

**AN ANALYSIS OF MUSCLE FATIGUE DUE TO COMPLEX TASKS
AND ITS RELATION TO THE STRAIN INDEX**

A Dissertation

by

JOHN-PAUL STEPHENS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2006

Major Subject: Interdisciplinary Engineering

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Approved by:

Chair of Committee,
Committee Members,

J. Steven Moore
Jerome Congleton
Charles Lessard
Gordon Vos
Nagamangala Anand

Head of Department,

August 2006

Major Subject: Interdisciplinary Engineering

ABSTRACT

An Analysis of Muscle Fatigue due to Complex Tasks

and Its Relation to the Strain Index. (August 2006)

John-Paul Stephens, B.S., Texas A&M University;

M.S., Texas A&M University

Chair of Advisory Committee: Dr. J. Steven Moore

The Strain Index was originally designed to analyze mono-task jobs. An experiment using a grip dynamometer was used to simulate six multiple task jobs to study the effect of complex tasks on localized muscle fatigue and to evaluate six different models used to calculate a Complex Strain Index score. These models included average Strain Index score, unadjusted summation, duration adjusted summation, complex equation, minimum intensity, and peak intensity. Two methods of calculating a continuous Strain Index score were also analyzed. Ratings of perceived exertion, hand and forearm fatigue and discomfort, Difficulty Rating, maximum voluntary contraction (MVC), and percent strength loss were recorded for each of the six treatments. Electromyography (EMG) was also recorded for the 24 subjects (12 males and females) who completed the experiment. The EMG signal was analyzed using root mean square (RMS), initial mean power frequency (IMnPF), and slope of the mean power frequency (MnPF).

Each treatment, lasting one hour each, contained a primary exertion (Task 1) of either 10% or 40% MVC for three seconds and a secondary exertion (Task 2) of either 10% or 40% MVC for one or three seconds.

Subjective variables linearly increased ($R^2 > 0.88$) over the duration of the treatments and significantly differed between treatments ($p < 0.05$). Percent strength loss was the only variable with a gender effect ($p < 0.05$). RMS values did not indicate fatigue and were constant over each treatment, but were highly correlated with percent MVC. A significant difference was not found in IMnPF between pre and post treatment values or between treatments ($p > 0.05$). A significant difference was found for MnPF slope pre and post treatment, but no treatment effect was found ($p > 0.05$).

The complex equation method of calculating a Strain Index score was the only model of the six evaluated that met all criteria for being an acceptable method of calculating a Complex Strain Index score. The two continuous methods presented for calculating a Strain Index score should not be used for job analysis until further research evaluates their reliability, validity, and critical scores for Hazard Classification.

DEDICATION

To my wonderful and beautiful wife

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NOMENCLATURE

ACGIH	American Conference of Governmental Industrial Hygienists
APL	Abductor Pollicis Longus
BEI	Biological Exposure Limit
DUE	Distal Upper Extremity
ECRB	Extensor Carpi Radialis Brevis
ECRL	Extensor Carpi Radialis Longus
ECU	Extensor Carpi Ulnaris
EDC	Extensor Digitorum Communis
EDM	Extensor Digiti Minimi
EIP	Extensor Indicis Proprius
EMG	Electromyography
EPB	Extensor Pollicis Brevis
EPL	Extensor Pollicis Longus
FCR	Flexor Carpi Radialis
FCU	Flexor Carpi Ulnaris
FDP	Flexor Digitorum Profundus
FDS	Flexor Digitorum Superficialis
HLR	High to Low Ratio
IMnPF	Initial Mean Power Frequency
LMF	Localized Muscle Fatigue
MPF	Median Power Frequency

MnPF	Mean Power Frequency
MU	Motor Unit
MUAP	Motor Unit Action Potential
MVC	Maximum Voluntary Contraction
NIOSH	National Institute for Occupational Safety and Health
RMS	Root Mean Square
RMS _A	RMS All Contractions
RMS _P	RMS Primary Contractions
RMS _R	RMS Resting Contractions
RMS _S	RMS Secondary Contractions
RPE	Ratings of Perceived Exertion
sEMG	Surface Electromyography
SI _A	Strain Index Method “A”
SI _B	Strain Index Method “B”
SI _C	Categorical Strain Index
STEL	Short-Term Exposure Limit
TLV	Threshold Limit Values
TWA	Time Weighted Average
VAS	Visual Analog Scale

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INTRODUCTION

The Strain Index is a job analysis tool that uses both qualitative and quantitative methods to identify jobs that do and do not expose workers to an increased risk of developing distal upper extremity (DUE) disorders (Moore and Garg, 1995). The DUE is defined as the elbow, forearm, wrist, and hand and includes all tissue structures therein such as the skin, blood vessels, nerves, muscle-tendon units, and even the bones themselves (Moore and Garg, 1995). Most work related DUE disorders, other than bone fractures, involve the nerves and muscle-tendon units and include conditions such as medial and lateral epicondylitis, tendon entrapment at the dorsal wrist and digits, peritendinitis, and carpal tunnel syndrome (Moore and Garg, 1995; Moore, 1992a; Moore, 1992b; Moore and Garg, 1992).

