: revised tables of maximum acceptable weights and forces. *Ergonomics, 34*(9), 1197-1213.

Sonne, M. W., Hodder, J. N., Wells, R., & Potvin, J. R. (2015). Force time-history affects fatigue accumulation during repetitive handgrip tasks. *Journal of Electromyography and Kinesiology, 25*(1), 130-135.

Sonne, M. W., & Potvin, J. R. (2015). A psychophysical study to determine maximum acceptable efforts for a thumb abduction task with high duty cycles. *Ergonomics, 58*(1), 118-127.

Sonne, M. W., & Potvin, J. R. (2016). A modified version of the three-compartment model to predict fatigue during submaximal tasks with complex force-time histories. *Ergonomics, 59*(1), 85-98.

Sood, D., Nussbaum, M. A., & Hager, K. (2007). Fatigue during prolonged intermittent overhead work: reliability of measures and effects of working height. *Ergonomics, 50*(4), 497-513.

Staudenmann, D., Potvin, J. R., Kingma, I., Stegeman, D. F., & van Dieën, J. H. (2007). Effects of EMG processing on biomechanical models of muscle joint systems: sensitivity of trunk muscle moments, spinal forces, and stability. *Journal of biomechanics, 40*(4), 900-909.

Stegeman, D., & Hermens, H. (2007). Standards for surface electromyography: The European project Surface EMG for non-invasive assessment of muscles (SENIAM). *Enschede: Roessingh Research and Development*, 108-112.

Steven Moore, J., & Garg, A. (1995). The strain index: a proposed method to analyze jobs for risk of distal upper extremity disorders. *American Industrial Hygiene Association Journal, 56*(5), 443-458.

Strimpakos, N., Georgios, G., Eleni, K., Vasilios, K., & Jacqueline, O. (2005). Issues in relation to the repeatability of and correlation between EMG and Borg scale assessments of neck muscle fatigue. *Journal of Electromyography and Kinesiology, 15*(5), 452-465.

Swart, J., Lamberts, R. P., Lambert, M. I., Lambert, E. V., Woolrich, R. W., Johnston, S., & Noakes, T. D. (2009). Exercising with reserve: exercise regulation by perceived exertion in relation to duration of exercise and knowledge of endpoint. *British journal of sports medicine, 43*(10), 775-781.

Szalma, J. L. (2014). On the application of motivation theory to human factors/ergonomics: Motivational design principles for human–technology interaction. *Human factors, 56*(8), 1453-1471.

Taylor, J. L., Butler, J. E., Allen, G. M., & Gandevia, S. (1996). Changes in motor cortical excitability during human muscle fatigue. *The Journal of physiology, 490*(2), 519-528.

Taylor, J. L., & Gandevia, S. C. (2008). A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *Journal of Applied Physiology, 104*(2), 542-550.

Troiano, A., Naddeo, F., Sosso, E., Camarota, G., Merletti, R., & Mesin, L. (2008). Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait & Posture, 28*(2), 179-186. doi:https://doi.org/10.1016/j.gaitpost.2008.04.002

Tsuboi, T., Sato, T., Egawa, K. i., & Miyazaki, M. (1995). The effect of fatigue caused by electrical induction or voluntary contraction on Ia inhibition in human soleus muscle. *Neuroscience letters, 197*(1), 72-74.

Van Lunteren, E., & Moyer, M. (1996). Effects of DAP on diaphragm force and fatigue, including fatigue due to neurotransmission failure. *Journal of Applied Physiology, 81*(5), 2214-2220.

Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics, 36*(7), 749-776.

Westerblad, H., Bruton, J. D., & Katz, A. (2010). Skeletal muscle: energy metabolism, fiber types, fatigue and adaptability. *Experimental cell research, 316*(18), 3093-3099.

Whittaker, R. L., La Delfa, N. J., & Dickerson, C. R. (2019). Algorithmically detectable directional changes in upper extremity motion indicate substantial myoelectric shoulder muscle fatigue during a repetitive manual task. *Ergonomics, 62*(3), 431-443.

Whittaker, R. L., Sonne, M. W., & Potvin, J. R. (2019). Ratings of perceived fatigue predict fatigue induced declines in muscle strength during tasks with different distributions of effort and recovery. *Journal of Electromyography and Kinesiology*.

Williams, C., & Ratel, S. (2009). *Human muscle fatigue*: Routledge.

