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Adaptation and validation of an analytical localized muscle fatigue model for workplace tasks

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ADAPTATION AND VALIDATION OF AN ANALYTICAL LOCALIZED MUSCLE FATIGUE MODEL FOR WORKPLACE TASKS

by

John Maurice Looft

A thesis submitted in partial fulfillment of the
requirements for the Doctor of Philosophy
degree in Biomedical Engineering
in the Graduate College of
The University of Iowa

December 2014

Thesis Supervisor: Associate Professor Laura Frey Law

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Graduate College
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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

John Maurice Looft

has been approved by the Examining Committee
for the thesis requirement for the Doctor of Philosophy
degree in Biomedical Engineering at the December 2014 graduation.

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To My Friends, Family, and Colleagues, for all your help, support, and patience

Remember to keep the horse in front of the cart and maintain control of the reins

John R. Looft
Grandpa's Everlasting Words of Wisdom

ACKNOWLEDGMENTS

The opportunities and journeys I have been able to partake in at the University of Iowa have led me on a path towards completing a childhood dream: receiving my Ph.D. The journey has been long and the road was winding and full of ups and downs and I have my friends to thank for keeping me focused and giving me the confidence I needed to keep going. I am also indebted to my advisor, colleague, and friend Professor Laura Frey Law for maintaining faith in me and letting me grow as a leader, researcher, teacher, and person. It was your faith in me which gave me the confidence I could actually accomplish this goal. I would also like to thank Professor Nicole Grosland, Nathan Fethke, David Wilder, and Tim Marler for continually pushing me to do better, dig deeper, and never be satisfied with good enough. You have all challenged and supported me throughout this process and I am extremely thankful. I also want to thank all of my undergraduate students for all the work you have done with me during my post graduate studies. I could not have completed all the work we have done without every one of you. Lastly I would like to thank my family for their unwavering support and willingness to continually answer late night phone calls to listen to me vocally workout a difficult problem. I would not have been able to reach this stage of my career without each and every one of you. Thank you.

ABSTRACT

Muscle fatigue is universally experienced in daily life, from recreational physical activity to the workplace. However, our ability to estimate fatigue is limited. Several attempts have been made to mathematically model the effects of fatigue, such as how long a muscle contraction may be sustained, known as 'endurance time.' However, these simple models of endurance time are limited to static contractions when the body is not moving, but muscles are contracted. This research aims to advance a previously proposed analytical model of muscle fatigue to represent complex tasks such as with rest intervals and dynamic contractions. Multiple methodologies were employed to assemble data to examine the model prediction accuracy, including 1) compiling previously published data involving intermittent rest intervals (i.e., meta-analysis); 2) experimentally collecting data on intermittent fatigue for shoulder flexion as it is not well represented in the literature; and 3) experimentally collecting data on fatigue during a dynamic task for elbow flexion as dynamic tasks have been virtually ignored in fatigue literature. The results of these investigations indicate that a mathematical model of fatigue is reasonably accurate in predicting an average fatigue response across multiple subjects for both intermittent and dynamic tasks, but does not currently reflect the often wide variation in muscle fatigue development that is observed between individuals. Accordingly, this type of modeling approach may have value for general assessments of fatigue accumulation, but will need further development and modification to better represent individual characteristics.

PUBLIC ABSTRACT

Fatigue is a part of everyone's daily lives. Some days we feel tired, other days our muscles are sore and we cannot perform the activities we would like. Muscle fatigue is a constant aspect of everyday life for many industrial, mechanical, and office workers. While it is a part of our everyday lives and has been studied for over a century, there is still much to learn about the long and short term effects of localized muscle fatigue. In order to learn about these effects, there first must be an objective way of measuring fatigue development. This dissertation attempts to improve on one such model to account for the variations and pauses that occur during the work day. The ability of the model to account for the rest muscles are given during these pauses and breaks during a particular work task would allow researchers and ergonomists to objectively assess muscle fatigue development and look at its potential health outcome effects. The first chapter outlines the increasing musculoskeletal disorder prevalence and what has already been examined. The next two chapters use published as well as collected experimental data to optimize the analytical fatigue model for each joint segment. The final chapter explores whether these model improvements increase the accuracy for dynamic tasks one might encounter in the workplace, while the last chapter summarizes the model improvements.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

CHAPTER 1:
INTRODUCTION

Musculoskeletal Risk

In the United States, musculoskeletal injuries and disorders continue to occur in epidemic proportions. The most recent U.S. Bureau of Labor Statistics (BLS) reports musculoskeletal disorders (MSDs) account for 33% of all illnesses and injuries requiring days from work with an incidence rate of 34/10,000 worker-years (BLS 2012). The economic burden MSDs cause the United States each year ventures into the billions. Many studies have estimated the direct cost of MSDs on the order of 50 billion dollars per year (Yelin, Callahan et al. 1995, Silverstein, Viikari-Juntura et al. 2002). However, the total cost of MSDs is more realistically on the order of 100's of billions of dollars per year, (Yelin, Callahan et al. 1995, Buckle and Devereux 2002).

The American Conference of Governmental Industrial Hygienists (ACGIH) have spent decades determining Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs) to set guidelines regarding safe levels of exposures for various chemicals and physical agents found in the workplace (ACGIH 2010). While MSDs continue to be a modern day epidemic, there are only TLVs for hand activity level (HAL TLV) and vibration (ACGIH 2010). However, there are no equivalent guidelines for other known ergonomic exposures (i.e. forceful exertions, awkward postures, etc.) thought to be contributive causes of MSDs (Gerr, Fethke et al. 2013).

Even the Occupational Safety and Health Administration (OSHA) declines to explicitly set ergonomic exposure guidelines, instead OSHA guidelines lean on the "General Duty Clause" to ensure ergonomics safety is enforced. The General Duty Clause states "each employer (1) shall furnish to each of his employees employment and place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees; (2) shall comply with occupational safety and health standards promulgated under this

Act."(Morey 1973). While this clause provides a degree of insurance to workers their workplaces are free from known hazards, there are no direct ergonomic guidelines and minimal TLVs available.

Ergonomic Tools

Ergonomics is derived from two Greek root words: "ergo" meaning work and "nomas" meaning natural laws of. So the literal definition of ergonomics is the natural laws of work. Occupational safety and health officials study workplace tasks with the hopes of 1) identifying and 2) minimizing potential musculoskeletal risk factors. Research efforts over the past decades have identified three categories of risk: physical, personal, and psychosocial (Table 1- 1). Ergonomists have also developed many risk assessment tools (Table 1- 2) aimed at identifying whether a workplace task has an increased risk of causing the development of MSDs. The most common ergonomic tools are aimed at using physical risk factors to calculate MSD risk. These types of tools fall under two categories 1) postural and 2) activity analysis.

A commonly used postural analysis tool, rapid entire body index (REBA), can be applied either as a measure of worst case scenario (Hignett and McAtamney 2000) or in a work sampling method (Janowitz, Gillen et al. 2006). The advantage of applying REBA as a work sampling method is task risk can be assessed for an entire exposure period. Work sampling allows ergonomist to calculate the percentage of time a worker spends in each of the REBA's risk categories. This gives a more detailed assessment of total exposure compared to the one worst case rating.

While REBA work sampling provides valuable exposure information, REBA does not capture the busyness or work rate of the distal upper extremities (DUE). Fortunately there are ergonomic tools designed to measure DUE risk; the Strain Index (SI) is commonly used due to its high specificity, inter-rater reliability and repeatability (Moore and Garg 1995, Knox and Moore 2001, Stevens, Vos et al. 2004). The SI is useful for determining whether performing a task would lead to an increased risk for developing DUE disorders due to intensity of exertion, duration of exertion, efforts per minute, hand and wrist posture, speed of work, and duration per day.

While both of these methods have been used individually to assess risk, performing ergonomic analyses using both these methods in parallel provides a better perspective on the total exposure dose experienced by the workers (Jones and Kumar 2007, Mukhopadhyay and Srivastava 2010, Chiasson, Imbeau et al. 2012, Kapellusch, Garg et al. 2013). Recent prospective studies have found strong associations between musculoskeletal outcomes and physical risk factors even though some associations were non-significant (Gerr, Fethke et al. 2013b, Meyers, Gerr et al. 2014). Even with these strong associations, there are still elements of risk not captured by these assessment methods.

Each of the common risk assessment tools (Table 1- 2) under the Postural Analysis and Activity Analysis headings do not take into account the human body is a dynamic system. As the worker performs an activity, their body fatigues and has less energy. This energy consumption is not accounted for in either of these assessment methods. The Rogers Muscle Fatigue Analysis (Rodgers 1992) is rarely used subjective checklist assessment tool of muscle fatigue development.

Objective measures of localized muscle fatigue could potentially be a useful tool as fatigue develops during repeated, sustained, and/or strong contractions analogous to ergonomic exposures: repetitive motions, forceful exertions, and heavy lifting. Many attempts have been made to prove fatigue development increases injury risk with mixed results (Voight, Hardin et al. 1996, Miura, Ishibashi et al. 2004, McLean, Felin et al. 2007, Borotikar, Newcomer et al. 2008), leading to the all too familiar "the chicken or the egg" paradox. Regardless, researchers and ergonomists agree fatigue is an important factor and requires consideration.

Muscle Fatigue Definition

Muscle fatigue has many diverse and common definitions, so it is important to explicitly define muscle fatigue for the purpose of this dissertation. The broad definition of fatigue will be condensed from the following definition: "any reduction in force generation in response to a voluntary muscle contraction" (Gandevia 1992, Chaffin, Andersson et al. 2006), to a more specific definition: localized muscle fatigue is any reduction in force generation about a particular joint in response to a series or individual event of voluntary muscle contraction. With localized muscle fatigue defined, it is important to review common practice methodology for assessing and measuring fatigue. Consider the following academic example:

Initial Muscle Fatigue Modeling

An individual picks up a dumbbell and holds the dumbbell with his elbow flexed at 90 degrees and holds the weight until the elbow can no longer maintain 90 degrees (Figure 1- 1). A researcher starts a stop watch when the individual first reaches 90 degrees and stops the watch at the moment the individual's arm moves. This measured time is known as the endurance time (ET) and is easily attainable during isometric (constant muscle length) contractions like the provided example.

Using constant load or constant angle (Figure 1- 2) isometric fatiguing tasks have been well studied and defined (Deeb, Drury et al. 1992, Hunter and Enoka 2001, Enoka, Christou et al. 2003, Dimitrova, Arabadzhiev et al. 2009). Throughout the past century ETs have been collected for a wide range isometric task intensities and joint regions (Hansen and Lindhard 1923, Reid 1929, Tuttle, Janney et al. 1950, Burke, Tuttle et al. 1953, Merton 1954, Naess and Stormmathisen 1955, Clarke, Hellon et al. 1958). Even these early studies suggested a nonlinear relationship between task intensity and ET.

The first model (Figure 1- 3) to demonstrate this nonlinearity was presented by Rohmert (1960). Since Rohmert's original paper many studies have confirmed the nonlinear relationship between intensity and ET holds across multiple joint complexes (Rohmert 1960, Monod and Scherrer 1965, Huijgens 1981, Sato, Ohashi et al. 1984, Manenica 1986, Rose, Ericson et al. 2000, Ma, Chablat et al. 2009, Frey Law and Avin 2010).

Rohmert's model and many others demonstrate lower intensity tasks have very large ETs (i.e. hours); this presents problems with validation efforts due to issues with maintaining subject concentration during long testing periods. These models were developed from static isometric tasks. However, workplace tasks are often intermittent and dynamic. ET also does not provide a useful time course of fatigue development which can be used to predict when injury risk increases. Thus, ET, while potentially useful for preliminary work task assessments, may provide a poor direct prediction of MSD risk development; whereas, predictive models of fatigue development may provide better representations of ergonomic exposures for future risk assessments.

Muscle Fatigue Modeling Advancements

In order to accurately predict muscle fatigue development, predictive models must be able to model workplace tasks. Biomechanical modeling has been a fascination of man since Leonardo Da Vinci's Vitruvian Man around 1490. From Da Vinci to the present day computer and mass data age, this passion has not waned but exponential exploded. Musculoskeletal models now range from modeling individual muscle contractile interactions (Hill 1938, Bendall 1952) to the musculoskeletal system (Van Der Helm, Veeger et al. 1992, Van Der Helm 1994, Charlton and Johnson 2001, Gatton, Pearcy et al. 2001, Desailly, Sardain et al. 2010) to whole body-environmental interactions (Delp, Anderson et al. 2007, Abdel-Malek, Arora et al. 2009).

The muscle fatigue realm has also seen its share of model development (Rohmert 1960, Rose, Ericson et al. 2000, El Ahrache, Imbeau et al. 2006, Ma, Chablat et al. 2009, Frey Law and Avin 2010). Many nonlinear intensity-ET regression models of isometric fatigue have been developed and are summarized in (El Ahrache, Imbeau et al. 2006). However, it is difficult to make industrial generalizations form these models due to work place tasks being more intermittent and dynamic (as briefly mentioned above).

Analytical Fatigue Model

Rohmert introduced empirical muscle fatigue modeling and provided the initial fatigue predictions for isometric tasks (Rohmert 1960). Recently an analytical model for predicting localized fatigue development and paved the way for implementing muscle fatigue predictions into digital human models (DHMs) (Liu, Brown et al. 2002). However, Liu's model can only assess tasks which occur at maximal effort (Liu, Brown et al. 2002). Most workplace tasks require different force outputs at varying submaximal intensities performed throughout the task. Some aspects may involve high forces for short durations and other aspects lower constant forces for an extended period of time. These types of tasks tend to be more dynamic and intermittent, which does not easily lend itself for fatigue outcomes to be assessed by simple empirical models.

The three-compartmental biophysical model proposed by (Xia and Frey Law 2008) is comprised of three differential equations (Equation 1-Equation 3) regulating the "flow" rate from one muscle phase to the next (Figure 1- 4). Unlike the Liu model design (Liu, Brown et al. 2002), flow is allowed from the fatigue phase back to the resting phase after a period of time regulated by the recovery "R" parameter. The Xia and Frey Law model also introduced a feedback proportional controller (C(t)) to regulate the activation and deactivation of the active muscle phase (Equation 4-Equation 6); where the controller is dependent on the relative "volumes" of the three compartments relative to the target task intensity level (TL). These deviations from similar models allow for discrete analysis of the three muscle phases at various time points. See (Xia and Frey Law 2008) for more detail.

Equation 1- 1: $dM_R/dt = -C(t) + R*M_F$

Equation 1- 2: $dM_A/dt = C(t) - F*M_A$

Equation 1- 3: $dM_F/dt = F*M_A - R*M_F$

Equation 1- 4: $C(t) = L * (TL – M_A)$, if $M_A < TL$ and $M_R > (TL - M_A)$,

Equation 1- 5: $C(t) = L * M_R$, if $M_A < TL$ and $M_R < (TL - M_A)$,

Equation 1- 6: $C(t) = L * (TL – M_A)$, if $M_A \geq TL$,

Where:

C(t) = the controller denoting the muscle activation-deactivation drive;

F = fatigue parameter defining the flow rate between the active and fatigued compartments;

R = recovery parameter defining the flow rate between the fatigued and resting compartments;

L = an arbitrary constant tracking factor to ensure good system behavior (=10).

While the model was originally presented as having the ability to model single fiber fatigue (Xia and Frey Law 2008), all validation efforts have employed the model at the 'joint-level' (Frey-Law, Looft et al. 2012, Looft 2012).