One theory of DUE disorders states that activity-related DUE disorders are caused by the exertional demands that are placed on the muscle-tendon. The Strain Index, derived from principles related to the physiology, biomechanics, and the epidemiology of DUE disorders (Moore and Garg, 1995), uses six task variables (Intensity of Exertion, Duration of Exertion per Cycle, Efforts per Minute, Hand/Wrist Posture, Speed of Work, and Duration of Task per Day) to describe these exertional demands of a job (Moore and Garg, 1995).

The Strain Index is currently designed to evaluate mono-task jobs where the worker does not rotate between different jobs and whose job consists of performing only one task (Moore and Garg, 1995).

More often than not, jobs contain multiple tasks of varying durations and intensities or workers rotate between completely different jobs. These situations are called complex tasks and job rotation, respectively. When two tasks or jobs have one or more Strain Index task variables that are different from each other, then the tasks or jobs are different. If these tasks have different Strain Index scores, then the combined Strain Index score must be equal to or greater than the highest of the Strain Index scores because of the additional strain the additional work places on the DUE.

Job Rotation

Job rotation is where a worker rotates between two or more different jobs sequentially throughout their shift. As mentioned above, if these jobs have different Strain Index scores, then the combined Strain Index score must be greater than the highest of the two independent Strain Index scores. One exception to this rule is when the additional tasks or jobs have the same Strain Index score. If a worker's first four-hour job has a Strain Index score of three and the worker's second four-hour job has a Strain Index score of three, then it is assumed that the combined Strain Index score would be the same as if the worker did either one of the two jobs for eight hours. This scenario does not mean that there is the same amount of stress placed on the DUE in performing the first job for four hours as performing both four-hour jobs sequentially. If each four-hour job has a Strain Index score of three, then the combined Strain Index score, or Cumulative Strain Index score would be four (the Duration of Task per Day increases from the four hour multiplier of 0.75 to the eight hour of 1.0). This example shows how

similar job rotation tasks can be combined and also demonstrates the increase in Strain Index score reflecting the additional work.

The issue of calculating the Cumulative Strain Index score for job rotation has two main problems: (1) how to combine Strain Index scores of different magnitude and (2) does the order of rotation effect the outcome of the Cumulative Strain Index score? Research outside the scope of the current study will be needed to answer these questions.

Complex Task Analysis

Complex Tasks are jobs that have several tasks with different Task Variable ratings, such as intensity or duration levels within the same job cycle. The Strain Index is robust enough to handle variations in Duration of Exertions as long as the different tasks have relatively the same intensities (no change in task variable ratings). This is due to the fact that the Duration of Exertion task variable is based on the percentage of the job cycle where exertions are being applied and not the individual durations themselves. The Efforts per Minute Task Variable is similar to Duration of Exertion in the fact that the Strain Index can simply be recalculated. For example, a job contains a task requiring five efforts per minute (multiplier of 1.0), each effort lasting for three seconds (25 percent duration, equaling a multiplier of 1.0), a light intensity level (a multiplier of 1.0), and the other task multipliers all equal to one has a Strain Index score of one. If a second task, identical Task Variables as the first, is added to the job cycle, then the new job has ten efforts per minute (multiplier of 1.5), lasting for three seconds each (50 percent duration equaling a multiplier of 2.0), a light intensity level (a multiplier of 1.0), and the other task

multipliers equal to one, the Complex Strain Index score is equal to three. The Complex Strain Index score has accounted for the additional stress applied to the DUE by the additional work by increasing the Strain Index score by three times its initial value. As with Job Rotation, the Complex Strain Index must be greater than the highest Strain Index score of the individual tasks to represent the collective demands of the additional stress.

As shown with the previous example, the published Strain Index score calculation method can be used for jobs where a task is added that has a similar intensity level (same rating category). The problem occurs when the task that is being added is of a different intensity level. The current mono-task method of calculating the Strain Index score does not account for the additional stress added when intensity levels change. It should be noted that if any task individually exceeds the Strain Index threshold of being a hazardous job (Strain Index score greater than five), then no matter how light or strenuous the additional job or task is, the Complex Strain Index score could only increase and would still be hazardous.

Possible Methods for Calculating a Complex Strain Index Score

When evaluating workplace stressors on the human body, many different methods are used to combine levels of exposure throughout the workday. Some of the most common methods of combining industrial exposures are averaging, time-weighted averaging (TWA), or using an extreme value (maximum or minimum).

TWA Method

The ACGIH's Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents are guidelines used to aide in the identification and prevention of exposure to workplace hazards. Throughout a workday, a worker may be exposed to different concentrations of hazardous chemicals for varying durations of time. The TLV is listed as a Short-Term Exposure Limit (STEL), which is a 15 minute exposure limit, a ceiling value, which should never be exceeded for any length of time, or as a daily exposure limit, which is an eight hour time-weighted average that is simply called the TLV-TWA. As the name TLV-TWA implies, ACGIH recommends using the TWA method for assessing the exposure of a worker to different levels of hazardous substances for a period of a workday or workweek (ACGIH, 1998). The ACGIH's TLV's and BEIs handbook states "TWAs permit excursions above the TLV provided they are compensated by equivalent excursions below the TLV-TWA during the workday" (ACGIH, 1998). The TWA method is used not only for TLVs, but also by OSHA for air contaminants (29 CFR 1910.1000), noise exposure, and much more.

A worker is not always limited to just chemical exposures, but may also be exposed to other work-related hazards such as musculoskeletal stressors to the DUE. Throughout a workday, the tasks a worker performs vary in intensity and duration, much as the pre-mentioned chemical exposures. Using this line of logic, the TWA method could be used for calculating a Strain Index score that takes into account all the different tasks that a worker performs throughout the day.