Wilmore, J. H. (1968). Influence of motivation on physical work capacity and performance. *Journal of Applied Physiology, 24*(4), 459-463.

Woods, J., Furbush, F., & Bigland-Ritchie, B. (1987). Evidence for a fatigue-induced reflex inhibition of motoneuron firing rates. *Journal of Neurophysiology*, *58*(1), 125-137.

Woods, S., Bridge, T., Nelson, D., Risse, K., & Pincivero, D. M. (2004). The effects of rest interval length on ratings of perceived exertion during dynamic knee extension exercise. *Journal of Strength and Conditioning Research, 18*(3), 540-545.

WSIB. (2017). *"By the numbers: 2017 WSIB statistical report"*. Ontario: Ontario Provincial Government.

Wu, L.-G., & Betz, W. J. (1998). Kinetics of Synaptic Depression and Vesicle Recycling after Tetanic Stimulation of Frog Motor Nerve Terminals. *Biophysical Journal, 74*(6), 3003-3009. doi:10.1016/S0006-3495(98)78007-5

Xia, T., & Law, L. A. F. (2008). A theoretical approach for modeling peripheral muscle fatigue and recovery. *Journal of biomechanics*, *41*(14), 3046-3052.

Yeung, S. S., Genaidy, A. M., Karwowski, W., & Leung, P. (2002). Reliability and validity of self-reported assessment of exposure and outcome variables for manual lifting tasks: a preliminary investigation. *Applied ergonomics*, *33*(5), 463-469.

Yung, M., Mathiassen, S. E., & Wells, R. P. (2012). Variation of force amplitude and its effects on local fatigue. *European journal of applied physiology*, *112*(11), 3865-3879.

Yung, M., & Wells, R. P. (2017). Documenting the Temporal Pattern of Fatigue Development. *IISE Transactions on Occupational Ergonomics and Human Factors, 5*(3-4), 115-135.

APPENDICES

Appendix A. Informed Consent – Study 1

UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

RESEARCH ETHICS BOARD
OFFICE OF RESEARCH SERVICES

Title of Research Study:
Effect of feedback on ratings of perceived fatigue during a repetitive upper extremity task

You are invited to participate in a research study entitled: *Effect of feedback on ratings of perceived fatigue during a repetitive upper extremity task*. This study has been reviewed the University of Ontario Institute of Technology Research Ethics Board REB #14969, and originally approved on August 15th, 2018.

Please read this consent form carefully, and feel free to ask the Researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, please contact the Research Ethics Coordinator at 905 721 8668 ext. 3693 or researchethics@uoit.ca.

Principal Investigator:

Dr. Nicholas J. La Delfa	Assistant Professor, Faculty of Health Sciences
	University of Ontario Institute of Technology (UOIT)
	2000 Simcoe Street North, Oshawa, ON L1H 7K4
	Phone #: 905.721.8668 ext. 2139
	Email: nicholas.ladelfa@uoit.ca

Student Lead:

Daniel M. Abdel-Malek	Graduate Student, Faculty of Health Sciences
	University of Ontario Institute of Technology (UOIT)
	2000 Simcoe Street North, Oshawa, ON L1H 7K4
	Phone #: 647.227.1629
	Email: daniel.abdel-malek@uoit.ca

<u>Supervisory Committee:</u>

Dr. Heather L. Sprenger — Assistant Professor, Faculty of Health Sciences

University of Ontario Institute of Technology (UOIT)

2000 Simcoe Street North, Oshawa, ON L1H 7K4

Phone #: 905.721.8668

Email: heather.sprenger@uoit.ca

Purpose:

The purpose of this study is to investigate whether a period of familiarization/practice improves the correlation between self-reported ratings of fatigue (RPF) with classical measures of neuromuscular fatigue.

Information for Participants:

We are seeking healthy participants between 18 and 45 years of age. We are looking for participants who do not have a history of acute or chronic shoulder or elbow pain/surgery within the past 12 months.

Procedure:

A. Initial Screening

Participants will have received a package of forms via email. This includes a copy of the informed consent, a questionnaire regarding demographic information, inclusion and exclusion criteria, and the Edinburgh Handedness Questionnaire. **Please note that the security of e-mail messages is not guaranteed. Messages may be forged, forwarded, kept indefinitely, or seen by others using the internet. Do not use e-mail to discuss information you think is sensitive. Do not use e-mail in an emergency since e-mail may be delayed.**

Participants are instructed to arrive at the laboratory either dressed, or prepare to be dressed (using the on-site change room facilities) in a comfortable athletic top or t-shirt. Upon arrival to the laboratory, participants will review the informed consent package with a member of the research team.