Model Validation Review

The model was validated for isometric tasks, optimizing the two model parameters (F and R) to joint-specific ET-intensity curves developed from a large meta-analysis (Frey Law and Avin 2010) summarized in Table 1- 3. The results of this study found the biophysical analytical muscle fatigue model was highly accurate for static isometric tasks (Table 1- 4) and resulted in unique F and R parameter values for each joint region (Frey-Law, Looft et al. 2012).

A similar method was used for the intermittent isometric validation study (Looft, 2012), but instead of comparisons to two-dimensional intensity-ET curves, three-dimensional curves including duty cycle (DC) were used. In addition, unlike static isometric studies, most intermittent fatiguing tasks are conducted to a specific time point instead of until ET is met. Thus, instead of using ET as the outcome variable of interest, percent torque decline (pTD) data relative to the initial maximal voluntary contractions (MVCs) at discrete times were used across multiple DC and intensities for each available joint region.

A comprehensive review of available literature revealed most of the available literature hovered around both high or low intensities and DCs (Figure 1- 5) making development of generalizable empirical models difficult. The results revealed the model predictions were unable to adequately predict the limited available data at the intermediate intensities and DCs at most joints. The analytical models were also shown to consistently over predict the empirical models. A closer inspection of intermittent contractions shows there are interspaced rest periods throughout the task, but the analytical model was validated against isometric tasks where these rest periods are absent. During these rest periods, muscle reperfusion can occur which would increase the muscle recovery. To account for the muscle reperfusion, a rest multiplier may need to be added to the model. Consequently, "gold standard" empirical surfaces for intermittent isometric tasks were not feasible to create for validation of the analytical model; however data sets from the meta-analysis could be used for validation against assimilated means at each available intensity and DC combination.

Project Goals

The overall goal of this dissertation was to advance the analytical fatigue model presented by (Xia and Frey Law 2008) though the inclusion of a rest multiplier (r) parameter to account for muscle reperfusion during intermittent rest periods and to compare adapted model predictions to available and newly collected experimental muscle fatigue data. To achieve these goals, the following three specific aims were assessed.

Specific Aim 1:

To determine the degree to which the addition of a rest multiplier (r) to the analytical fatigue model improves model predictions accuracy relative to available published fatigue data.

Hypothesis 1a:

A rest multiplier (r) parameter will represent the improved muscle recovery due to muscle reperfusion during intermittent rest periods absent during sustained contractions and the rest multiplier (r) will improve model predictions of pTD at multiple time points by greater than 50% RMS error.

Rationale: The analytical model was originally designed for static isometric tasks, thus the model does not take into account the increased blood flow through the muscles during the resting phase of the intermittent task. During a static isometric task the muscle is in a constant state of contraction, after a period of time blood flow to the muscle is minimized. This is not the case for intermittent tasks where blood flow can occur during the rest periods.

Hypothesis 1b:

Optimal rest multiplier (r) parameters across task intensities and DC will vary between joints similar to the optimal fatigue (F) and recovery (R) parameters found by (Frey-Law, Looft et al. 2012).

Rationale: The large meta-analysis conducted by (Frey Law and Avin 2010) demonstrated different joints fatigue at different rates. This trend was also shown during model optimization of the fatigue (F) and recovery (R) parameters for isometric tasks (Frey-Law, Looft et al. 2012). These results suggest the optimal rest multiplier (r) parameter will also vary by joint.

Specific Aim 2:

To collect data on muscle fatigue during intermittent shoulder fatiguing tasks and to assess how well the adapted analytical fatigue model matches these experimental findings

Hypothesis 2:

The inclusion of a rest multiplier (r) parameter will improve model predictions (i.e. decrease RMS error) of pTD at multiple time points.

Rationale: Although insufficient pTD data for the shoulder was found during the initial meta-analysis; a single observational study will provide preliminary insights into model accuracy with the additional rest multiplier (r).

Specific Aim 3:

To test the adapted analytical fatigue model's ability to predict fatigue behavior during dynamic elbow flexion/extension task.

Hypothesis 3:

The analytical model will provide reasonable predictions of pTD and ET during a dynamic isotonic elbow flexion fatiguing task by evaluating model agreement (Bland-Altman plots and Intraclass correlation coefficients (ICC)).

Rationale: Although intermittent tasks are more common in industrial settings, they are not the most common types of contractions. Dynamic contractions are the most common types of motions performed in the workplace. In order for fatigue accumulation to be included in ergonomic assessments, models must be able to predict fatigue development during these complex motions where the worker determines the rate and speed at which they perform forceful exertions similar to (Snook and Ciriello 1991).

In summary, this dissertation focused on advancing and validating the analytical fatigue model proposed by Xia and Frey Law (2008). The model advancements was the addition of a rest multiplier during non-contraction phases of tasks. A sensitivity analysis was performed using literature data sets. In addition to literature data sets, subject data sets were collected for the shoulder joint, while simultaneously accessing the fatigue development and muscle recruitment strategies during an intermittent shoulder flexion fatiguing task. Lastly, model predictions for dynamic tasks were piloted. This last stage aimed at demonstrating whether the presented advanced analytical fatigue model could appropriately be used to quantify the development of fatigue during dynamic tasks.

Table 1- 1: List of Ergonomic Risk Factors

Personal	Physical	Psychosocial[±]
Age	Static postures	Decision latitude (“control”)
Sex	Heavy lifting	Psychological job demand
Medical history	Awkward postures	Coworker support
Smoking	Forceful exertions	Supervisor support
Obesity	Fatigue	Negative affectivity
	Repetitive motions	Stress
	Vibration	Task or job change

±Types of psychosocial risk factors listed by (Gerr, Fethke et al. 2013)

Table 1- 2: Exposure factors assessed by different methods adapted from David (2005).

	Postures	Load/ Force	Movement frequency	Duration	Recovery	Vibration	Others±
REBA[1]	X	X	X				X
RULA[2]	X	X	X				
OWAS[3]	X	X					
PATH[4]	X	X	X				
OCRA[5]	X	X	X	X	X	X	X
Strain Index[6]	X	X	X	X			X
HAL TLV[7]	X	X	X				
NIOSH Lifting Eq[8]	X	X	X	X	X		X
Rodgers Muscle Fatigue Analysis[9]	X	X	X	X			

1: (Hignett and McAtamney 2000) 2: (Mcatamney and Corlett 1993) 3: (Karhu, Kansi et al. 1977)
4: (Buchholz, Paquet et al. 1996) 5: (Colombini and Occhipinti 2006) 6: (Moore and Garg 1995)
7: (ACGIH 2010) 8: (Waters, Putzanderson et al. 1993) 9: (Rodgers 1992)

±These include mechanical compression, glove use, environmental conditions, equipment, load coupling, team work, visual demands, psychosocial and individual factors (David 2005).

Table 1- 3: Summary table of the studies[+] used to develop the power equation for each of the joint regions (ET = b0 * (Intensity)^{b1}) (Frey Law and Avin 2010).

Joint	Sample Size (N)	Data Points[±]	Studies	b_0	b_1	R^2
Ankle	207	40	20	21.92	-1.98	0.884
Knee	875	93	56	34.71	-2.06	0.789
Trunk	307	33	17	22.69	-2.27	0.885
Shoulder	176	17	13	17.98	-2.21	0.897
Elbow	838	126	60	33.55	-1.61	0.915
Hand/Grip	786	60	42	19.38	-1.88	0.748
General	3189	369	194[++]	14.86	-1.83	0.814

+ All studies included healthy young adults (18 - 55 yrs), with a range of reported activity levels (untrained to elite athletes).

++ The sum of all joint studies (general model) is greater than those meeting inclusion criteria (N = 194) due to 15 studies reporting multiple joints.

± Data points are defined as the number of ETs taken from the literature

Table 1- 4: Optimal fatigue F and R parameters by joint (Frey Law and Avin 2010)

Joint Region	F	R	Within 95% PI	RMS Error
Ankle	0.00589	0.00058	8/9	101.19
Knee	0.01500	0.00149	8/9	60.53
Trunk	0.00755	0.00075	8/9	83.67
Shoulder	0.01820	0.00168	8/9	24.01
Elbow	0.00912	0.00094	8/9	88.79
Hand/Grip	0.00980	0.00064	7/9	50.04
General	0.00970	0.00091	8/9	59.22

+ The inclusion criteria were: studies with healthy human subjects, ages between 18-55 years old, intermittent/static tasks with force/torque data, a task time of at least 30 seconds, and published in English

Figure 1- 1: An example of an isometric fatiguing bicep curl task using a constant load.

Figure 1- 2: A controlled isometric fatiguing bicep curl task using a constant angle.

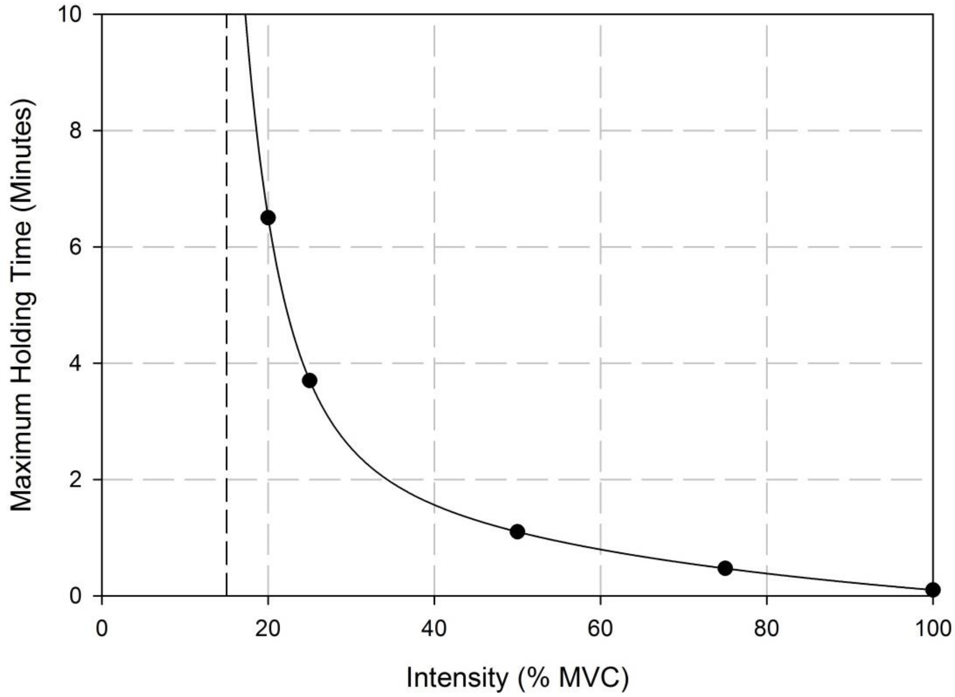

Figure 1- 3: Representation of (Rohmert 1960)'s original curve where tasks can last to infinity at 15% MVC.

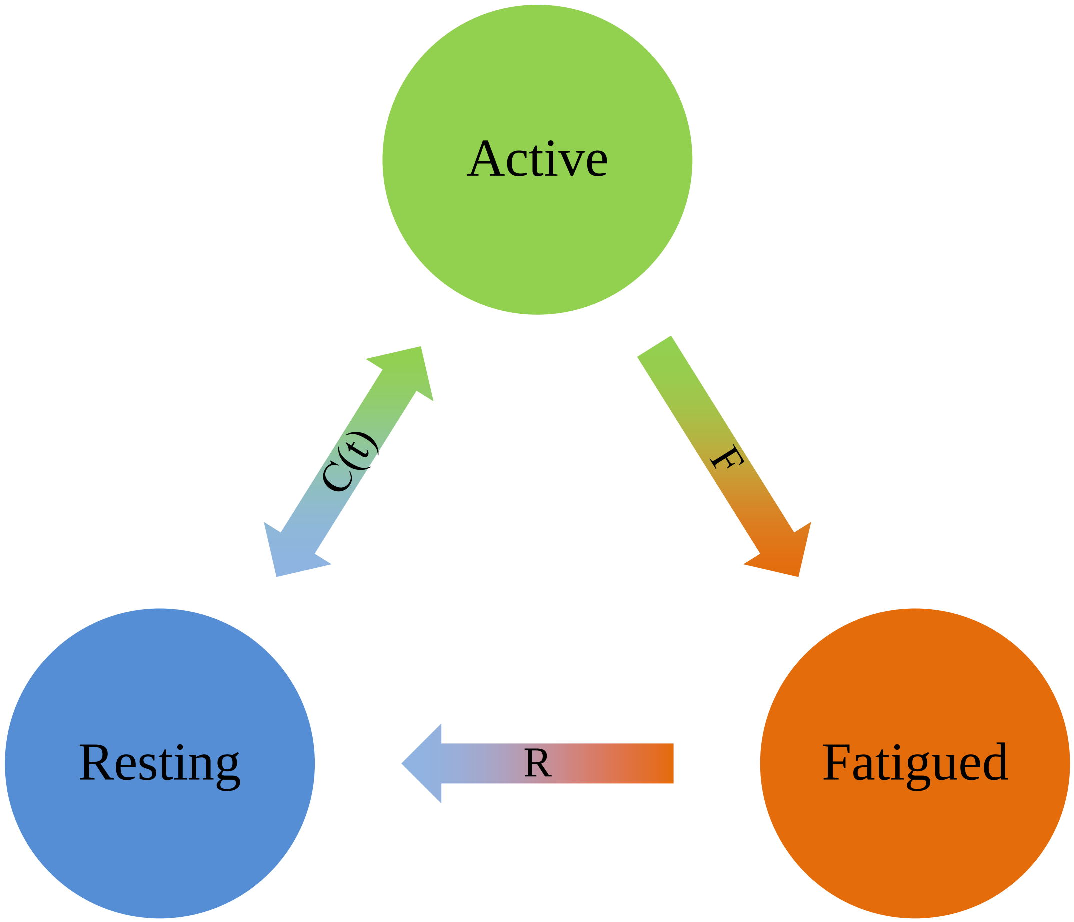

Figure 1- 4: Visual representation of the analytical model proposed by (Xia and Frey Law 2008)

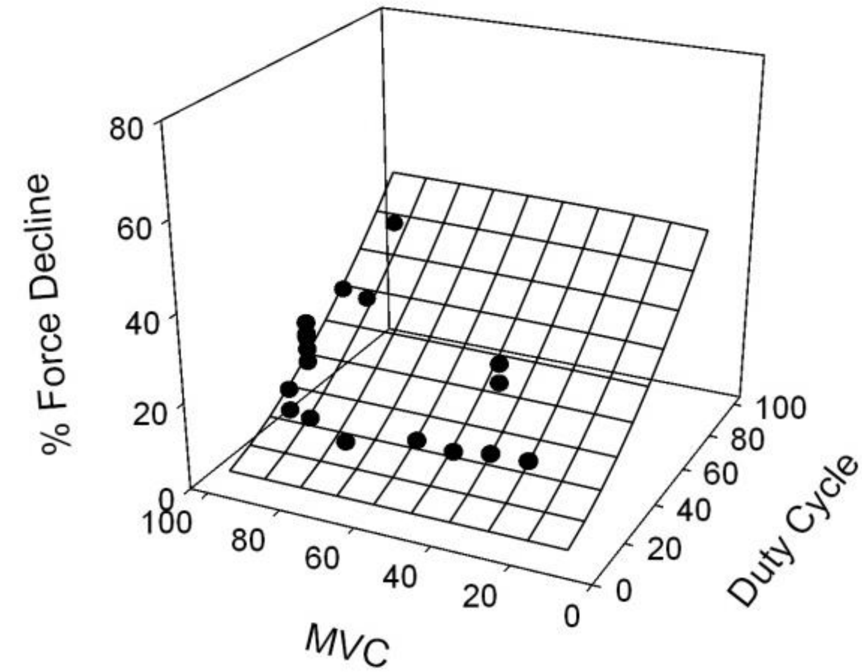

Figure 1- 5: Empirical percent torque decline model for the ankle at 60 seconds and the data points used to create the empirical model from (Looft 2012).