One of the criticisms of using the TWA method for analyzing workplace exposure is that the TWA method places significance on short durations of very high levels of

exposures as long as the exposures are accompanied by a sufficient periods of lower level exposures (Scott, 1997). ACGIH does add that some chemicals and physical agents cannot be assessed by this approach because there are levels of these agents at which workers should never be exposed for any duration of time. These levels are known as ceiling limits (ACGIH, 1998).

Most likely, the Strain Index would fall into this ceiling limit caveat because once a job exceeds the Strain Index score for being a hazardous job, no amount of additional light activity throughout the day would make the hazardous job safe again. As mentioned above, if two tasks, during either a job rotation cycle or a complex task, have different Strain Index scores, then the combined Strain Index score must be equal to or greater than the highest of the two Strain Index scores because of the additional strain the work places on the DUE. If the first task's Strain Index score is considered "hazardous" then the "ceiling limit" has been reached and no additional work, no matter the duration, can make the combined job safe. This scenario shows the difficulty in using the TWA method for calculating a composite Strain Index score for a complex job. Despite the aforementioned problems, the TWA method will be used for comparison of different methods of calculating a Complex Strain Index score in this study because of its widespread use and familiarity among occupational safety and health practitioners.

Extreme Values (Maximum and Minimum Values)

Using extreme values is another method to evaluate exposure to workplace stressors. The extreme value method uses either the maximum value (peak value) or the minimum value to simplify a complex task down to a mono-task job. The TLV for Hand

Activity Level (HAL) is a similar tool to the Strain Index, but uses only the peak value of hand force to evaluate the intensity of the workers' exertions and average hand activity to evaluate the frequency of activity (ACGIH, 2002). One problem with employing peak force is that by using the maximum intensity of the worker's exertions to represent all exertions will tend to overestimate the potential risk to the DUE. To utilize this method when calculating the Composite Strain Index score would mean that all Intensity of Exertion ratings would be set to the value of the highest rating for any exertion in the job and thus the job could be analyzed as a mono-task job under the currently published methods. Similarly, the minimum method would use the minimum intensity of the task to represent all tasks.

Complex Task Equation and the Continuous Strain Index

The authors of the Strain Index have long discussed moving from the Strain Index calculations from a five factor categorical system to continuous multipliers. Two different methods for calculating a continuous Strain Index score will be discussed in greater detail under the section titled Comparison Calculations and Complex Strain Index Methodology. This section will also detail an equation to calculate a Complex Strain Index score designed by one of the Strain Index authors. This method will be evaluated along with the methods mentioned above.

Localized Muscle Fatigue

One of the problems with studying muscle fatigue is there is no universal definition and there are many types of fatigue (NIOSH, 1992). The two most mentioned types of fatigue are a general full-body feeling of exhaustion or tiredness known as central fatigue and a more location-specific muscle fatigue caused by activity known as Localized Muscle Fatigue (LMF). The current study is focused on LMF and defines it as the inability of a muscle to maintain a required or desired force even in the presence of increased effort due to previous muscle exertions (Blackwell et al, 1999; Dugan and Frontera, 2000; Jurell, 1998).

As mentioned before, the methodology behind the Strain Index was derived from epidemiological, biomechanical, and physiological models and “for the DUE, the primary physiological endpoint of interest is localized muscle fatigue” (Moore and Garg, 1995). The reason that LMF is an important endpoint is that it shows the physiological manifestation of strain in the DUE caused by the task or job’s biological stressors. Exhaustion, discomfort (including soreness, aching, tingling, pain, and stiffness), increased perceived exertion, decreased strength, or losses of neuromuscular control are some of the symptoms associated with LMF (Kuorinka, 1983; Moore and Garg, 1995; Radwin and Ruffalo, 1999). It has also been suggested that fatigue may be a “safety factor” to protect muscles from damage due to overexertion (Dugan and Frontera, 2000).

EMG and Muscle Fatigue

The EMG signal is an electrical summation or representation of the motor unit action potentials (MUAPs) (Jurell, 1998; Petrofsky, 1981). One of electromyography's (EMG) most popular uses in ergonomics is to study LMF (Blackwell et al, 1999; Esposito et al, 1998; Krivickas et al, 1998; Lowery et al, 2002; Moritani et al, 1986b; NIOSH, 1992; Radwin and Ruffalo, 1999). EMG's role in quantifying LMF is focused on the electrical changes that affect the motor unit (MU), such as action potential firing rates, firing synchronization, and MU recruitment (Esposito et al, 1998). To compensate for fatigue, muscles can increase the number of firing motor units as well as their firing frequency (Jurell, 1998). The two most popular methods of evaluating LMF are through monitoring changes in the frequency spectrum characteristics and RMS amplitude (Blackwell et al, 1999; Krivickas et al, 1998; Lowery et al, 2002; Radwin and Ruffalo, 1999).

For constant isometric contractions of at least 10% MVC, the EMG measures of LMF appear to be reliable and are considered a reasonable measure of the physiological changes due to LMF (NIOSH, 1992). Studies also show that under experimental situations (static and consistent postures), RMS strongly correlates with grip force (Grant et al, 1994).