B. Baseline Measures

Once informed consent has been obtained and all forms have been submitted, participants will be ready to begin the study. Participants will be fitted with surface electromyography (sEMG) electrodes which passively measure muscle activity. You will be seated facing an adjustable table, with the dominant arm supported at 90° of shoulder and elbow flexion. From a supinated forearm position (palm of the hand facing you), you will be performing a repetitive work task involving isometric (constant posture) contractions at the elbow against a padded cuff that is connected to a force sensor that measures strength.Participants will first conduct strength tests of the biceps and triceps muscles of the upper arm via maximal elbow flexion and extension contractions(MVC’s) by performing maximal, respectively, for 3 seconds against resistance. Each participant will complete two MVC trials for each muscle with one-minute rest periods separating these trials. In addition, a subjective rating of perceived fatigue (RPF) will be recorded by asking the participants of their perceived fatigue level prior to beginning the protocol. Once these initial baseline procedures have been completed, the participant is ready to begin the study protocol.

C. Study Protocol

The experimental protocol involves a repetitive elbow flexion task that will be performed by an experimental and a control group, with the only difference being the provision of feedback of strength declines to the experimental group. You will be placed in one of the two groups. If you are placed in the control group, you will perform the same fatigue protocol for three identical sessions without feedback provided. For participants in the experimental group, you will receive feedback on your strength decline during the fatigue protocol. The same protocol will be repeated for 3 sessions, each on a separate day (separated by at least three days of rest), with the only difference in protocol being the provision of feedback to the experimental group in the second session. During this session, participants in the experimental group will be provided feedback on their strength decline from the initial baseline measurement, in both verbal and visual forms. The third session be the identical fatigue protocol to the first session.

You will be guided through the timing and effort level for the elbow flexion exertions by tracing a profile that will be presented in real-time on a computer monitor. These exertions will be completed in distinct 5 minute ‘cycles’. Each cycle consists of 4.5 minutes of exertions, followed by a 30-second rest interval between each cycle. During the 30-second rest periods, you will be asked to provide a rating of perceived fatigue. After every 10 minutes (or 2 cycles), a 3-second maximum elbow flexion test (identical to the strength tests performed before the protocol) will be conducted so we can assess how strength has decreased from baseline. During the second session, participants in the experimental group will be provided verbal and visual feedback on strength decline from rest after every MVC test, or 2 cycles. The cycles will be performed until volitional fatigue (participant communicates that they cannot continue), or until 60 minutes have elapsed (max. of 12 cycles).

Following task completion/termination, you will begin recovery while remaining seated, providing a series of measures, including strength tests (MVC’s) and RPF ratings, at 5 minute intervals. In the second session, participants in the experimental group will continue to receive feedback on their strength declines during recovery at these intervals. Once three recovery measures have been obtained (15-minutes), instrumentation will be removed, and the participant will be free to leave.

Potential Benefits:

You will not benefit *directly* from participating in this study. However, participation entails a direct contribution to current and future ergonomics guidelines: understanding whether providing feedback improves the correlation of perceived fatigue ratings to other fatigue measures can help reduce fatigue-related risks of injury in the workplace, should we be able to better predict fatigue onset in physical tasks.

Potential Risk or Discomforts:

There are very few risks associated with participation in the study. The main task requires you to perform repetitive contractions at the elbow for 4.5 minute cycles until volitional fatigue or 1-hour. The movement itself is common in everyday life, similar to a resistance exercise regimen, and does not pose a great threat to your health. However, you should know that localized muscle fatigue will set in during the study, which commonly results in a 'burning' sensation in the muscles. As soon as this discomfort becomes too severe and intolerable, notify the investigators immediately. Remember that you can withdraw from the study at any time, for any reason, without penalty. Your safety is the number one priority and you should not feel obligated to continue if you are in severe discomfort. However, you may experience mild discomfort with this task and will be asked to report your comfort levels periodically.

Secondly, the surface EMG markers pose a very low risk of skin irritation from the alcohol swab, razor, light abrasion, electrode gel or tape. These complications are not serious and they should subside within a few days. Participants will have access to soap and water to cleanse the affected area if this occurs. However, if these irritations persist, we recommend that the participant goes directly to the campus health clinic for medical advice and then contact the researchers to report the adverse event.