CHAPTER 2:
ANALYTICAL FATIGUE MODEL ADAPTATION: INTERMITTENT CONTRACTIONS

Introduction

The recent emphasis in developing analytical simulations and computerized solutions to facilitate potential solutions to the musculoskeletal disorder epidemic has led to the development of many ergonomic software solutions. One interesting software development is the digital human model (DHM) (Delp, Anderson et al. 2007, Abdel-Malek, Arora et al. 2009). DHMs are advertised as computer representations of soldiers, consumers, workers, etc. These models have the potential to provide ergonomists with additional analysis of various work tasks, including biological measures such as localized muscle fatigue.

Traditionally, muscle fatigue has been described by non-linear curves commonly referred to as Rohmert curves (Rohmert 1960). Rohmert curves describe the non-linear relationship between intensity and endurance time for static isometric tasks. Over the past half century several authors have studied and confirmed the non-linearity for various joint segments (El Ahrache, Imbeau et al. 2006). A recent meta-analysis compiled endurance time data from 208 publications to create joint specific empirical intensity-ET models for many joint regions (ankle, knee, trunk, shoulder, elbow, and hand/grip) (Frey Law and Avin 2010).

However, these models provide little information on localized muscle fatigue development due to work. These models are inherently limited due to isometric contractions are observed less than intermittent or dynamic contractions in common workplace settings. This limitation has led to an increased interest in modeling intermittent and dynamic contractions (Ma, Chablat et al. 2009, Ma, Chablat et al. 2011).

The analytical fatigue model proposed by (Xia and Frey Law 2008), was validated for isometric tasks (Frey-Law, Looft et al. 2012). However, the validation effort for intermittent tasks (Looft 2012) was found to be inconclusive due to **(1)** the limited available literature data at low duty cycles (DC) and intensities, **(2)** the restricted inclusion criteria, and **(3)** the analytical model's conceptual design.

The analytical model was conceptually developed with three compartments (resting, active, and fatigued) with three differential equations (Equation 1- 1-Equation 1- 3) describing the flow rate from one state to another with a feedback proportional controller to define activation and deactivation of muscle activity (Figure 1- 4) (Xia and Frey Law 2008, Frey-Law, Looft et al. 2012).

After a closer inspection of the differential equations describing the flow rate from fatigued to resting (Equation 1- 3), one can observe there is no parameter or state case to increase the rate of recovery during the rest periods between contractions. This is particularly important for intermittent contractions where the rest breaks between contractions have been shown to increase the ET of a fatiguing task (Alway 1991, Wood, Fisher et al. 1997, Iridiastadi and Nussbaum 2006, Iridiastadi and Nussbaum 2006b). During these rest breaks there is an opportunity for an increase in blood flow. This increase in blood flow is thought to increase the ability for the muscle to recover which leads to longer ET for intermittent isometric compared to static isometric contractions (Lanza, Wigmore et al. 2006). Blood flow occlusion studies have also found decreased ETs compared to free flow for identical fatiguing protocols (Birtles, Rayson et al. 2003, Chung, Callahan et al. 2007).

The plethora of evidence for increased recovery during the rest period phase of intermittent tasks suggests the analytical model should have a rest multiplier (r) included (Figure 2- 1 and Equation 2- 1). Thus, the objectives of this study were to test the hypotheses: **1) A rest multiplier (r) parameter will represent the improved muscle recovery due to muscle reperfusion during intermittent rest periods absent during sustained contractions and 2) the optimal rest multiplier (r) parameters across task intensities and DC will vary between joints**, by conducting a meta-analysis of available torque decline literature data to create data sets to compare to the model predictions for a range of potential (r).

Equation 2- 1: Increased Recovery State $dM_R/dt = -C(t) + R*r*M_F$, if $C(t)=0$

Methods

Systematic Literature Review

A 2-stage systematic review of available literature was conducted to find all relevant torque decline data as a function of intensity and DC. The first stage literature search was conducted using the following databases: PubMed, Cumulative Index to Nursing and Allied Health Literature (CINAHL), Web of Science, and Google Scholar. A total of 17 search terms/keyword combinations were used to elicit relevant articles including: intermittent static fatigue, intermittent fatigue, intermittent isometric, endurance intermittent, intermittent and fatigue, isometric and fatigue, muscle torque decline, and combinations of the above with specific joints: ankle, knee, elbow, trunk, shoulder, elbow, wrist/hand. In addition, early searches found studies with creatine supplementation often used a double blind study design, where a control group was given a placebo and incorporated intermittent fatiguing tasks. Thus creatine supplementation was added as a secondary search term.

The outcome measure, percent torque decline (pTD), was selected due to intermittent tasks at low intensities and DC can last on the order of hours. These types of fatiguing tasks are commonly stopped before ET due to issues maintaining subject concentration and attention to performing the task. The inclusion/exclusion criteria (see below) were then implemented to include only studies of interest.

The second search involved examining the bibliographies of inclusion articles to find additional relevant publications. The inclusion/exclusion criteria were then applied to this second set of articles. All authors reviewed the studies to ensure agreement on the inclusion/exclusion criteria as well as data extraction. All data were double checked against the original articles to minimize the possibility of extraction errors.

Inclusion and Exclusion Criteria

The inclusion criteria included: healthy human subjects, 18-55 years old, intermittent isometric tasks with force/torque data, and published in English. Exclusion criteria included: dynamic contractions, simultaneous multi-joint testing (e.g. squat lifts), functional tasks, body/limb weight as primary resistance, and electrically stimulated contractions. Similar to (Frey Law and Avin 2010), data from patient populations or interventions studies (i.e. creatine supplementation) were not used for the analysis, but any control subjects' data were included when available.

Sensitivity Analysis

pTD data at 30 second time intervals were assimilated in Microsoft Excel along with the intensity and DC for each joint region. The analytical model was then run for each intensity and DC and pTD was calculated as each available time point. The pTD was then calculated after the rest multiplier was then varied from 1 (i.e. no change) to 40.

The optimal rest multiplier (r) parameter values were determined as those producing the least error compaired to the data set found by the meta-analysis for each joint region: ankle, knee, trunk, shoulder, elbow, and grip. Error was calculated as the root mean square (RMS) (Equation 2- 2)between the predicted and observed pTD data points at each available time point across each intensity and DC combination found during the meta-analysis of available pTD data. The optimal rest multiplier (r) for each joint region was determined by a combination of lowest RMS error. RMS error percent difference was also calculated between the best (r) and model predictions with no rest multiplier (i.e. r=1).

Equation 2- 2: RMS Error = $\sqrt{((\Sigma (\text{modeled-observed})^2)/n)}$

Where:

Modeled- the analytical model predictions at each available intensity and DC

Observed- the empirical data at each available intensity and DC

Results

Literature Review

The search stragey elicited 2781 potential publications, search refinements (human studies, writtent in English) yeilded 2392 articles. The selected inclusion and exclusion criteria found 78 appropriate articles to create data sets for each joint region outlined by (Frey Law and Avin 2010). The meta anaylsis found no studies met the inclusion and exclution criteria for the shoulder and tunk joint regions. The final number of studies for each avaiable joint region is outlined in Table 2- 1. The grip joint region included studies of grip, first dorsal interosseaus (FDI), abductor pollicis brevis (ABP), and adductor pollicis (ADP), similar to (Frey Law and Avin 2010). The total number of data for each joint region ranged for 70 (elbow)-155 (ankle) with a total of 457 extacted data points Table 2- 1.

Sensitivity Analysis

The optimal joint specific rest multiplier found as a result of varying the r values from 1 to 40 are provided in Table 2- 2. The analytical model performed better with the addition of the rest multiplier (r) decreasing the RMS error between the model and the meta-analysis observations for each available joint region (Table 2- 2).

Discussion

The objectives of this study were to test the hypothesis: **1) A rest multiplier (r) parameter will represent the improved muscle recovery due to muscle reperfusion during intermittent rest periods absent during sustained contractions and 2) the optimal rest multiplier (r) parameters across task intensities and DC will vary between joints**, by conducting a meta-analysis of available torque decline literature data to create data sets to compare to the model predictions for a range of potential (r). The meta-analysis was able to collect a range of data sets for the ankle, knee, elbow, and grip joint regions. However the meta-analysis was unable to ascertain relevant studies for both the trunk and joint regions.

The available joint specific data sets were then used to assess model predictions with the addition of a rest multiplier to the analytical model to test the hypothesis. The resulting model sensitivity analysis found the rest multiplier (r) increased the accuracy of the analytical model across each available joint region nearly by nearly 100% (Table 2- 2). These study results support the hypothesis and demonstrate the proposed new analytical model has a degree of validation for intermittent isometric tasks.

The current study's RMS error ranged between 3.0% and 15.5%, well below the demonstrated expected subject variations found in ETs which ranged between 29% and 47% (Frey Law and Avin 2010). Suggesting model errors are well below the normal inter subject variation. Overall the joint specific r values resulted in an increase of recovery to fatigue rate (R:F) ratios varied from 1.09 to 1.70, indicating during rest periods muscles can be thought of as recovering 1.09 - 1.70% faster than they were during the contraction period Table 2- 3. This is expected due to the increased ETs for intermittent compared to static isometric contractions. (Frey Law and Avin 2010) found "the shoulder is the most rapidly fatigable followed by the knee, grip and elbow, trunk and the ankle is the most fatigue-resistant". The observed (R*r): F ratio follows this general trend with grip being the most recoverable followed by the ankle, elbow, and knee. With the exception of the grip, the ankle, elbow, and knee follow the same association found by (Frey Law and Avin 2010) with the ankle being more fatigue resistant than the elbow and knee followed by the elbow over the knee.

The grip region was found to be the outlier of the original observation by (Frey Law and Avin 2010) during the isometric validation study as well (Frey-Law, Looft et al. 2012) due to the "hand/grip studies involving the first dorsal interosseus (FDI), abductor pollicis brevis (APB), adductor pollicis (ADP), and transverse volar type grip" (Frey Law and Avin 2010) were collapsed to create the original empirical model and the data sets used for this analysis. This heterogeneous sample at each stage of validation could explain the grip parameter analysis showing a discrepancy between the observed fatigability rate and the model predicted.

These results suggest a certain level of varication for the additional model parameter as well as model validity for intermittent isometric contractions. However, the fatige model's continued development and validation efforts have been focused to ultimately predict the develop of localized muscle fatigue during workplace tasks. In order to be a viable ergonomic assessment tool, the model must be valid for the shoulder joint due to the significant degredation in quality of life incured after the development of a musculoskeltal disorder. Thus more validation efforts must be conducted before the model can be stated as valid for intermittent isometric tasks.

Table 2- 1: Studies included in the meta-analysis by author for the ankle, knee, elbow, and grip

Joint	Author, Date	N	Sex	Intensity (%MVC)	Duty Cycle (%)	Data Points
Ankle	(Alway, Hughson et al. 1987)	8	M	100	50	1
	(Bemben, Massey et al. 1996)	74	M	100	40	1
	(Bigland-Ritchie, Furbush et al. 1986b)	10	MX	50	60	8
	(Birtles, Minden et al. 2002)	22	MX	100	50	20
	(Birtles, Rayson et al. 2003)	10	MX	100	50	17
	(Chung, Callahan et al. 2007)	12	M	100	50	11
	(Egana and Green 2007)	7	M	60, 50, 40	33	54
	(Fimland, Helgerud et al. 2010)	13	M	100	83	6
	(Finlayson, Majerus et al. 2008)	8	F	80	80	1
	(Kent-Braun, Sharma et al. 1994)	8	MX	10	40	1
	(Kent-Braun, Ng et al. 2002)	20	M	10	40	8
	(Lanza, Russ et al. 2004)	9	M	100	50	3
	(Lanza, Wigmore et al. 2006)	12	MX	100	50	1
	(Mademli and Arampatzis 2008)	11	M	65	40	2
	(McNeil, Murray et al. 2006)	10	M	50	67	1
	(Mitsukawa, Sugisaki et al. 2009)	7	M	100	50	2
	(Russ and Kent-Braun 2003)	32	MX	100	50	8
	(Russ, Towse et al. 2008)	16	MX	100	70	10
	Totals: 19 studies, N=289, Data Points=155					
Knee	(Armatas, Bassa et al. 2010)	13	M	100	50	7
	(Baker-Fulco, Fulco et al. 2006)	17	M	40	50	1
	(Bemben, Tuttle et al. 2001)	19	M	100	50	1
	(Bigland-Ritchie, Cafarelli et al. 1986)	6	MX	50, 30	60	15
	(Bigland-Ritchie, Furbush et al. 1986b)	10	MX	50	60	5
	(Burnley 2009)	8	M	100	60	10
	(Callahan, Foulis et al. 2009)	16	MX	100	50	7
	(Callahan and Kent-Braun 2011)	11	MX	100	50	7
	(Hamada, Sale et al. 2003)	4	M	100	63	3
	(Hornby, Lewek et al. 2009)	10	MX	100	50	3
	(Kalmar and Cafarelli 2006)	8	M	50	67	1
	(Katayama, Amann et al. 2006)	6	M	62	50	1
	(Meyers and Cafarelli 2005)	10	M	50	86	2
	(Morana and Perrey 2009)	15	M	50	50	2
	(Morse, Wust et al. 2007)	10	M	100	50	4
	(Morse, Pritchard et al. 2008)	12	M	100	50	1
	(Mulder, Kuebler et al. 2007)	10	M	45	60	5
	(Ordway, Kearney et al. 1977)	27	M	100	50	5
	(Saugen, Vollestad et al. 1997)	8	M	40	60	4
	(Stackhouse, Stevens et al. 2001)	20	MX	100	71	5
	(Vollestad, Sejersted et al. 1988)	13	MX	30	60	9
	(Vollestad, Sejersted et al. 1997)	7	MX	30, 45, 60	60	9
	(Wust, Morse et al. 2008)	64	MX	100	75, 50	16
	Totals: 23 studies, N=324, Data Points=123					