An EMG signal can be obtained from either fine wires inserted into the muscle of interest (indwelling intramuscular electrodes) or surface electrodes, which are Ag-AgCl electrodes placed on the skin's surface above the muscle of interest (Pease and Elinski, 2003). One of the benefits of using intramuscular electrodes is that it allows the

investigator to target specific muscles while minimizing signals from surrounding muscles, also known as crosstalk (NIOSH, 1992; Pease and Elinski, 2003). Besides being less reliable, intramuscular electrodes can also break during intensive muscle activity and are uncomfortable to subjects, especially during insertion, which usually involves a hypodermic needle (Pease and Elinski, 2003). Surface EMG (sEMG) electrodes have shown better reliability than intramuscular electrodes (NIOSH, 1992; Pease and Elinski, 2003). As with many other EMG studies, disposable bipolar Ag-AgCl electrodes will be used to recover the EMG signal (Bilodeau et al, 2003; Blackwell et al, 1999; Mogk and Keir, 2003; Moritani et al, 1986a; Petrofsky, 1981; Radwin and Ruffalo, 1999; West et al, 1995).

RMS amplitude is commonly used to characterize the EMG signal. The amplitude is a reflection of the number of active MUs and the frequency of their firing (Esposito et al, 1998; NIOSH, 1992; Petrofsky, 1981). One of the benefits of using RMS is that the amplitude increases progressively with increasing force for submaximal contractions (Bilodeau et al, 2003; Dimitrova and Dimitrov, 2003; Esposito et al, 1998; Jurell, 1998; Lowery et al, 2002; Moritani et al, 1986a; Praagman et al, 2003; Petrofsky, 1981; Rainoldi et al, 1999). The RMS increase is caused by decreases in conduction velocity, recruitment of additional MUs, synchronization, and increasing firing frequency (Esposito et al, 1998; NIOSH, 1992). At sustained maximum exertions the RMS amplitude will increase as MUs are being recruited, but will begin to decrease in both frequency of firing and amplitude as MUs fatigue and drop out, especially the fast twitch muscles (Jurell, 1998). This may be due to lack of further recruiting capability or

switching from high frequency to low frequency stimulation to “ensure the optimal force output” (Jurell, 1998; Moritani et al, 1986a; Moritani et al, 1986b).

Subjective Measures

The use of EMG to quantify LMF has been shown to be reliable (Krivickas et al, 1998), but other subjective factors such as pain tolerance, motivation, and synergistic accommodation have been argued to be important (NIOSH, 1992) because these subjective measures can effect a subject or worker’s perception of being fatigued and thus reduce his or her time until “fatigued” (West et al, 1995). Because of their effect on a subject’s perception of fatigue, these subjective factors need to be incorporated into fatigue studies.

Localized discomfort surveys and ratings of perceived exertions (RPE) are two different types of subjective measures that are used in handgrip fatigue studies. Grant et al showed that predictive models were able to explain 51.7% to 74.2% grip force variation when both RPEs and EMGs were used (Grant et al, 1994). The Borg CR-10 and visual analog scale (VAS) are two scales that are used to rate perceived exertions, discomfort, and fatigue. Both scales are considered useful psychophysical estimation of exertions, but the CR-10 scale is more efficient than the VAS (Neely et al, 1992).

RPEs are used in ergonomic studies because they have been found to be highly reproducible (Flaherty, 1996; Stamford, 1976), representative of physical strain (Borg, 1982), and strongly correlated with grip force (Grant et al, 1994). Localized discomfort

surveys are used in experimental studies because they coincide with muscle loading and are associated with fatigue (Kuorinka, 1983; Radwin and Ruffalo, 1999).

Muscles of Interest

The proposed experiment relies on hand grip exertions to simulate job tasks in order to induce fatigue in muscles of the DUE. The muscles that are involved in hand gripping tasks are the flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), flexor carpi ulnaris (FCU), flexor carpi radialis (FCR), extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), extensor carpi ulnaris (ECU), extensor digiti minimi (EDM), extensor digitorum communis (EDC), abductor pollicis longus (APL), extensor pollicis brevis (EPB), extensor indicis proprius (EIP) and extensor pollicis longus (EPL). The extrinsic finger flexors, FDS and FDP, account for 68% of the moment-generating capacity of the fingers (Gonzalez et al, 1997).

Even though the finger flexors are the primary muscles involved during a gripping exertion, workers have more complaints and injuries on the extensor side of the wrist (Byström and Kilbom, 1991; Hägg et al, 1997; Mogk and Keir, 2003; Ranney et al, 1995). In a study of 146 female workers in highly repetitive jobs, Ranney et al (1995) found that 44 workers had disorders in the extensors and 27 had disorders in the flexors with the ECRB and ECRL being the most often affected. As a special interest to this study, not only do extensors have more injuries than the flexors, but they also fatigue faster during gripping exertions (Hägg et al, 1997; Mogk and Keir, 2003). The primary role of the extensors during a grasping or gripping exertion is to stabilize the wrist and

control wrist posture (Mogk and Keir, 2003; Ranney et al, 1995). The extension moment potential, about the wrist, is broken up between the finger/wrist extensors (EDC, EDM, EPL, and EIP) providing 45% of the moment potential and the dedicated wrist extensors (ECU, ECRB, ECRL) providing 55% (Gonzalez et al, 1997), though the ECU is considered more of a wrist deviator than a wrist extensor (Mogk and Keir, 2003). Due to postural, gravitational, and stabilizing exertions of the extensors, they are more subject to static loading and typically get less recovery time than do the flexors (Hägg et al, 1997). The extensors are considered a sensitive indicator of fatigue for gripping exertions (Byström and Kilbom, 1991).