Storage of Data:

Collected data will be stored in a locked area at UOIT on an encrypted USB and hard-drive for seven years from the completion of the study. After this period, the data will be destroyed in accordance with university protocol.

Confidentiality:

Data to be collected will include muscle activation levels, strength decline, tissue oxygenation levels, and self-reported fatigue ratings. This data is collected for the purpose of monitoring the onset of neuromuscular fatigue during the work task, and will be stored on an encrypted hard-drive that is only accessible by the research team indicated above.

Identifiers will be removed from all data to maintain confidentiality of the participants.

Your privacy shall be respected. No information about your identity will be shared or published without your permission, unless required by law. Confidentiality will be provided to the fullest extent possible by law, professional practice, and ethical codes of conduct. Please note that confidentiality cannot be guaranteed while data are in transit over the Internet.

Right to Withdraw:

Your participation is voluntary, and you have the right to decline/discontinue participation without providing a reason. The information that is shared will be held in strict confidence and discussed only with the research team. You may withdraw participation at any time throughout the study without loss of any relevant compensation.

If you withdraw from the research project at any time, any data that you have contributed will be removed from the study and you need not offer any reason for doing making this request.

Compensation:

Participants will be compensated with a choice of either a $20 Tim Horton's gift card, or credit towards a course within the Faculty of Health Sciences program from a pre-organized list of available options.

Debriefing and Dissemination of Results:

The intent of this research is to improve the methods used in ergonomics. As such, the data for this research may be submitted to scientific conferences and peer-reviewed journals for publication. Published data will be coded and no personal identifiers will be included. If you wish to receive an aggregate of the research findings, please check the box at the bottom of this form and provide an email address to receive the results.

Thank You!

Thank you very much for your time and help in making this study possible!

If you have any questions concerning the research study, or experience any discomfort related to the study, please contact the researcher, Daniel Abdel-Malek, at 647.227.1629 or daniel.abdel-malek@uoit.ca. Alternatively, you may contact the principal investigator, Dr. Nicholas J. La Delfa, at 905.721.8668 ext. 2139, or nicholas.ladelfa@uoit.ca.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905.721.8668 x. 3693.

Sincerely,

Dr. Nicholas J. La Delfa

Assistant Professor, Faculty of Health Sciences

University of Ontario Institute of Technology

2000 Simcoe Street North, Oshawa, ON L1H 7K4

Phone #: 905.721.8668 ext. 2139

Email: nicholas.ladelfa@uoit.ca

Daniel M. Abdel-Malek

Graduate Student, Faculty of Health Sciences

University of Ontario Institute of Technology

2000 Simcoe Street North, Oshawa, ON L1H 7K4

Phone #: 647.227.1629

Email: daniel.abdelmalek@uoit.ca

By consenting, you do not waive any rights to legal recourse in the event of research-related harm.

Consent to Participate:

1. I have read the consent form and understand the study being described;
2. I have had an opportunity to ask questions and my questions have been answered. I am free to ask questions about the study in the future;
3. I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this Consent Form has been made available to me.

I give consent for the data from this study to be used in future research as long as there is no way that I can be identified in this research.

YES ☐ **NO** ☐

I would like to receive a short report about the outcomes of this study. (If you answer yes, please provide an email) ___________________________ **YES** ☐ **NO** ☐

By signing this form, you consent to participate in the study and you indicate that you understand the information provided to you within this document.

______________________________________ __________________________________

(Name of Participant) (Date)

______________________________________ __________________________________

(Signature of Participant)/ (Signature of Researcher)

To be signed by the Primary Investigator and/or Student Lead:

I have fully explained the study to the participant to the best of my ability. I have provided ample opportunities for the participant to ask questions and I have provided clear answers. It is my opinion that the participant fully understands the requirements of the study, the potential risks and benefits of the study. The participant has provided voluntary consent and was not coerced into taking part in the study.

____

____

Signature of the Investigator/Student Lead Date

Appendix B. Informed Consent – Study 2

UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

RESEARCH ETHICS BOARD
OFFICE OF RESEARCH SERVICES

Title of Research Study:

Neuromechanical response to repetitive workloads relative to current upper extremity ergonomics thresholds

You are invited to participate in a research study entitled: **Neuromechanical response to repetitive workloads relative to current upper extremity ergonomics thresholds**. This study has been reviewed the University of Ontario Institute of Technology Research Ethics Board REB #14962, and originally approved on August 21st, 2018.