Table 2-1: Continued

Joint	Author, Date	N	Sex	Intensity (%MVC)	Duty Cycle (%)	Data Points
Elbow	(Allman and Rice 2001)	7	M	60	60	4
	(Allman and Rice 2003)	6	M	60	60	1
	(Bemben, Tuttle et al. 2001)	19	M	100	50	2
	(Bilodeau 2006)	8	MX	100	86	6
	(Dorfman, Howard et al. 1990)	10	MX	20	83	1
	(Hunter, Critchlow et al. 2004)	20	M	50	60	2
	(Hunter, Critchlow et al. 2004b)	20	MX	20	60	2
	(Jakobi, Rice et al. 2000)	14	M	50	60	2
	(Jubeau, Muthalib et al. 2012)	12	M	100	21	10
	(Lloyd, Gandevia et al. 1991)	13	M	30	60	8
	(Mazzini, Balzarini et al. 2001)	28	MX	100	50	1
	(Mendez-Villanueva, Baudry et al. 2009)	9	M	50	60	4
	(Mottram, Hunter et al. 2006)	29	MX	15	50	2
	(Muthalib, Jubeau et al. 2010)	10	M	100	21	10
	(Ordway, Kearney et al. 1977)	27	M	100	50	5
	(Seghers and Spaepen 2004)	10	MX	25	50	1
	(Taylor, Allen et al. 2000)	9	MX	100	50	4
	(Thomas and del Valle 2001)	4	MX	50	60	5
	Totals: 18 studies, N=255, Data Points=70					
Grip	(Bemben, Massey et al. 1996)	74	M	100	40	2
	(Benwell, Sacco et al. 2006)	15	MX	100	70	10
	(Benwell, Mastaglia et al. 2007)	8	MX	100	70	1
	(Benwell, Mastaglia et al. 2007b)	12	MX	30	60	5
	(Bystrom and Sjogaard 1991)	21	MX	25	83	4
	(Carpentier, Duchateau et al. 2001)	8	MX	50	80	1
	(Ditor and Hicks 2000)	24	MX	100	71	12
	(Duchateau and Hainaut 1985)	18	MX	86	33, 50, 67	6
	(Duchateau, Balestra et al. 2002)	13	MX	25	60	1
	(Fujimoto and Nishizono 1993)	14	M	40	60	7
	(Fulco, Cymerman et al. 1994)	8	M	50	50	2
	(Fulco, Rock et al. 2001)	33	MX	50	50	6
	(Gonzales and Scheuermann 2007)	32	MX	50	50	4
	(Hunter 2009)	40	MX	50	60	2
	(Jaskolska and Jaskolski 1997)	22	M	100	50	1
	(Liu, Zhang et al. 2005)	14	MX	100	67	4
	(Newham and Cady 1990)	6	MX	25, 50, 100	50	12
	(Pitcher and Miles 1997)	9	M	80	54	1
	(Quaine, Vigouroux et al. 2003)	20	M	80	50	2
	(Saito, Iemitsu et al. 2008)	16	MX	100	50	12
	(Thickbroom, Sacco et al. 2006)	15	MX	40	70	1
	(Vigouroux and Quaine 2006)	10	M	80	50	1
	(Wood, Fisher et al. 1997)	20	F	16, 32, 48	21, 31, 63	12
	Totals: 23 studies, N=452, Data Points=109					

Table 2- 2: Optimal rest multiplier (r) parameter by joint region

Joint	r	RMS* error	Original RMS* Error (r=1)	% Difference
Ankle	17	3.0%	29.5%	163.6%
Knee	11	6.7%	24.1%	113.0%
Elbow	14	10.3%	29.9%	97.5%
Grip	26	15.5%	30.2%	90.0%

*RMS Error was calculated as a weighted average of number of data points * N to provide more wieght to studies with larger sample sizes and available data

Note: Errors calculated between predicted and expected decline in torque based on the data sets found by the meta-analysis

Table 2- 3: Optimal fatigue (F), recovery (R), and rest multiplier (r) parameters by joint region

Joint	F	R	r	R*r	F:R Ratio	R:F Ratio	(R*r):F Ratio
Ankle	0.00589	0.00058	17	0.00986	10.2	0.098	1.67
Knee	0.01500	0.00149	11	0.01639	10.1	0.099	1.09
Elbow	0.00912	0.00094	14	0.01316	9.7	0.103	1.44
Grip	0.00980	0.00064	26	0.01664	15.3	0.065	1.70

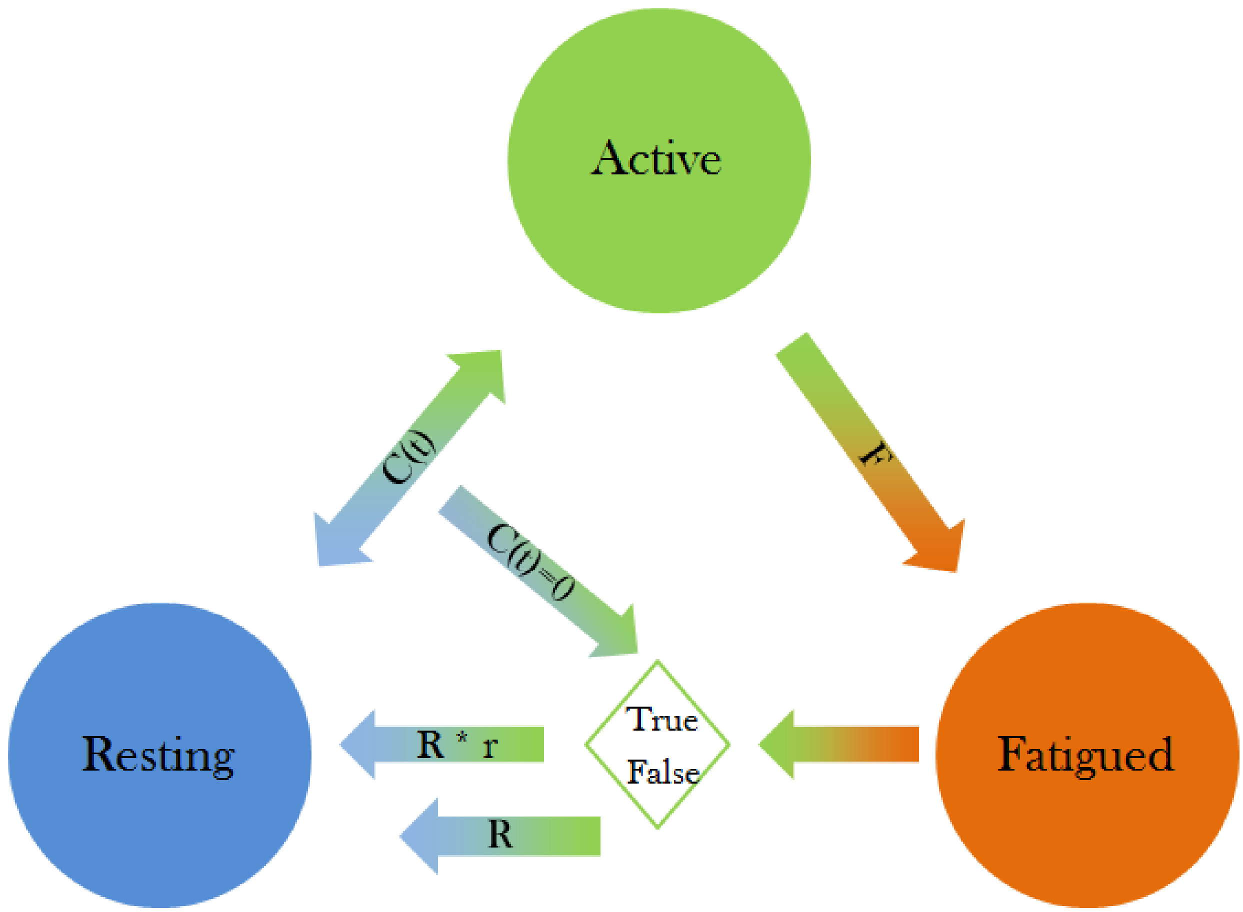

Figure 2- 1: Visual representation of the analytical fatigue model with the addition of a rest multiplier (r) when the controller shows a rest break in the simulated task.

CHAPTER 3:
ANALYTICAL FATIGUE MODEL ADAPTATION: SHOULDER INTERMITTENT CONTRACTIONS

Introduction

Work related musculoskeletal disorders continue to be on the rise even though the United States has transitioned from the industrial age to the current computer modernization age (BLS 2012, Horton, Nussbaum et al. 2012). The shoulder is an important part of performing any work task that requires use of the upper extremities. Shoulder injury rates have also been increasing throughout the years and shoulder muscle susceptibility to injury has also been shown to increase with additional psychosocial demands (Westgaard and Bjorklund 1987, Waersted, Bjorklund et al. 1991, Mehta and Agnew 2012). Along with the increase of shoulder injury prevalence and incidence, the cost of MSDs that are associated with the shoulder complex are increasing to amounts greater than ~$30,000 in direct costs for rotator cuff syndromes (Silverstein, Viikari-Juntura et al. 2006).

The increasing incidence of shoulder MSDs as well as the decreasing quality of life associated with the development of these disorders indicates any potential muscle fatigue model should account for the shoulder's role in performing work. Even simple empirical models such as the intensity-ET curves, show variability between joints (Avin and Frey-Law, 2010) suggesting fatigue models need to be validated for each individual joint region. For intermittent tasks, as shown in the previous chapter, the adapted analytical fatigue, modified with a rest multiplier (r), was validated for ankle, knee, elbow, and grip; however there was insufficient shoulder data to assess rest multipliers for the shoulder. Therefore, the lack of shoulder fatigue data available in the literature for intermittent tasks (Looft 2012) is problematic for any model development or validation.

To address these deficiencies, the goals of this chapter were **to collect data on muscle fatigue during intermittent shoulder fatiguing tasks and to assess how well the adapted analytical fatigue model matches these experimental findings**. I hypothesise a rest multiplier (r) applied during the relaxation periods of intermittent tasks will increase the accuracy of the analytical model for the shoulder joint, as was demonstrated previously for other joint regions.

Methods

Subjects

20 (9 M) healthy subjects between the ages of 18-32 years with no history of musculoskeletal disorders and shoulder trauma from the surounding university community were recruited to participate (for subject demographics, see Table 3- 1). All subjects provided written informed consent and were compensated for their time. The study protocol was approved by the University of Iowa International Review Board.

Fatigue Task

The shoulder flexion fatigue task started with a warm-up on a stationary bike, follwed by performing maximum torque generating capability using a Biodex Isokinetic Dynamometer System 3 (Biodex Medical Systems, Shirley, NY). Maximum torque was operationally defined as the maximum of three MVC trails seperated by one minute intervals. The intermittent shoulder flextion fatigue task (10 second cycle time) was then performed using the isokinetic dynamometer at either 50% MVC or 70% MVC at 50% DC or 70% DC, respectively, with interspaced 3 second MVCs (1, 3, 5, 10, and 15 minutes) until volitional failure with visual and verbal feedback. Failure was operationally defined as the inability to maintain torque within 10% of the target level for 3 seconds, or falling below the target level three concutive tries. The testing order of the fatigue tasks were randomized between subjects to minimize order effects. Subjects were seated with the arm positioned at 90 degrees shoulder flexion.

Data Analysis

Torque signals were collected using custom LabVIEW (National Instruments, Austin, TX) software at 1000Hz. Torque signals were low-pass filtered at 10 Hz. Absolute peak torque values were used in the analysis. Time to fatigue were determined from torque tracings offline and corroborated with stop watch results collected at the end of each fatigue trial. Precent torque decline (pTD) was calculated by comparing the initial MVC to the interspaced (1, 3, 5, 10, and 15 minutes). Endurance times were also collected using a stop watch and compared against LabVIEW software outputs.

Statistical Analysis

Summary statistics were calculated for endurance time, peak torque, and demographic data. Data are reported as mean ± SD within the text and figures. Independent and paired *t*-tests were used to compare endurance time and peak torque between sexes. All statistical analyses were performed using the Statistical Package for the Social Sciences for Windows (Version 20.0, SPSS Inc., Chicago, IL) with alpha set at 0.05.

Model Sensivity Analysis

Similar to the previous chapter, pTD results were compared to the analytical model at each MVC time interval (1, 3, 5, 10 and 15 min) at both intensity and DC combinations. pTD was also compaired at each subjects ending MVC as well to maximize the number of data observations to be used in the optimization process. The model's rest multiplier (r) was again varied from 1 (i.e. no change) to 40. The optimal r parameter for the shoulder was determined as the least error compaired to the subject data. Error was calculated as the root mean square (RMS) error (Equation 2- 2) between the predicted and subject pTD data. RMS error percent difference was also calculated between the best (r) and model predictions with no rest multiplier (i.e. r=1).

Results

Subject Data

Subject demographic results are described in Table 3- 1. Shoulder flexion strength and body fat % were found to be significantly different between male and female participants, however other demographic information as well as ET were found to be similar. Subject pTD data as well as mean and standard deviations (SD) recorded at each time point (1, 3, 5, 10, and 15 minutes) are presented in Figure 3- 1A, and Figure 3- 2A. The pTD at each subjects at endurance time for both tasks are also presented in Figure 3- 1A and Figure 3- 2B.

Sensitivity Analysis

The optimal shoulder rest multiplier was found varying the r values from 1 to 40 and calculating the RMS error between the resulting model predictions and the subject mean data for pTD as well as the individual pTD at ET. The optimal r value of 16 was determined as the least RMS error (Table 3- 2). Similar with the other joint regions, the addition of the r parameter increased the accuracy of the model by 94.2% (Table 3- 2).

Discussion

The objectives of this study were **to collect shoulder fatigue data on intermittent fatiguing tasks and assess how well model predictions match experimental results to further develop and validate the adapted analytical fatigue model for the shoulder joint.** The resulting sensitivity analysis found inclusion of the optimal rest multiplier (r=16) for the shoulder joint increased the accuracy of the analytical model for predicting pTD by 94.2% (Table 3- 2). This study further supports the original hypothesis a **rest multiplier (r) during the relaxation periods of intermittent tasks will increase the accuracy of the analytical model**, and demonstrates the adapted model has a degree of validation for intermittent isometric tasks including those involving the shoulder.

The observed shoulder fatigue task, while only one study, appears to be consistent with the limited previous data available at the shoulder. The coefficient of variation (CV) for this shoulder flexion task was found to fall within the range of other similar studies (Table 3- 4). This demonstrates our study shows similar range of variability relative to the mean population. We cannot compare mean outcomes as no other study has evaluated these DC and intensity conditions at the shoulder.

The model predictions RMS error for the shoulder, using r = 16, was 15.5%, which fell below the range of expected subject variations found by (Frey Law and Avin 2010) which ranged between 29% and 47%.

The increased recovery to fatigue rate (R*r):F ratio was 1.50, which fell within the ratios found during the previous chapter 1.09-1.76 (Table 3- 3). However, while the shoulder joint was found by (Frey Law and Avin 2010) to be the most fatigable for sustained isometric tasks, the observed (R*r):F ratio does not appear to follow this trend as the increased recovery rate for the shoulder was greater than the both the knee and elbow joint (Table 3- 3).

The results of this study as well as the previous chapters provide a level of verification of the adapted analytical fatigue model, suggesting the addition of a rest multiplier improves the accuracy of the model across all tested joints, including the shoulder. This rest multiplier may represent the increased muscle reperfusion during rest periods that is not occurring during sustained contractions.

In addition to the primary analyses, the model predictions of shoulder ET were then compared to the shoulder empirical model developed by (Iridiastadi and Nussbaum 2006), and the limited data on intermittent ETs for the shoulder in the available literature (Mathiassen 1993, Hermans and Spaepen 1997, Iridiastadi and Nussbaum 2006b, Mehta and Agnew 2012). Absolute errors between both models and the experimental study results (both this study and the 4 additional studies available) were calculated as well as the RMS errors between each model (Table 3- 4).

The results of show the Iriastadi and Nussbaum empirical model had the least RMS error, however when the empirical model was extrapolated to the full range of intensities and DC (Figure 3- 3) the predictions become non physiological (i.e. negative ETs). These non-physiological ET predictions suggest the modified analytical model, while over predicting ET, would be the more feasible model.

The large RMS error between the analytical model predictions for ET suggests the model rest multiplier may not be as suitable for predicting ETs as pTD, or that the value determined using pTD data is different. To examine this possibility, a secondary optimization of the rest multiplier, r, was performed using the limited ET information provided in Table 3- 4. The model's rest multiplier (r) was again varied from 1 (i.e. no change) to 40. The optimal rest multiplier (r) using ET instead of pTD was found to be 3 instead of 16 (Table 3- 5). Due to the large subject variations observed in this study, and the limited number of data points available in the literature, more studies would need to be used to determine the best optimization result.