Purpose of Research

The purpose of this research is to investigate the effects of complex tasks on physiological and subjective measures of fatigue. Proposed methods used to create a Complex Strain Index score will be evaluated and compared to physiological indicators of LMF as well as subjective responses for subjects completing a handgrip experiment designed to model jobs of varying intensity and duration.

Application of Research

Being able to calculate a Complex Strain Index score has many uses in industry. The first use is simply to be able to calculate the Complex Strain Index score for jobs that contain two or more tasks of different intensity levels. Another important use of the

Complex Strain Index score is in line balancing or setting up lean manufacturing cells. This would allow industrial engineers and managers to evaluate the effects of altering the current line or cell balance, from an ergonomic perspective, before implementing changes. Jobs that have high incident rates of DUE disorders could be evaluated to see how changing the job would affect the Strain Index score and ultimately reduce the risk to workers performing that job.

METHODS: PART I – TREATMENT EFFECTS

Recruitment of Subjects

Twenty-four subjects participated in the current study. The 12 male and 12 females were recruited from Texas A&M University and the Texas A&M University System Health Science Center. People with current DUE disorders or symptoms such as chronic pain, numbness, and tingling were excluded from participating in the study.

Several studies have focused on the fatigue times of women and men with mixed results. In two trials, women displayed longer times to fatigue (or time to task failure) than men (Hicks et al, 2001; West et al, 1995), but another trial shows that men and women have similar times to fatigue (Hunter et al, 2004). EMG activity variations are one of the consistent differences between men and women (Hunter et al, 2004; Krivickas et al, 1998). Women, on average, have larger amounts of subcutaneous tissue that acts as a low pass filter on the EMG signal. This low pass filtering removes some of the high frequencies from the women's power spectrum and decreases their initial median frequency (IMPF) (Krivickas et al, 1998).

Even though absolute strength is not being evaluated, on average, women can produce 60-65% the hand grip strength and require 5-10% more extensor activation to maintain the same relative force as a man (Mogk and Keir, 2003). By using 12 male and 12 female subjects for this study, the differences between the genders mentioned above can be further examined.

Treatments

Each subject completed six different treatments that simulated a complex task job by squeezing a hand dynamometer. Treatments were administered to subjects randomly with a minimum of 48 hours and a maximum of seven days between treatments. Each subject only saw each treatment once.

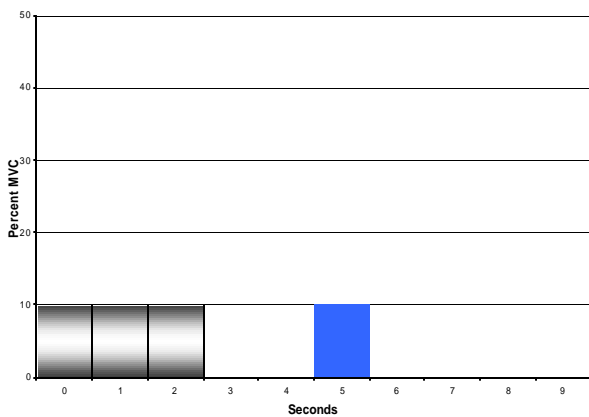
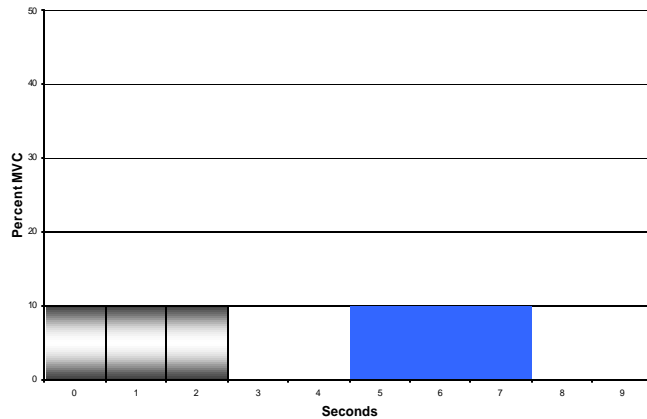
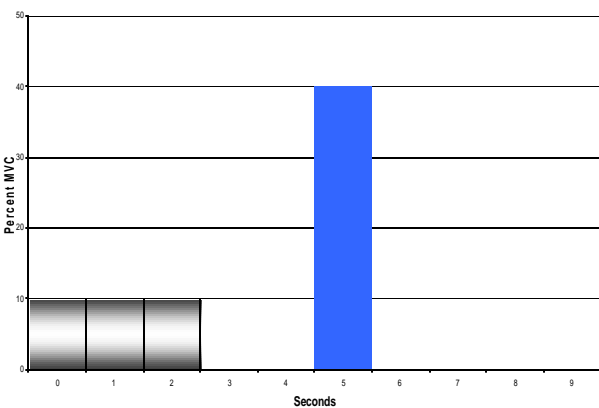
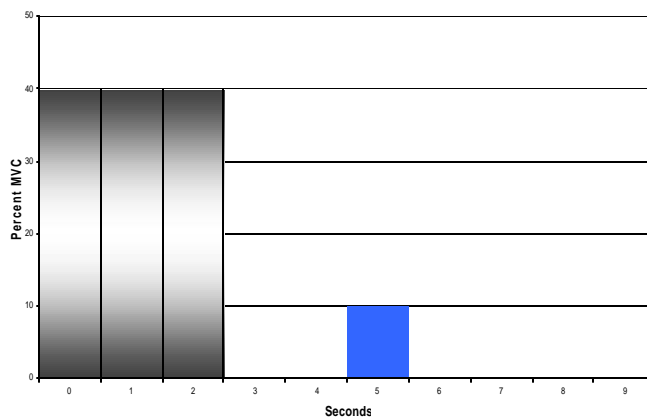
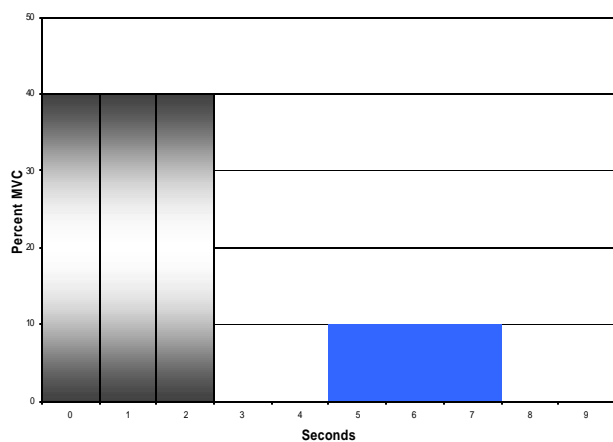
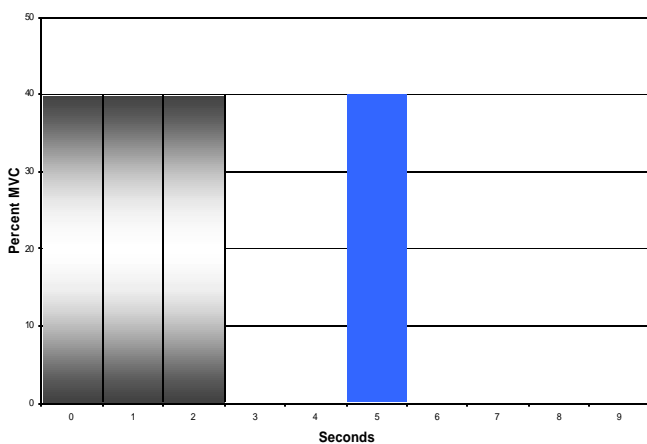
Out of the six Strain Index task variables, only intensity and duration were independent variables during this experiment. The other four Task Variables were fixed at the following values: frequency at 12 exertions per minute, a slow speed of work, good (or neutral) hand/wrist posture, and duration of task per day is governed by the length of the experiment, which is one hour.