Please read this consent form carefully, and feel free to ask the Researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, please contact the Research Ethics Coordinator at 905 721 8668 ext. 3693 or researchethics@uoit.ca.

Principal Investigator:

Dr. Nicholas J. La Delfa — Assistant Professor, Faculty of Health Sciences
University of Ontario Institute of Technology (UOIT)
2000 Simcoe Street North, Oshawa, ON L1H 7K4
Phone #: 905.721.8668 ext. 2139
Email: nicholas.ladelfa@uoit.ca

Student Lead:

Daniel M. Abdel-Malek — Graduate Student, Faculty of Health Sciences
University of Ontario Institute of Technology (UOIT)
2000 Simcoe Street North, Oshawa, ON L1H 7K4
Phone #: 647.227.1629
Email: daniel.abdel-malek@uoit.ca

<u>Supervisory Committee:</u>

Dr. Heather L. Sprenger — Assistant Professor, Faculty of Health Sciences

University of Ontario Institute of Technology (UOIT)

2000 Simcoe Street North, Oshawa, ON L1H 7K4

Phone #: 905.721.8668

Email: heather.sprenger@uoit.ca

External Funder/Sponsor: Centre of Research Expertise for the Prevention of Musculoskeletal Disorders (CRE-MSD)

Purpose:

The purpose of this study is to investigate how physiological measures of neuromuscular fatigue are influenced by duty cycles above and below acceptable limits of upper extremity tasks. This research aims to validate these currently implemented threshold limit values (TLV) using the following neuromuscular measures: muscle activation, strength decline, tissue oxygenation, and self-perceived ratings of fatigue.

Information for Participants:

We are seeking healthy participants between 18 and 45 years of age. We are looking for participants who do not have a history of acute or chronic shoulder or elbow pain/surgery within the past 12 months.

Procedure:

Participants will have received a package of forms via email. This includes a copy of the informed consent, a questionnaire regarding demographic information, inclusion and exclusion criteria, and the Edinburgh Handedness Questionnaire. Participants are instructed to arrive at the laboratory either dressed, or prepare to be dressed (using the on-site change room facilities) in a comfortable athletic top or t-shirt. Upon arrival to the laboratory, participants will review the informed consent package with a member of the research team.

Once informed consent has been obtained and all forms have been submitted, participants will be ready to begin the study. Participants will be fitted with surface electromyography (sEMG) electrodes and near-infrared spectroscopy (NIRS) sensors, which passively measure muscle activity and tissue oxygenation, respectively. You will be seated facing an adjustable table, with the dominant arm supported at 90° of shoulder and elbow flexion. From a supinated forearm position (palm of the hand facing you), you will be performing a repetitive work task involving isometric (constant posture) contractions at the elbow against a padded cuff connected to a force sensor that measures strength.

Participants will first conduct maximum voluntary contractions (MVC's) for the biceps and triceps brachii via maximal elbow flexion and extension contractions, respectively, for 3 seconds against resistance. Each participant will complete two MVC trials for each muscle with one-minute rest periods separating these trials. In addition, a subjective baseline rating of perceived fatigue (RPF) will be recorded by asking the participants of their perceived fatigue level prior to beginning the protocol. Once these initial baseline procedures have been completed, the participant is ready to begin the study protocol.

The experimental protocol involves a repetitive elbow flexion task that will be performed at three different work:rest ratios (i.e. duty cycles), each to occur on a separate day. In total, participants will attend four sessions, which include an initial familiarization session (Day 1), followed by three randomized experimental sessions with varied duty cycles (Days 2-4). Each day will be separated by at least three days to allow for adequate recovery. Participants will be guided through the timing and effort level for the elbow flexion exertions by tracing a profile that will be presented in real-time on a computer monitor. The timing of these exertions will be the only thing that changes between the three experimental session days, and are the main experimental manipulation in this study. Participants will complete these exertions in distinct 5 minute 'cycles'. Each cycle consists of 4.5 minutes of exertions, followed by 30-seconds of rest in between each cycle. During the 30-second rest periods, participants will be asked to provide their rating of perceived fatigue. After every 10 minutes (or 2 cycles), participants will conduct a 3-second maximum elbow flexion test so we can assess how much their strength has decreased. The cycles will be performed until volitional fatigue (participant communicates that they cannot continue), or until 60 minutes have elapsed (max. of 12 cycles). Following task completion/termination, the participant will begin recovery while remaining seated, providing a series of measures, including strength tests (MVC's) and RPF ratings, at 5 minute intervals. Once three recovery measures have been obtained (15-minutes), instrumentation will be removed, and the participant will be free to leave.