In summary, this study provides new data on the development of shoulder flexion fatigue using a relatively high and moderate intensity/DC combintiaon. The study also found the addition of a rest multiplier improves the analytical fatigue model accuracy for shoulder pTD and ET, regardless of outcome measure. These results were similar to those in the previous chapter, further supporting our hypothesis that the addition of a rest multiplier to the analytical fatigue model improves model behavior.

Table 3- 1: Subject demographics, Mean (SD), for male and female participants (p=0.05)

	Male	Female	p-value
Age (years)	20.9 (3.5)	23.5 (4.8)	0.192
Height (cm)	161.9 (8.8)	166.3 (4.6)	0.167
Weight (kg)	66.6 (8.7)	60.9 (6.9)	0.119
Body Fat %	12.4 (5.8)	24.4 (4.8)	<0.001
Mean Strength (Nm)	35.2 (8.6)	20.7 (3.6)	<0.001
Endurance Time (s) 50 MVC 50 DC	381.6 (248.3)	413.9 (254.7)	0.783
Endurance Time (s) 70 MVC 70 DC	81.8 (48.5)	64.6 (39.4)	0.419

Table 3- 2: Optimal rest multiplier (r) parameter by joint region with shoulder study results

Joint	r	RMS* error	Original RMS* Error (r=1)	% Difference
Ankle	17	3.0%	29.5%	163.6%
Knee	11	6.7%	24.1%	113.0%
Elbow	14	10.3%	29.9%	97.5%
Grip	26	11.6%	30.2%	90.0%
Shoulder	16	15.5%	43.1%	94.2%

*RMS Error was calculated as a weighted average of number of data points * N to provide more wieght to studies with larger sample sizes and available data

Note: Errors calculated between predicted and expected decline in torque based on the data sets found by the meta-analysis

Table 3- 3: Optimal fatigue (F), recovery (R), and rest multiplier (r) parameters by joint region with shoulder study results

Joint	F	R	r	R*r	F:R Ratio	R:F Ratio	(R*r):F Ratio
Ankle	0.00589	0.00058	17	0.00986	10.2	0.098	1.67
Knee	0.01500	0.00149	11	0.01639	10.1	0.099	1.09
Elbow	0.00912	0.00094	14	0.01316	9.7	0.103	1.44
Grip	0.00980	0.00064	26	0.01664	15.3	0.065	1.70
Shoulder	0.00970	0.00091	16	0.01456	10.7	0.094	1.50

Table 3- 4: Endurance times (ET) and coefficient of variations (CV) for the current study and similar shoulder intermittent fatiguing tasks. Mean (SD) As well as (Iridiastadi and Nussbaum 2006) model predictions and the current model predictions and each models respective relative errors. RMS error between each model prediction's and published observations are also shown.

Author	**N**	**Mean Age (yrs)**	**Sex**	**%DC**	**%MVC**	**ET (s)**	**CV**	**(Iridiastadi and Nussbaum 2006) Model Predictions (relative error)**		**Current Model Predictions (r=16) (relative error)**		**% Difference**
Current Study	20	23.4	MX	50	50	382.9 (246.2)	0.64	2286.5	(1903.6)	4200	(3817.1)	73.2
				70	70	72.2 (43.2)	0.60	-1671.0	(-1743.2)	750	(677.8)	-420.4
(Hermans and Spaepen 1997)	10	18.9	F	70	20	1596 (298)	0.19	2971.5	(1375.5)	4200	(2604.0)	72.6
				70	20	1758 (94)	0.05	2971.5	(1213.5)	4200	(2442.0)	70.9
(Iridiastadi and Nussbaum 2006b)	36	21.8	MX	75	28	1632 (1002)	0.61	1856.0	(224.0)	4203	(2571.0)	593.4
				25	28	3450 (369)	0.11	3812.0	(362.0)	4203	(753.0)	207.4
				50	30	3498 (246)	0.07	3231.5	(-266.5)	4200	(702.0)	-3428.3
				80	20	1878 (1344)	0.72	2369.1	(491.1)	4203	(2325.0)	2863.2
(Mathiassen 1993)	6	32.5	F	83	25	1507.5 (-)	-	1545.2	(37.7)	825	(-682.5)	60.8
				67	25	810 (-)	-	2691.5	(1881.5)	4203	(3393.0)	43.8
				50	25	750 (-)	-	3467.7	(2717.7)	4200	(3450.0)	19.1
				33	25	1320 (-)	-	3789.0	(2469.0)	4203	(2883.0)	10.4
(Mehta and Agnew 2012)	12	21.8	MX	50	35	979.1 218.8)	0.22	2995.2	(2016.1)	4200	(3220.9)	50.2
				50	55	187.8 (20.8)	0.11	2050.2	(1862.4)	4200	(4012.2)	73.7
						Range:	**0.05-0.72**	RMS	**4070.6**		**7260.04**	

Table 3- 5: RMS error results for model predictions of pTD and ET

Shoulder	r	RMS* error	Original RMS* Error (r=1)	% Difference
pTD	16	15.5%	43.1%	94.2%
ET	3	1340.5	1360.7	1.5%
	16	2666.1	1360.7	-64.8%

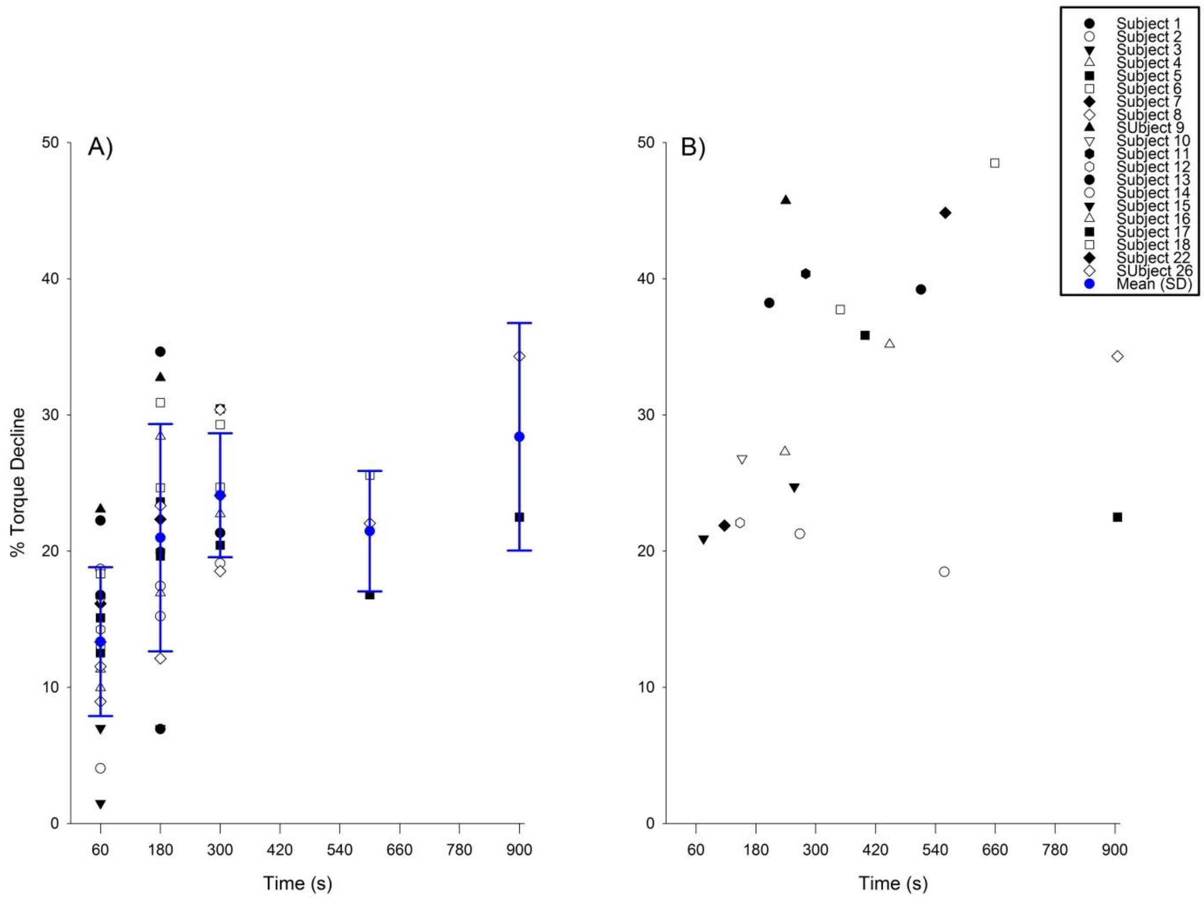

Figure 3- 1: Presents torque decline data at each of the specified time points as well as the mean and SD (A) also includes the torque decline information at each subjects ET (B) for the 50% MVC and 50% DC.

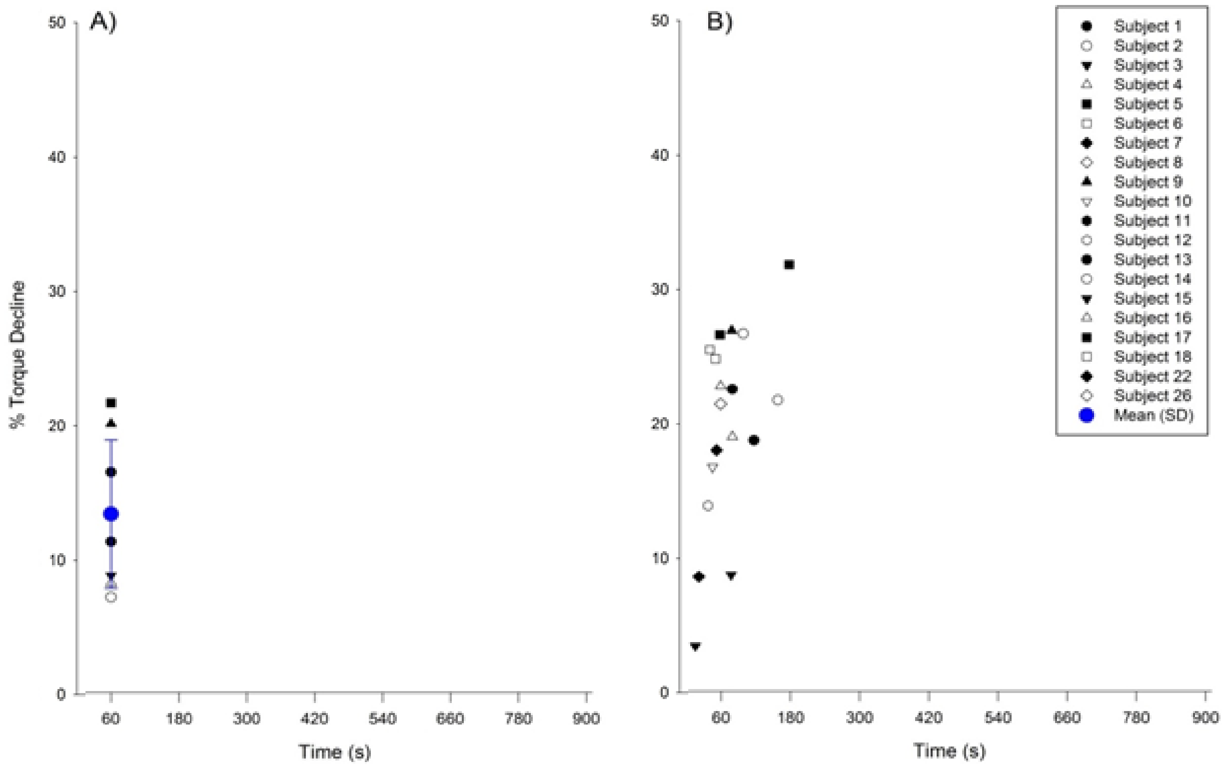

Figure 3- 2: Presents torque decline data at each of the specified time points as well as the mean and SD (A) also includes the torque decline information at each subjects ET (B) for the 70% MVC and 70% DC.

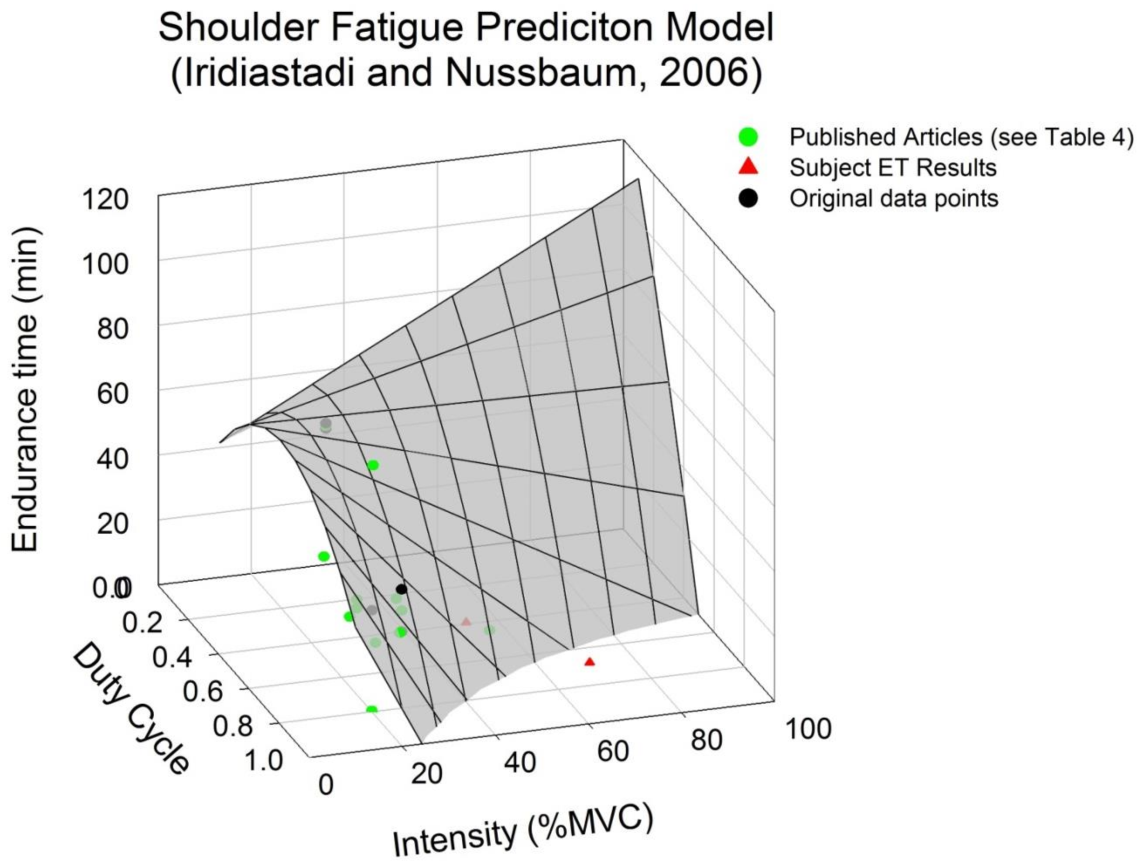

Figure 3- 3: (Iridiastadi and Nussbaum 2006) empirical model extrapolated to the full range of intensities and DC as well as the data points used to create the empirical model, the study results found in Table 4, and the subject results from the current study

CHAPTER 4:
ANALYTICAL FATIGUE MODEL PRELIMINARY ANALYSIS: DYNAMIC CONTRACTIONS

Introduction

Although intermittent tasks are relatively common in industrial settings, they are not the most common type of contractions. Dynamic contractions are the most common type of motions performed in the workplace. Dynamic contractions are defined as those where motion occurs during the muscle contraction, unlike isometric contractions where the joint angle remains constant. In order for fatigue accumulation to be included in ergonomic assessments, models must be able to predict fatigue development during these complex motions, where the worker determines the rate and speed at which they perform forceful exertions. (Snook and Ciriello 1991) performed a study where the workers determined the load and the rate they could perform for an 8 hour period. This study led to the development of the Snook Tables used in manual material handling (Snook and Ciriello 1991). However, instead of using tasks similar to those presented by (Snook and Ciriello 1991), isokinetic (i.e. constant velocity) tasks are commonly used (Komi and Tesch 1979, Sargeant 1987, Beck, Stock et al. 2014, Christian, Bishop et al. 2014).