Each treatment consisted of two intensity levels and two durations of exertions, which may or may not differ depending on the given treatment. The two different intensity levels that were used were 10% (light) and 40% (hard) of the subject's maximum voluntary contraction (MVC), which correlates to a task variable rating of one and three respectively. Preliminary experiments have shown that subjects could not perform treatments with an intensity task variable rating of four (very hard, 60% MVC) for more than 35 minutes at a Duration of Exertion of 40%. Since the experiment calls for subjects to perform the treatment tasks at duration percentages at or greater than 40%, intensity levels greater than 60% could not be used. Duration of Exertions was limited to a one second hand grasp and a three second hand grasp. With each intensity being exerted six times a minute, the duration of exertion for each intensity level was either 10% (one second exertion) or 30% duration (three second exertion). These combined

durations are either 40% (one 10% and one 30%) or 60% (two 30%). The Strain Index score can be calculated for treatments where both intensities are the same, but there is not a validated method to calculate the Strain Index score when the two intensities differ. The treatments listed in Table 1 were chosen to be representative of a broad range of Strain Index scores, while staying within the “safe” Hazard Classification. Three treatments have constant intensities so that the Strain Index score could be calculated. The treatments are graphed in figures 1 through 6.

Table 1 Treatments and their respective Strain Index Classifications

Level/MVC	Intensity Rating	Duration	Strain Index	Hazard Class
Light 10%	1/1	30%/10%	0.56	Safe
Light 10%	1/1	30%/30%	0.75	Safe
Light/Hard	1/3	30%/10%	Complex	?
Light/Hard	1/3	10%/30%	Complex	?
Light/Hard	1/3	30%/30%	Complex	?
Hard 40%	3/3	30%/10%	3.38	Safe

**Figure 1** Treatment 1**Figure 2** Treatment 2**Figure 3** Treatment 3**Figure 4** Treatment 4**Figure 5** Treatment 5**Figure 6** Treatment 6

MVC and Percent Strength Loss

The maximum voluntary contraction is the maximum amount of force that a subject will voluntarily produce and is measured before and after each experimental session to determine if force-producing capability has been lost. The MVC was acquired by using the maximum value of three maximal isometric contractions, as long as the maximum value is within 10% of the other two contractions (Esposito et al, 1998; Krivickas et al, 1998; Lowery et al, 2002; Petrofsky, 1981; Rainoldi et al, 1999; West et al, 1995). Percent strength loss will be calculated by subtracting the post treatment MVC from the pre treatment MVC and dividing the delta by the pre treatment MVC.