Potential Benefits:

You will not benefit *directly* from participating in this study. However, participation entails a direct contribution to current and future ergonomics guidelines: evaluation of current recommendations for upper extremity work will provide society with evidence-informed guidelines to reduce risk of injury in the workplace.

Potential Risk or Discomforts:

There are very few risks associated with participation in the study. The main task requires you to perform repetitive contractions at the elbow for 4.5 minute cycles until volitional fatigue or 1-hour. The movement itself is common in everyday life, similar to a resistance exercise regimen, and does not pose a great threat to your health. However, you should know that localized muscle fatigue will set in during the study, which commonly results in a 'burning' sensation in the muscles. As soon as this discomfort becomes too severe and intolerable, notify the investigators immediately. Remember that you can withdraw from the study at any time, for any reason, without penalty. Your safety is the number one priority and you should not feel obligated to continue if you are in severe discomfort. However, you may experience mild discomfort with this task and will be asked to report your comfort levels periodically.

Secondly, the surface EMG markers pose a very low risk of skin irritation from the alcohol swab, razor, light abrasion, electrode gel or tape. These complications are not serious and they should subside within a few days. Participants will have access to soap and water to cleanse the affected area if this occurs. However, if these irritations persist, we recommend that the participant goes directly to the campus health clinic for medical advice and then contact the researchers to report the adverse event.

Storage of Data:

Collected data will be stored in a locked area at UOIT on an encrypted USB and hard-drive for seven years from the completion of the study. After this period, the data will be destroyed in accordance with university protocol.

Confidentiality:

Data to be collected will include muscle activation levels, strength decline, tissue oxygenation levels, and self-reported fatigue ratings. This data is collected for the purpose of monitoring the onset of neuromuscular fatigue during the work task, and will be stored on an encrypted hard-drive that is only accessible by the research team indicated above.

Identifiers will be removed from all data to maintain confidentiality of the participants.

Your privacy shall be respected. No information about your identity will be shared or published without your permission, unless required by law. Confidentiality will be provided to the fullest extent possible by law, professional practice, and ethical codes of conduct. Please note that confidentiality cannot be guaranteed while data are in transit over the Internet.

Right to Withdraw:

Your participation is voluntary, and you have the right to decline/discontinue participation without providing a reason. The information that is shared will be held in strict confidence and discussed only with the research team. You may withdraw participation at any time throughout the study without loss of any relevant entitlements.

If you withdraw from the research project at any time, any data that you have contributed will be removed from the study and you need not offer any reason for doing making this request.

Compensation:

Participants will be compensated with a choice of either a $20 Tim Horton's gift card, or credit towards a course within the Faculty of Health Sciences program from a pre-organized list of available options.

Debriefing and Dissemination of Results:

The intent of this research is to evaluate ergonomics guidelines. As such, the data for this research may be submitted to scientific conferences and peer-reviewed journals for publication. Published data will be coded and no personal identifiers will be included. If you wish to receive an aggregate of the research findings, please check the box at the bottom of this form and provide an email address to receive the results.

Thank You!

Thank you very much for your time and help in making this study possible!

If you have any questions concerning the research study, or experience any discomfort related to the study, please contact the researcher, Daniel Abdel-Malek, at 647.227.1629 or daniel.abdel-malek@uoit.ca. Alternatively, you may contact the principal investigator, Dr. Nicholas J. La Delfa, at 905.721.8668 ext. 2139, or nicholas.ladelfa@uoit.ca.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905.721.8668 x. 3693.

Sincerely,

Dr. Nicholas J. La Delfa

Assistant Professor, Faculty of Health Sciences

University of Ontario Institute of Technology

2000 Simcoe Street North, Oshawa, ON L1H 7K4

Phone #: 905.721.8668 ext. 2139

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Daniel M. Abdel-Malek
Graduate Student, Faculty of Health Sciences

University of Ontario Institute of Technology

2000 Simcoe Street North, Oshawa, ON L1H 7K4

Phone #: 647.227.1629

Email: daniel.abdelmalek@uoit.ca

By consenting, you do not waive any rights to legal recourse in the event of research-related harm.