Muscle strength, similarly to muscle fatigue, has also been extensively studied over the past century (Evans and Hill 1914). These studies have led to the discovery of several established muscle strength relationships. Two muscle strength relationships with strong implications in ergonomics are 1) maximum joint torque varies with joint angle (Gordon, Huxley et al. 1966, Frontera, Meredith et al. 1988) and 2) joint torque depends on contraction velocity due to the well-known "S-shaped" force-velocity relationship (Hill 1938, Lindle, Metter et al. 1997).

These muscle relationships are also used when analyzing muscle fatigue. Isometric fatiguing contractions look at the fatiguing properties of muscle along the muscle length-tension curve, while isokinetic contractions look at muscle fatiguing properties along the force-velocity curve. However, it is difficult to perform a constant velocity isokinetic task at submaximal contractions, so most studies looking at isokinetic fatiguing tasks are performed at constant velocity and maximum intensity (Komi and Tesch 1979, Sargeant 1987, Beck, Stock et al. 2014, Christian, Bishop et al. 2014). Work tasks are not commonly performed at either constant velocity or maximum intensity; some work tasks are performed with changing intensity and velocity. So, analytical models used for predicting muscle fatigue development during dynamic tasks should also account for the wide range of variabilities inherent to these complex motions even about one joint segment.

Thus when predicting the development of localized muscle fatigue during dynamic contractions, the subject should have control over the rate at which they lift a certain known load. To accomplish this in a confined experimental case, the accuracy of the analytical model should be compared to dynamic isotonic tasks. An isotonic contraction is where the load stays constant, but the rate of contraction can vary. These types of contractions are more like the dynamic efforts we see in the workplace. Thus the aim of this study was to **test the adapted analytical model's ability to predict fatigue behavior during a dynamic elbow flexion/extension tasks**. The elbow was chosen as it is an essential part of the kinematic chain for preforming work, and motion is restricted to one plane. This makes it an important and relatively straight forward joint to test for piloting model prediction behavior.

Methods

Subjects

35 (17 M) healthy subjects between the ages of 18-45 years with no history of musculoskeletal disorders and shoulder trauma from the surounding university community were recruited to participate (for subject demographics, see Table 1). All subjects provided informed consent and were compensated for their time. The study protocol was approved by the University of Iowa International Review Board. All participants were reimbersed for their time.

Fatigue Task

The dynamic elbow fatigue tasks started with a warm up on a stationary bike, followed by assessing maximum torque generation capabilities using a Biodex Isokinetic Dynamometer System 3 (Biodex Medical Systems, Shirley, NY). Maximum torque was operationally defined as the maximum of three MVC trials each directoin (i.e. flexion and extension) seperated by thirty seconds, so one minute intervals between each independent flexion and extension maximum trial. The dynamic fatigue task used the isotonic capabilities of the isokinetic dynamometer to set the flexion and extension resistance to 20%, 40% and 60% MVC for both flexion and extension. This created a dynamic task where the subject can control the rate of work for the given intensity similar to the snook experimental set-up (Snook and Ciriello 1991). Subjects's were informed to only exert enough energy to keep their arm continually flexing and extending until volitional failure. Volitional failure was operational defined as the point were the subjecs could nolonger flex or extend their arms. MVICs were collected at 2-minute intervals during the fatigue task. The subjects arms were locked at 90 degrees for the 3 second MIVC, and then instructed to continue the fatigue task. MVICs were also at failure for each task. Subjects were seated with the arm positioned and supported at 90 degrees of shoulder flexion.

Data Analysis

All toque data were collected using custom LabVIEW (National Instruments, Austin, TX) software at 1000Hz and low-pass filtered at 10 Hz. Absolute peak torque values were used in the analysis. Time to fatigue were determined from torque tracings offline and corroborated with stop watch results collected at the end of each fatigue trial. Torque decline was calculated by comparing the initial MVC to the interspaced (2, 4, 6, 8, and 10 minutes).

Model Analysis

Individual subject torque data was feed into the analytical model by first converting the subject data to a percent of max (pT_{max}) profile for elbow flexion torque. pT_{max} was calculated using publised normative maximum elbow strength surfaces (Frey Law and Avin 2010) to calculate the z-score for each subject by comparing the maximum predicted torque and the subjects maximum initial MVC at 90 degrees of elbow flexion. The z-score was then used to scale the predicted maximum torque surface for each subject. This surface was then used to calculate the pT_{max} for each subject was exerting at every angle and velocity (Frey-Law, Laake et al. 2012).

The pT_{max} profile for each subject was feed into the model to predict the subjects decline in torque at each of the time points and to calculate the torque decline and ET for each subject's task profile. The model was run using Matlab (R2013b), first using the optimal r value found for the elbow joint (see Chapter 2) assuming no muscle co-contraction during the extension phase. During this "quiet" phase, the rest multiplier (r=14) increases the recovery rate of the analytical model. In addition, secondary analyses were performed where an average co-contraction of the elbow flexors (5% of maximum) (Frey-Law and Avin 2013) was programmed into the pT_{max} profile and the model predictions re-calculated using these altered torque profiles. In this case, the rest multiplier is functionally omitted, as the modeled torque never reaches zero (r=1).

Statistical Analysis

Summary statistics were calculated for endurance time, peak torque, torque decline and demographic data. Data are reported as mean ± SD within the text and figures. Independent and paired *t*-tests were used to compare demographic results and peak torque between sexes.

Bland-Altman (Bland and Altman 2010) plots and intraclass correlations (ICC) were used to test agreement between the model predictions (with and without flexor co-contraction) and experimental ET and torque decline data, respectively. Three-way repeated-measures analysis of variance (ANOVA) was used to compare model predictions to subject experimental data for pTD and ETs across each of the three test intensities and time points (2, 4, 6, 8, and 10 minutes) considering both with and without co-contraction. The Huynh-Feldt correction was used to adjust for correlated, non-independent measures (non sphericity). If subject data were unavailable at any time point (i.e. after reaching fatigue) torque capability was assumed to be the task intensity (i.e. extended data points). All statistical analyses were performed using the Statistical Package for the Social Sciences for Windows (Version 20.0, SPSS Inc., Chicago, IL) with alpha set at 0.05.

Results

Subject demographic results are decribed in Table 4- 1. Only age was found to not to be significantly different between male and female participants ($p > 0.05$). The three-way repeated measures ANOVA (Table 4- 2) found the predicted pTD values were significantly lower then experimental overall mean effect of group ($p<0.001$). Further, this difference was not constant but varied across intensities (group x intensity interaction $p < 0.001$) and time (group x time interaction $p < 0.001$) (Table 4- 2). While these results found the two models to be significantlly different from each other, it is also important to assess model agreement.

Model agreement was assessed by creating Bland-Altmon plots and observing whether the predicted ETs fell within the 95% confidence interval (2 standard deviations (SD)) as well as calculating ICCs between the predicted pTD and observed. Model agreement was found to be better for the 40% and 60% tasks than the 20% task (Figure 4- 1 - Figure 4- 3 and Table 4- 3). The good model agreement lead to a closer examination of the ANOVA models and found the analytical model underpredicted the experimental pTD data at the 20% and 40% tasks, but predictions well with in the experimental SD at the 60% task (Figure 4- 7). While the model seemingly underpredicts the experimental data the trends did have general agreement as was shown by both the Bland-Altmon plots and the ICCs.

This initial analysis ran the model assuming extensors were inactive during the flexion motion and vise versa during the extension motion. Previous studies, however, have shown low levels of co contraction occur during dynamic tasks(Frey-Law and Avin 2013). The secondary analysis test he effects of assuming a low level (5% maximum) of co contraction during the dynamic task (i.e. during extension, flexors were set at 5% of maximum instead of 0%). The three-way repeated measures ANOVA (Table 4- 4) again found the predicted pTD values were significantly lower then experimental overall mean effect of group

($p<0.001$). Further, this difference was not constant but varied across intensities (group x intensity interaction $p < 0.001$) and time (group x time interaction $p < 0.001$) (Table 4- 4). Model agreement was reassessed using Bland-Altmon plots and ICCs (Figure 4- 4 - Figure 4- 6 and Table 4- 4, respectively) Model agreement was found to be better with the inclusion of low level co contraction with agreement again being higher for the 40% and 60% tasks than the 20% task. Closer examination of the ANOVA models found model predictions fell within the experimental SD for the 20% and 40% tasks, but over predicted pTD for the 60% task (Figure 4- 7).

Only the extended torque decline data was used for all statistical analyses, however the mean observed torque decline values without these imputed values are also shown in Figure 4- 7. In general, the model predictions for torque decline were significantly different than the observed, the overall agreement was better for the model predictions assuming co-contraction, particularly at the lower intensities.

Discussion

The primary finding of this investigation was that the analytical fatigue model was partially able to predict a dynamic fatiguing task, but the addition of the rest recovery factor was less helpful than previously observed with intermittent tasks. The final aim of this dissertation was to test the ability of the analytical fatigue model to predict muscle fatiguing behavior during dynamic tasks. The previous aims of this dissertation were designed to better equip the analytical model for predicting localized muscle fatigue development during complex work tasks one might observe on an industrial work site. The final aim applies the analytical fatigue model to an isotonic task, where the load is set a set intensity and the subject selects the rate of work. This is similar to the (Snook and Ciriello 1991) study which lead to the development of the Liberty Mutual tables.

The hypothesis for this aim was **the analytical model will provide reasonable predictions of pTD and ET during an isotonic elbow flexion task**. A 3-way repeated measures ANOVA was used to assess statistical differences between the model predictions and the experimental data. Bland-Altman plots and ICC's were used to assess agreement between the model and the experimental endurance times and torque decline, respectively. While the Bland-Altman plots and ICC show general agreement, the 3-way repeated measures ANOVA found the predicted and experimental data to be statistically different, indicating we should reject the hypothesis Table 4- 2. However, the aim of this study was to demonstrate the model predictions with the inclusion of the rest multiplier would also have good agreement with the experimental data (i.e. fail to reject the null).

While this result was slightly disappointing, co-contraction effects have been observed during dynamic contractions (Frey-Law and Avin 2013), thus indicating there might be enough co-contraction occuring such that the rest multiplier is never activated. To test this possibility, a secondary analysis was run assuming a low-level (5% maximum) of co-contraction to test whether the model predictions would be more representative of the experimental data. The secondary analysis found greater agreement between the predicted and experimental data. However, the 3-way repeated measures ANOVA found the predicted and experimental data again to be statistically different Table 4- 4. While the models were found to be statistically different from each other, the addition of the co contraction increased model agreement and demonstrated an agreement with the experimental data. Suggesting the analytical model has validity when co contraction is included.

Recently, another dynamic fatigue model (Ma, Chablat et al. 2009) was validated only against published models of the static isometric intensity-ET relationship and demonstrated general agreement and correlation. The Ma model was compared to three other fatigue models (Liu, Brown et al. 2002), (Ding, Wexler et al. 2000), and (Freund and Takala 2001) with the assumption there is “no recovery during physical work and workers are trying their best to finish the task”, and found their model to have general agreement with these other models (Ma, Chablat et al. 2009). While their model found general agreement, the analytical models they used in their analysis were not developed as dynamic fatigue models. Thus, no previous models have attempted to be validated against fatigue outcome measures during experimental dynamic fatiguing tasks.

The result of this study demonstrates the adapted analytical fatigue models predictions show general agreement with the experimental data, but does not provide definitive proof the model can accurately predict fatigue outcome measures for dynamic isotonic tasks. When co-contraction was included the model demonstrated better agreement indicating additional studies are needed to assess co-contracts throughout the duration of the task.

Table 4- 1: Mean (SD) subject demographics for male and female participants (p=0.05)

	Male (N=17)	Female (N=18)	p-value
Age (years)	24.3 (6.2)	23.6 (7.5)	0.766
Height (cm)	178.6 (14.7)	167.7 (8.1)	0.010
Weight (kg)	78.6 (13.3)	58.9 (9.3)	<0.001
Body Fat %	14.3 (6.5)	22.1 (7.9)	0.003
Mean Strength (Nm)	69.8 (24.8)	36.8 (10.9)	<0.001

Table 4- 2: Three-way ANOVA results for analytical model (r=14) predictions vs experimental pTD data (no co contraction)

Term	Df +	F	p-value
Intensity	2,68 (44.0)	7.517	0.005
Group (Model vs Experimental)	1,34 (34.0)	98.085	<0.001
Time	4,136 (84.7)	132.915	<0.001
Intensity* Group	2,68 (59.0)	48.848	<0.001
Intensity* Time	8,272 (176.6)	2.384	0.038
Group* Time	4,136 (78.1)	14.753	<0.001
Intensity* Group* Time	8,272 (164.5)	8.183	<0.001

+degrees of freedom (df), with corrected df for Huynh-Feldt adjustment for non-sphericity in parentheses

Table 4- 3: Agreement (Intraclass Correlation Coefficient) between model predictions and experimental torque decline data

Intensity	No Co-contraction (r=14)	Co-contraction (r=1)
20	0.188	0.514
40	0.491	0.685
60	0.488	0.568

Table 4- 4: Three-way ANOVA results for analytical model predictions with the inclusion or 5% co-contraction vs experimental data.