Studies have shown no significant differences in intra-subject MVC between testing periods (West et al, 1995). One of the problems with MVC is that it is not only affected by fatigue, but is also affected by subject motivation and comfort (West et al, 1995). Subjects will be encouraged during MVC recordings to minimize variability in subject motivation.

Subjective Measures

The subjective measures that were recorded during this study were RPE, localized discomfort and fatigue (Corlett and Bishop, 1976) in the hand and forearm, and a measure of the subjects' perceived difficulty at the end of the experimental session (Difficulty Rating). The Borg CR-10 scale was the chosen method of recording the RPE and difficulty rating subjective measures because it is more efficient than the VAS (Neely

et al, 1992) and it is easier to administer to the subjects. Since the subjects will be positioned such that their right arm will be immobilized, they would have to mark the 10 cm VAS with their left hands as well as trying to focus on the ongoing tasks presented by the treatments. The CR-10 allows the observer or researcher to ask the subjects to verbally rate their perceived exertion without diverting attention away from the treatment. For fatigue, subjects used a discomfort survey based on Corlett and Bishop's study (1976). In the current study, the survey was limited to the DUE.

All subjective variables, except Difficulty Rate, were recorded every five minutes throughout each treatment. Locations of fatigue and discomfort were also recorded with the subjective variables.

EMG Measures

Subject Positioning and Equipment

When designing a handgrip experiment using EMGs as an outcome indicator, many factors such as grip size, wrist position, and muscle length must be taken into consideration. Grip size does not affect the EMG frequency shifts of the FDS, but it does affect the absolute grip strength (Blackwell et al, 1999). Wrist posture (degree of flexion, extension, supination, pronation or deviation) can also affect the absolute grip strength. Maximum gripping force is reduced up to 50% by flexing the wrist and continues to decrease as the wrist is pronated (Mogk and Keir, 2003). When the wrist is flexed or extended, the muscle lengths change and affect the EMG amplitude as well as the characteristics of the frequency spectrum (Jurell, 1998; Krivickas et al, 1998; Mogk and

Keir, 2003; NIOSH, 1992). In order to get reliable results from EMG characteristics, the grip width was set to the middle of a subject's grip width, the arm was kept from moving to limit muscle length changes, and the wrist posture was fixed (Blackwell et al, 1999; Jurell, 1998; Krivickas et al, 1998; Mogk and Keir, 2003; NIOSH, 1992). Figure 7 is a picture of the experimental setup.

Comfort was considered in designing experiment because pain and discomfort can demotivate subjects and give a false sensation that is often interpreted by the subject as fatigue (West et al, 1995). Discomfort and pain can also reduce endurance times and lower MVC (Ciubotariu et al, 2004). Preliminary testing showed that subjects report pain and discomfort in the thenar region of the hand when performing intensive sustained gripping tasks with the JAMAR dynamometer. A cushioning wrap, similar to those used to wrap tennis rackets, was added to the dynamometer/hand interface to help reduce the pressure on the thenar. Discomfort was also one of the variables monitored in the current study.

Target Muscles for EMG

EMG signals were collected from one extensor muscle group and one flexor muscle group. The flexor group selected for the current study was the extrinsic finger flexors, FDS and FDP. These two muscles account for 68% of the force-generating capacity of the fingers (Gonzalez et al, 1997). The FDS is the primary flexor muscle of focus, but because the FDP is directly beneath the FDS, surface electrodes cannot distinguish between them. For the purpose of this study, any further references to the flexors will mean both the FDS and FDP muscles.