Consent to Participate:

1. I have read the consent form and understand the study being described;
2. I have had an opportunity to ask questions and my questions have been answered. I am free to ask questions about the study in the future;
3. I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this Consent Form has been made available to me.

I give consent for the data from this study to be used in future research as long as there is no way that I can be identified in this research. **YES** ☐ **NO** ☐

I would like to receive a short report about the outcomes of this study. (If you answer yes, please provide an email) _________________________ **YES** ☐ **NO** ☐

By signing this form, you consent to participate in the study and you indicate that you understand the information provided to you within this document.

_____________________________________ _________________________________

(Name of Participant) (Date)

_____________________________________ _________________________________

(Signature of Participant)/ (Signature of Researcher)

To be signed by the Primary Investigator and/or Student Lead:

I have fully explained the study to the participant to the best of my ability. I have provided ample opportunities for the participant to ask questions and I have provided clear answers. It is my opinion that the participant fully understands the requirements of the study, the potential risks and benefits of the study. The participant has provided voluntary consent and was not coerced into taking part in the study.

____

____

Signature of the Investigator/Student Lead Date

Appendix C. Edinburgh Handedness Inventory

Surname______________________ Given Name ______________________________

Date of Birth_____________________________Sex___________________________________

Please indicate your preferences in the use of hands in the following activities by *putting + in the appropriate column*. Where the preference is so strong that you would never try to use the other hand unless absolutely forces to, put ++. If any case you are really indifferent put + in both columns.

Some of the activities require both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object or task.

	Left	Right
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking Match (match)		
10. Opening box (lid)		
L.Q. Leave the spaces blank	DECLE	

Appendix D. Participant Demographics – Study 1

Title: ***Effect of feedback on ratings of perceived fatigue during a repetitive upper extremity task***

This study has been approved by the UOIT Research Ethics Board REB [#2517] on August 15th, 2018.

If you would like a copy of this consent form for your records, please ask the investigators. ***Received Copy:*** ***YES*** ☐ ***NO*** ☐

Name: ______________________________________ Gender (Circle one): Male Female

Date of Birth: _____________________________ Age: __________

Email Address: ____

Have you experienced shoulder and/or elbow pain in the last 12 months? **YES** ☐ **NO** ☐

Have you ever had upper arm/forearm surgery? **YES** ☐ **NO** ☐

Would you like to be notified with the aggregate results of the study when they are released in early 2019 via email? **YES** ☐ **NO** ☐

I hereby give consent for the information contained in this package to be used for the purposes of this study and in future research as long as there is no way that I can be identified**.** **YES** ☐ **NO** ☐

If you have any questions concerning the research study, please contact the researcher Daniel Abdel-Malek at 647.227.1629 or daniel.abdel-malek@uoit.ca. Alternatively, you can contact the principal investigator Dr. Nicholas La Delfa at 905.721.8668 x2139 or nicholas.ladelfa@uoit.ca.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905.721.8668 x. 3693.

________________________________ ______________________________

Participant Signature **Date**

Appendix E. Participant Demographics – Study 2

Title*: Neuromechanical response to repetitive workloads relative to current upper extremity ergonomics thresholds*

This study has been approved by the UOIT Research Ethics Board REB [#14962] on August 21st, 2018.

If you would like a copy of this consent form for your records, please ask the investigators. ***Received Copy:*** *YES* ☐ *NO* ☐

Name: ________________________________ Gender (Circle one): Male Female

Date of Birth: ____________________________ Age: _________

Email Address: ____

Have you experienced shoulder and/or elbow pain in the last 12 months? **YES** ☐ **NO** ☐

Have you ever had upper arm/forearm surgery? **YES** ☐ **NO** ☐

Would you like to be notified with the aggregate results of the study when they are released in early 2019 via email? **YES** ☐ **NO** ☐

I hereby give consent for the information contained in this package to be used for the purposes of this study and in future research as long as there is no way that I can be identified**.** **YES** ☐ **NO** ☐

If you have any questions concerning the research study, please contact the researcher Daniel Abdel-Malek at 647.227.1629 or daniel.abdel-malek@uoit.ca. Alternatively, you can contact the principal investigator Dr. Nicholas La Delfa at 905.721.8668 x2139 or nicholas.ladelfa@uoit.ca.

Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905.721.8668 x. 3693.

______________________________ ______________________________

Participant Signature **Date**