Term	Df +	F	p-value
Intensity	2,68 (45.6)	18.685	<0.001
Group (Model vs Experimental)	1,34 (34.0)	21.914	<0.001
Time	4,136 (83.9)	494.159	<0.001
Intensity* Group	2,68 (55.5)	71.148	<0.001
Intensity* Time	8,272 (192.1)	3.926	0.001
Group* Time	4,136 (81.6)	95.675	<0.001
Intensity* Group* Time	8,272 (169.3)	11.560	<0.001

+degrees of freedom (df), with corrected df for Huynh-Feldt adjustment for non-sphericity in parentheses

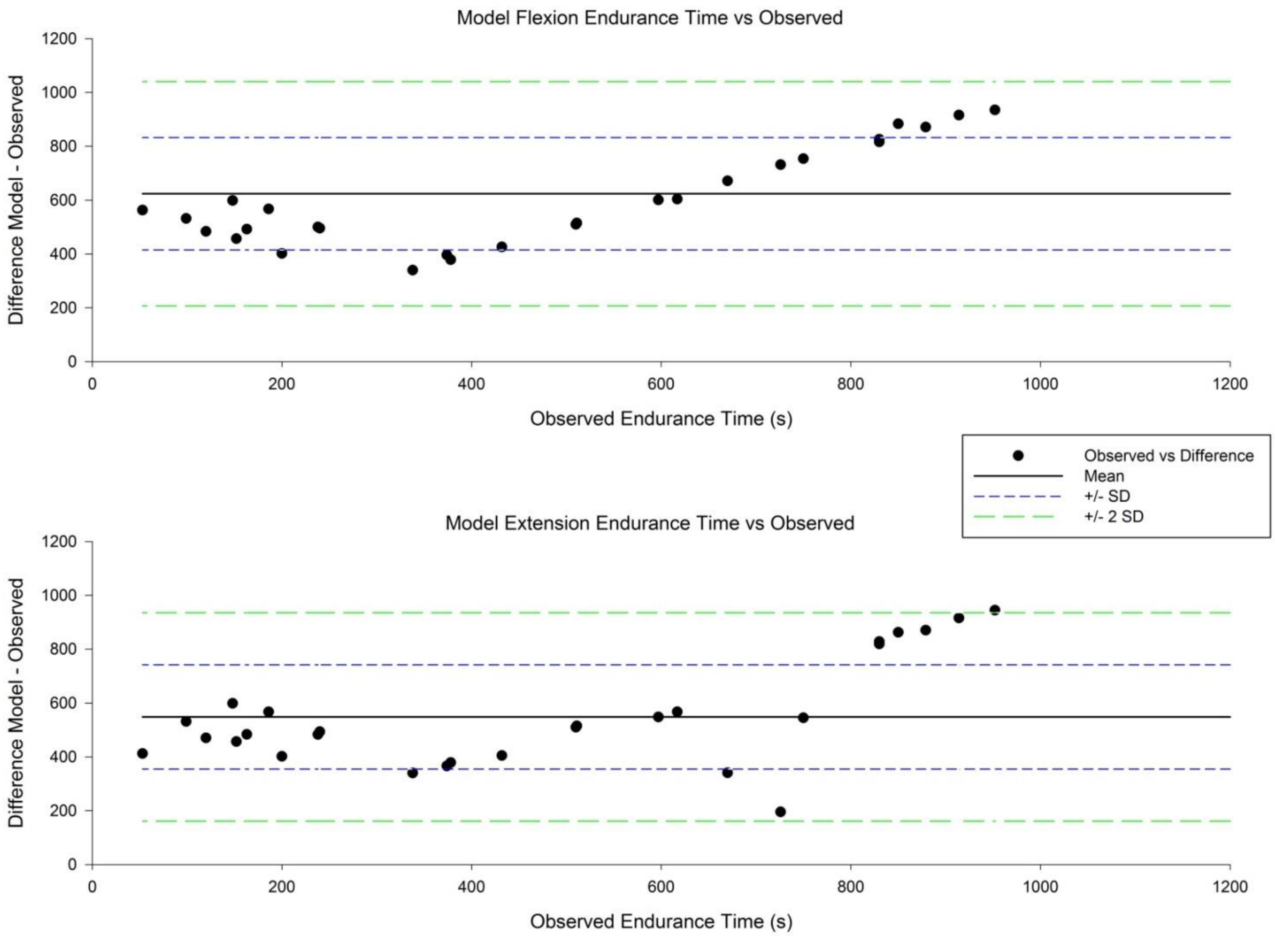

Figure 4- 1: Bland-Altman plots for 20% task comparing assessing model agreement between the observed endurance time and the model predictions.

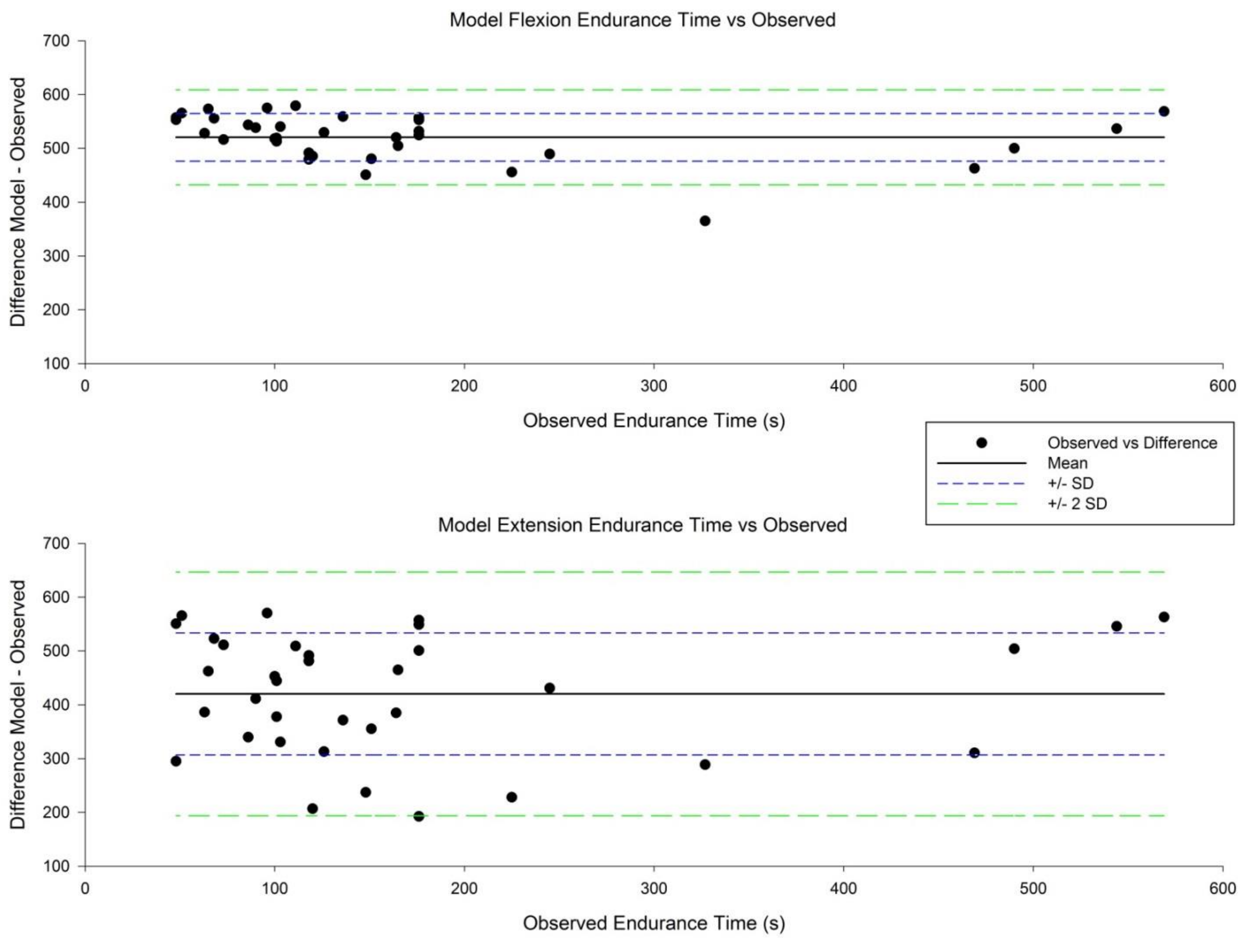

Figure 4- 2: Bland-Altman plots for 40% task comparing assessing model agreement between the observed endurance time and the model predictions.

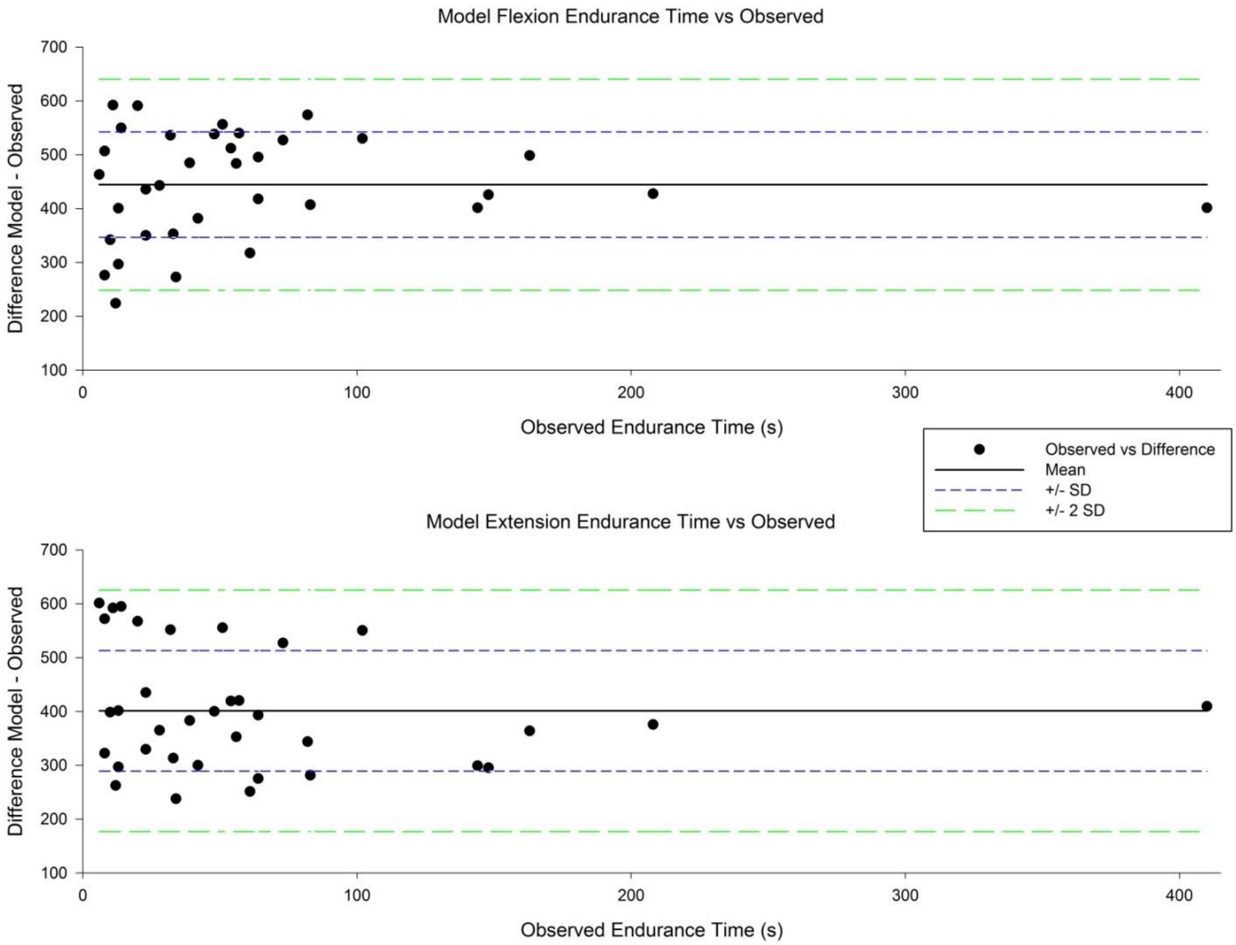

Figure 4- 3: Bland-Altman plots for 60% task comparing assessing model agreement between the observed endurance time and the model predictions.

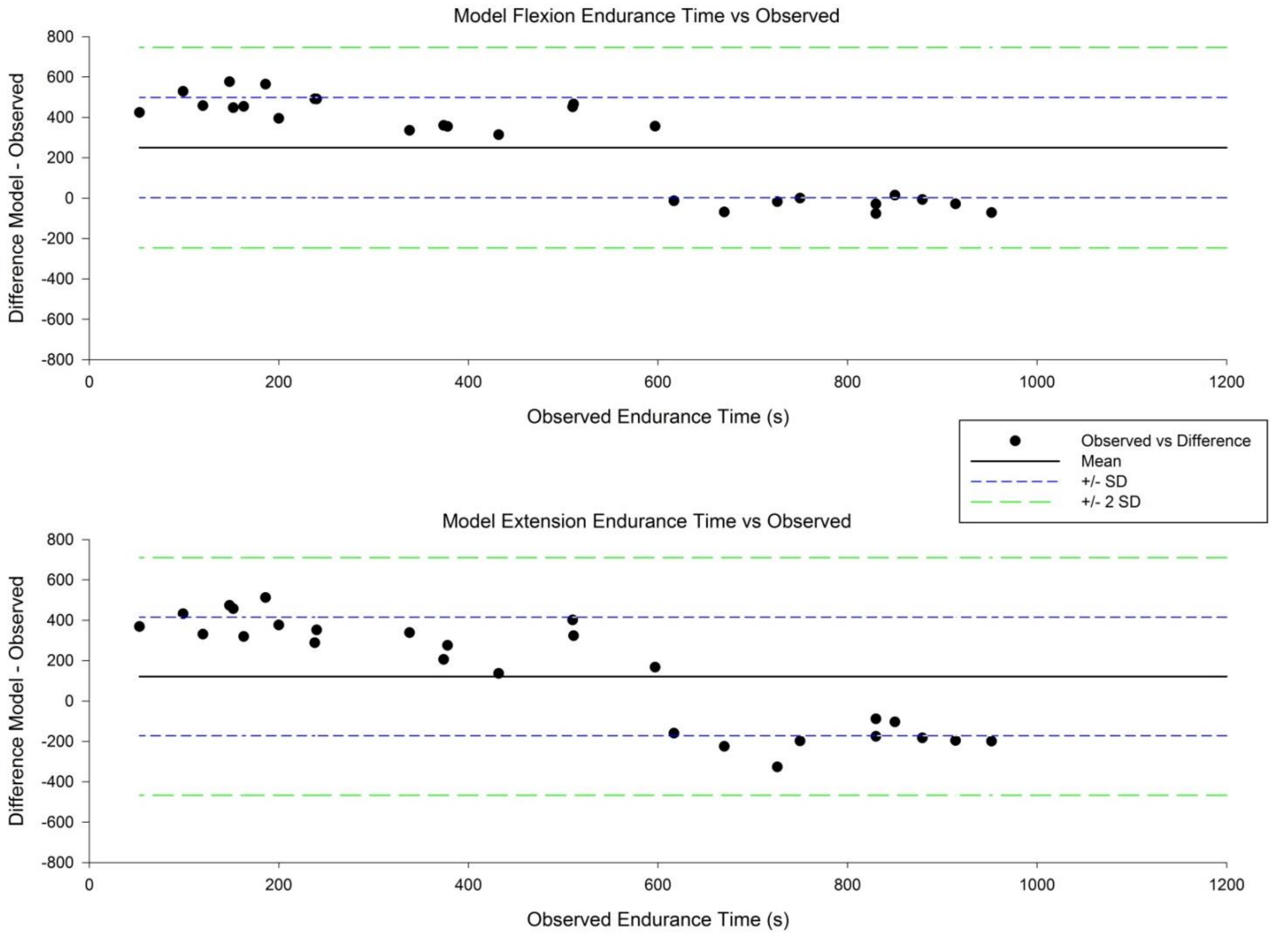

Figure 4- 4: Bland-Altman plots for 20% task comparing assessing model agreement between the observed endurance time and the model predictions when 5% co-contraction is included in the model prediction.

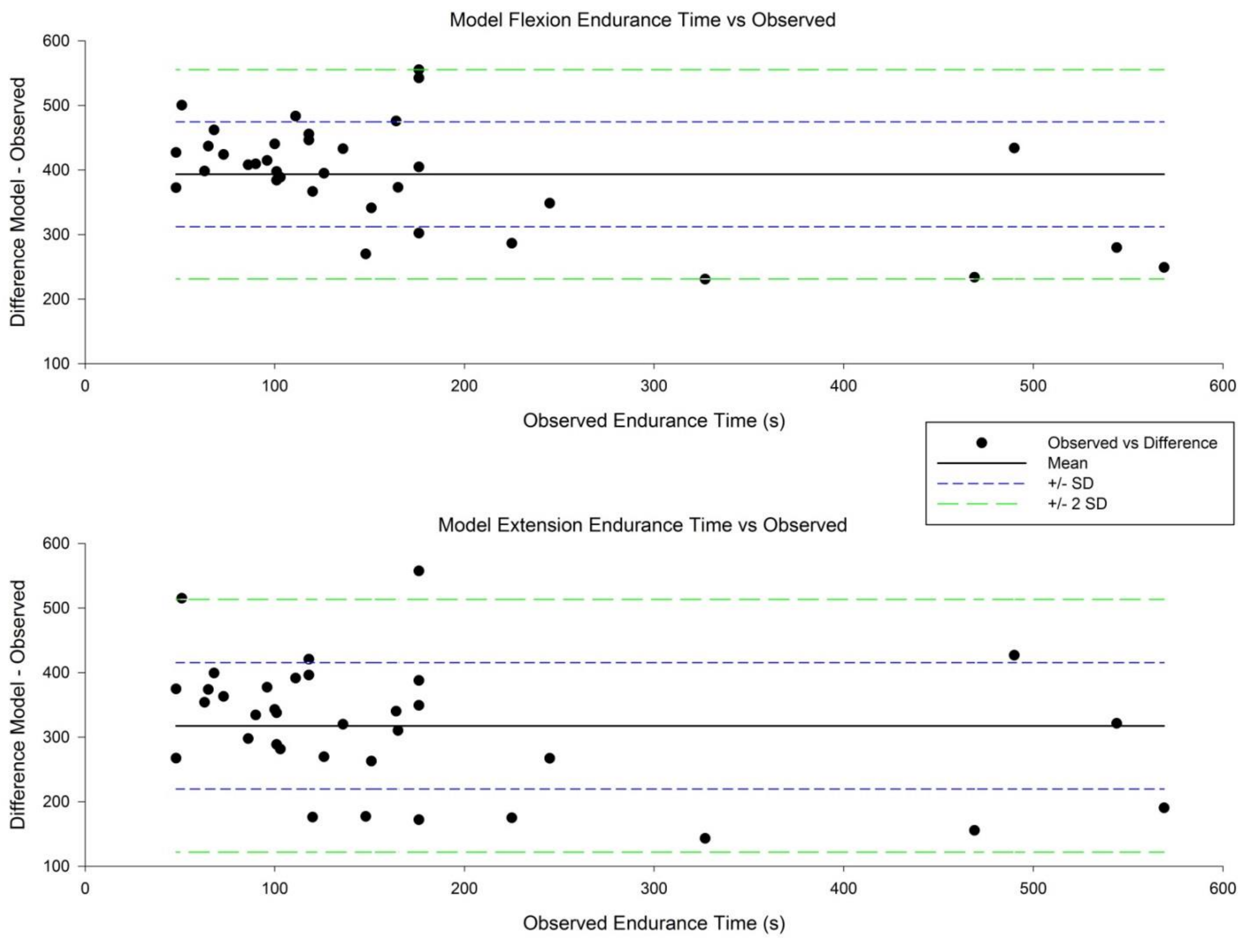

Figure 4- 5: Bland-Altman plots for 40% task comparing assessing model agreement between the observed endurance time and the model predictions when 5% co-contraction is included in the model prediction.

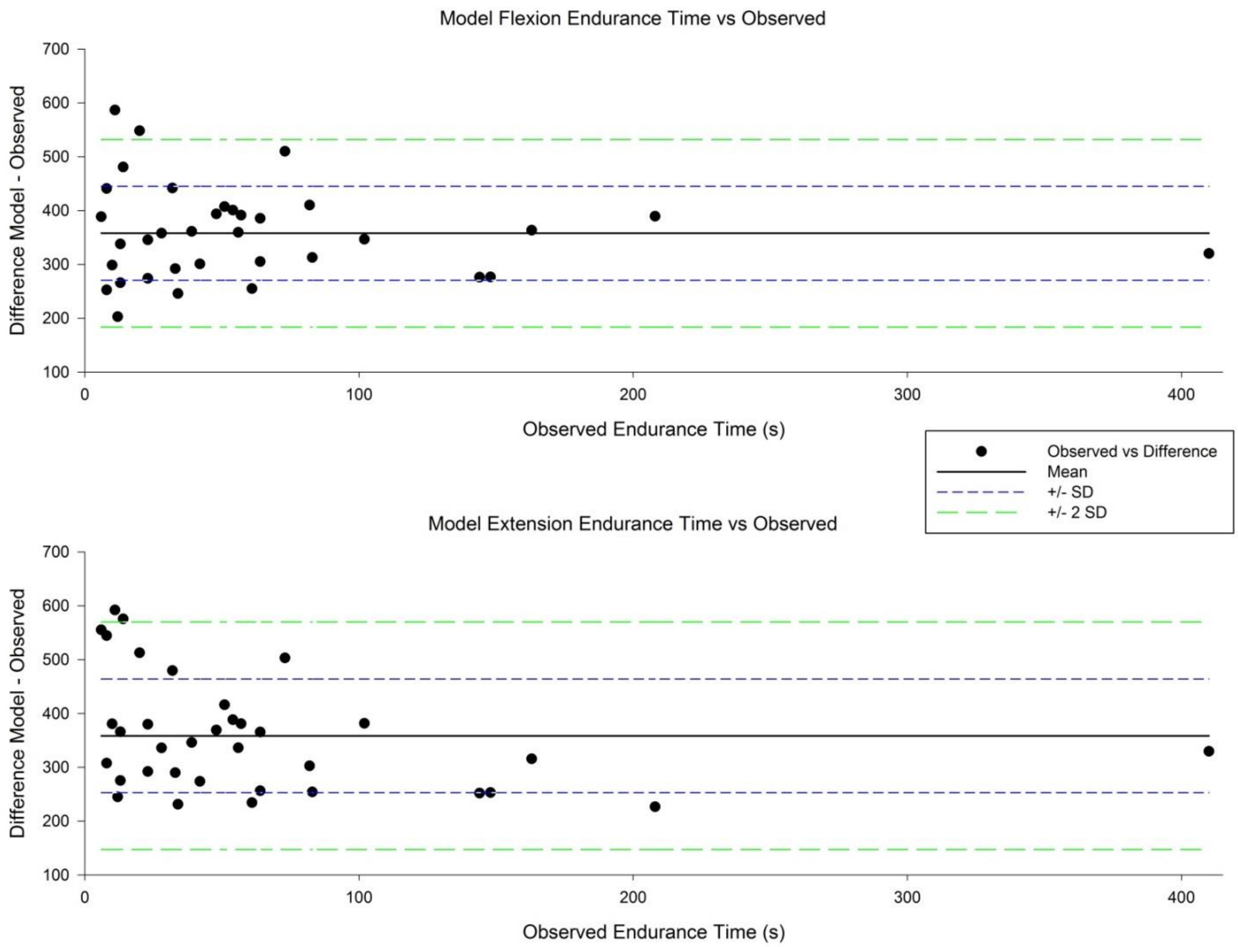

Figure 4- 6: Bland-Altman plots for 60% task comparing assessing model agreement between the observed endurance time and the model predictions when 5% co-contraction is included in the model prediction.

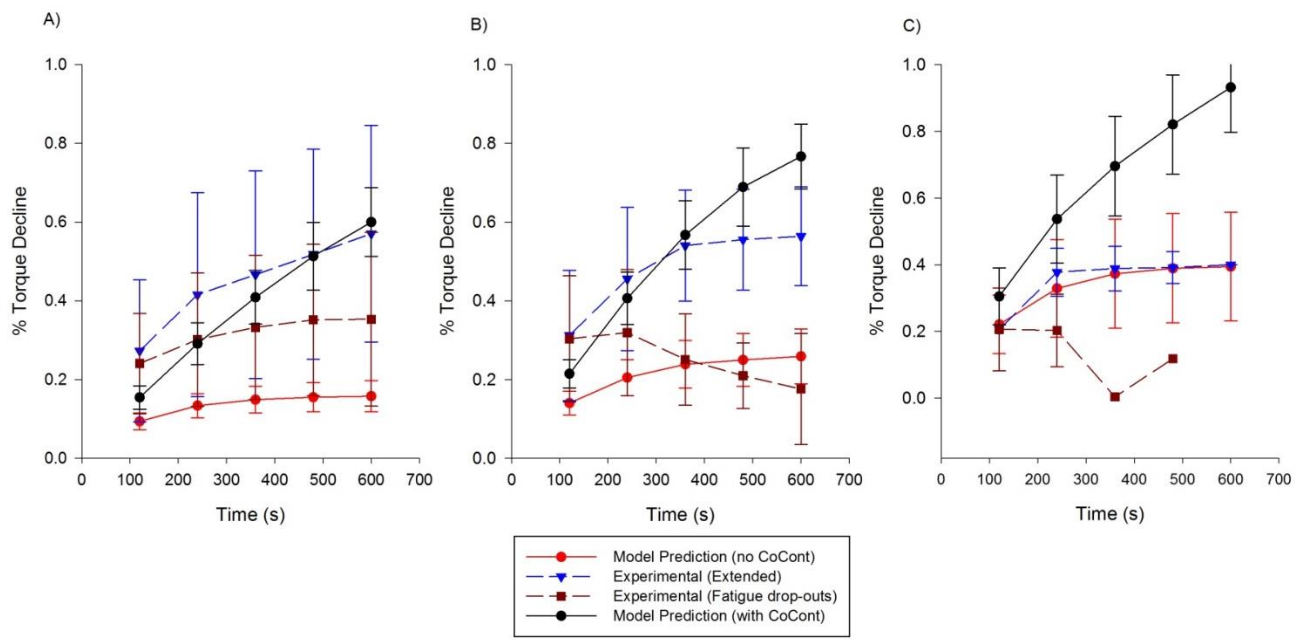

Figure 4- 7: Comparisons of model with (black circles) and without (red circles) considering co-contraction means (SD) to experimental means (SD) with dropouts (maroon squares) as well as with extending the subject data (blue triangles)

CHAPTER 5:
CONCLUSION

Review

The goal of this dissertation was to advance the analytical fatigue model's ability to predict fatigue development for more complex tasks by introducing a new model parameter. The rest multiplier (r) was added to the model to account for muscle reperfusion during the intermittent rest periods which are absent during sustained contractions.

The first aim of this dissertation was to determine the degree to which the rest multiplier would improve model accuracy across the range of intensities and DCs across joint regions. During this basic optimization of model predictions with available literature data found the rest parameter increased the accuracy of the model by nearly 100% across each available joint region, supporting our initial hypothesis. The rest multipliers were also found to vary between joints in a similar fashion to the fatigue and recovery parameters found by (Frey-Law, Looft et al. 2012), also supporting the secondary hypothesis.

The first aim provided a degree of initial validation for the addition of the rest multiplier to the analytical fatigue model and improved the ability of the model to predict degradation of torque for the joint regions where literature data were available. Unfortunately the meta-analysis did not elicit a substantial amount of data for validating the shoulder. Since the shoulder has a high prevalence and incidence of workplace injury (BLS 2012), it was important to provide some validity for the model's ability to predict the development of shoulder fatigue.

The second aim was to assess model predictions versus experimental data collected during an intermittent shoulder flexion fatiguing task. Twenty participants were recruited and their torque decline data were assessed at multiple time points (1, 3, 5, 10, and 15 min). Due to insufficient published data, the model predictions were optimized to this single study and found the additional rest multiplier again improved accuracy of the model.

Since, the model was optimized to a single study, a secondary analysis was performed to compare the analytical models ET predictions against an empirical model (Iridiastadi and Nussbaum 2006) using the collected experimental data as well as published observational data of similar intermittent shoulder fatigue tasks. The hypothesis was the analytical model would perform equally well against the empirical model. However it was discovered the optimal rest multiplier found by assessing torque degradation performed poorly vs the empirical model for predicting ET. While the addition of a rest parameter did improve the model predictions of ET, the improvements were not to the same degree as was the case for pTD. This indicates more data is needed to determine the "real" optimal r parameter for the shoulder.

The final aim of this dissertation was to test the ability of the analytical fatigue model to predict muscle fatiguing behavior during dynamic tasks. The previous aims of this dissertation were designed to better equip the analytical model for predicting localized muscle fatigue development during complex work tasks one might observe on an industrial work site. The final aim applies the analytical fatigue model to an isotonic task, using a constant load and allowing the subject to select the rate of work. This is similar to the (Snook and Ciriello 1991) study which led to the development of the Liberty Mutual tables.

The hypothesis for this aim was the model will provide reasonable predictions of ET and torque decline during the elbow isotonic dynamic fatiguing task. A 3-way repeated measures ANOVA was used to assess statistical differences between the model predictions and the experimental data. Bland-Altman plots were used to assess agreement between the model and the experimental endurance times. This study found the adapted analytical fatigue model did perform as well for the isotonic dynamic task. However when the task was modeled to include a small degree (5%) of co-contraction, the model predictions demonstrated better agreement.

The overall goal of this dissertation was to assess whether an additional rest multiplier parameter (r) would increase the validity, accuracy, and scope of the analytical model proposed by (Liu, Brown et al. 2002), improved by (Xia and Frey Law 2008), and optimized for static isometric tasks by (Frey-Law, Looft et al. 2012). This latest improvement of a rest multiplier during intermittent rest periods has been supported, by this dissertation, to be a viable advancement. Increasing torque decline prediction accuracy by nearly 100% across all observed joint regions as well as performing reasonably well compared to collected experimental intermittent and dynamic data; suggesting the model has a degree of validity. The results presented in this dissertation indicate the advancement to Xia and Frey Law's analytical model increased prediction accuracy for more complex tasks and provided a method for assessing model predictions for simulated workplace dynamic tasks.

Limitations

The entirety of the optimization process is based on a few studies which hovered around the midrange intensities and DC. Thus the model is biased toward to mid-range of intensities and DC instead of near the end points such as light intensity work at a higher or low DC, similarly for high intensities at low DC. It has been suggested fatigue maybe a risk factor for the development of MSDs, however there is little proof and even less insight into which combination of intensity and DC is/are the most harmful. Thus it is imperative to develop models which are accurate across the range of expected intensities and DC, not just what is convenient to study. While this is a potential source of error, there is little reason to believe the model was systematically biased by the methods of collecting potential studies. Every study's TD data at a specified time point were included in the study.

The second sets of limitations of this study are the small sample sizes of the individual studies which were used to perform the shoulder optimization and the dynamic repeated measures analysis. While the optimization process should have been performed against more intensity and DC combinations, the resulting r parameter was assessed in relation to the other optimized parameters and was found to reside within the range of rest multiplier values. Model accuracy was also assessed against other study outcomes measures as well as against accepted empirical models and was found to perform reasonably.

Future Work

This dissertation provides advancement to the analytical fatigue model as well as provides initial validation for predicting isometric intermittent and isotonic dynamic contractions during a movement about a singular joint. Future studies are needed to determine how well the model behaves during complex, multi-joint motions similar to those observed in the workplace. Even typing at a computer requires more than one joint segment to move in sequence to complete the task. Thus before this model can be adapted as a valid workplace ergonomics tool, it must be able to reasonably predict multi-joint level fatigue development during common workplace motions, such as computer typing or box lifting.

Summary

This dissertation is not without limitations; however these studies demonstrated **1)** the addition of a rest multiplier increases the model accuracy for predicting empirically collected pTD data for intermittent ankle, knee, elbow, and grip tasks, **2)** the additional rest multiplier also increased the model accuracy for predicting experimental pTD data for intermittent shoulder tasks, and **3)** the model provided accurate predictions of pTD for a dynamic isotonic elbow flexion task. This was the first study to directly compare analytical fatigue model predictions with experimental results for a dynamic task. These results support the model advancements, specifically the addition of the rest multiplier, and provide the necessary intermediate steps in developing a practical ergonomic muscle fatigue prediction tool. Future validation efforts are needed for common workplace tasks.

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