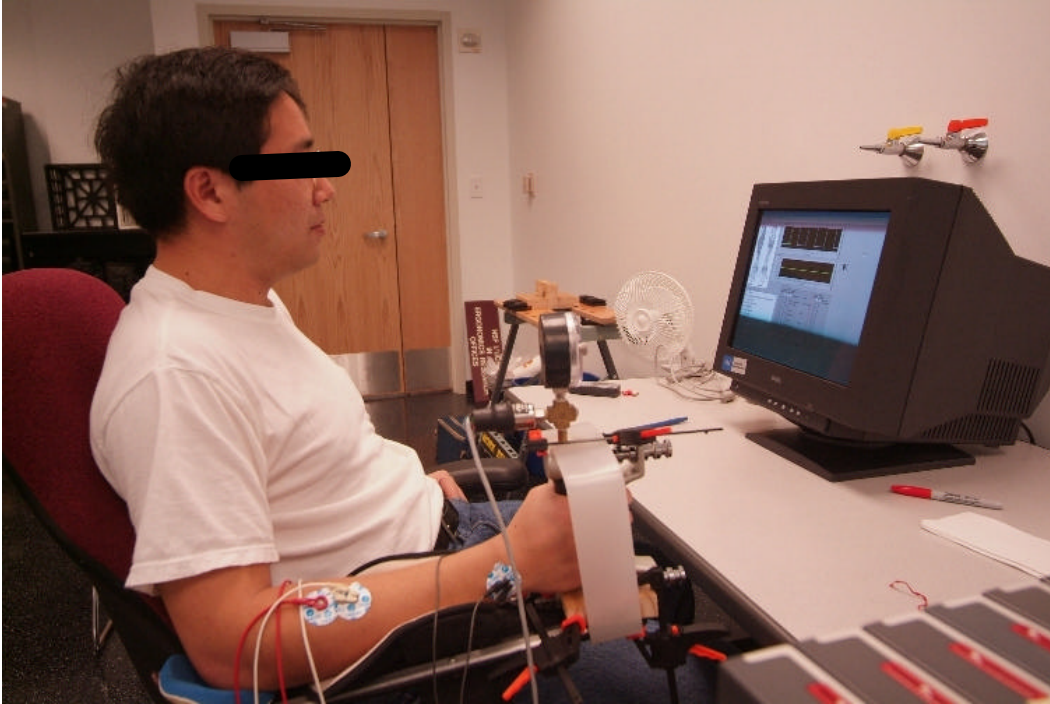


Figure 7 The experimental dynamometer and subject interface

Ranney et al (1995) found that disorders in the extensors most often affected the ECRB and ECRL. These two muscles, in addition to the ECU, provided 55% of the extensor force potential through the wrist (Gonzalez et al, 1997). The ECU was removed from consideration for use in this study because it is considered more of a wrist deviator than a wrist extensor (Mogk and Keir, 2003). For the purpose of this study, the ECRL and ECRB will be the extensor muscles of focus.

Electrodes and Skin Preparation

Disposable Ag-AgCl surface electrodes were used to collect the EMG signal. In order to use surface electrodes, the skin must be prepared properly to reduce its electrical resistance and thus provide a cleaner signal to the applied surface electrodes. The skin was abraded with fine steel wool and then scrubbed with rubbing alcohol above the

electrode sites for the finger flexors and finger extensors. (Bilodeau et al, 2003; Blackwell et al, 1999; Ciubotariu et al, 2004; Esposito et al, 1998; Lowery et al, 2002; Rainoldi et al, 1999; West et al, 1995).

Equipment

Grip hand force was measured on a JAMAR hand dynamometer and then amplified using a BIOPAC Systems, Inc.'s General Purpose Transducer Amplifier (DA 100) before being sent to a BIOPAC MP100 Workstation system (channel one). Two channels of EMG (one flexor and one extensors) were amplified by Electromyogram Amplifiers (EMG 100C) before also being sent to the BIOPAC MP100 Workstation system. The three channels were filtered before being amplified or digitized. A National Instruments™ Data Acquisition Board PCI-6023E was used to digitize the signals for recording and processing using National Instruments'™ LabVIEW™ software (V7.0, Austin, TX, USA). Once recorded, the signals for each subject were burned to DVD and analyzed using DaDiSP™ software.

Signal Processing

The EMG signal was sampled at 1000 samples per second. To prevent aliasing, each EMG signal was low-pass filtered before it was digitized. The low-pass filter was set to the Nyquist cut-off frequency of 500 Hz for the current sampling rate (Jurell, 1998). Because of low frequency noise, such as skin, electrode, and cable movements, the signals were also high-pass filtered (Jurell, 1998; NIOSH, 1992). The high-pass filter for this experiment was set at 10 Hz creating a band-pass frequency range of 10 to 500

Hz, similar to many studies found in literature (Esposito et al, 1998; Lowery et al, 2002; Mogk and Keir, 2003; Pease and Elinski, 2003). Several preliminary experiments demonstrated that 60-cycle noise was not present in the EMG channels. The channels were continuously monitored for 60-cycle noise.

EMG Signal Analysis

As mentioned earlier, the two most popular methods of analyzing EMG are through monitoring changes in the frequency spectrum characteristics and RMS amplitude (Blackwell et al, 1999; Krivickas et al, 1998; Lowery et al, 2002; Radwin and Ruffalo, 1999). The frequency spectrum, also known as the spectral density function or power spectrum is an estimate of the power distribution in the frequencies of the signal. Before the power spectrum can be calculated, the signal must be independent and stationary (statistical properties are time invariant) because the method of estimating the power spectrum is parametric. The RUNS test, a nonparametric test, was used to determine if the EMG signals were ergodic (time averages completely represent the full ensemble) and thus could be assumed to be stationary and independent. If a signal is not stationary for a given window, either the signal is not stationary or the viewing window (time) needs to be increased to show any underlying trends. The expected viewing window for this experiment was one second. If the EMG signals were not stationary during for this window size, the window would be increased a second at a time until either an appropriate window size was found or the signal was deemed non-stationary. Once the signals were shown to be ergodic, the power spectrum was calculated.

Spectral Analysis Methods

The frequency spectrum of the EMG can be analyzed through the ratio of high to low frequencies (HLR), median (MPF) and mean power frequency (MnPF), peak frequency, and zero crossings. When fatiguing activities are performed by a muscle, the amplitude of the high frequency components of the power spectrum start to decrease and the low frequency components increase (Blackwell et al, 1999; Dimitrova and Dimitrov, 2003; Elfving et al, 1999; Esposito et al, 1998; Hummel et al, 2005; Jurell, 1998; Lowery et al, 2002; Moritani et al, 1986a; Moritani et al, 1986b; NIOSH, 1992; Petrofsky, 1981).

HLR is a ratio of the high frequencies to the low frequencies and is sensitive to power shifts, but is also too sensitive to the shape of the spectrum curve. Another problem with HLR is that the high and low bands are arbitrary, chosen by the investigator, which make the ratios difficult to generalize between studies (NIOSH, 1992). HLR was not used in the current study.

Zero crossings and peak frequency are two methods that analyze the raw EMG signal. Zero crossings is a measure of how many times the raw EMG signal crosses 0 volts. Peak Frequency or spike counting is a method of counting the number of positive and negative spikes within the raw EMG signal. Peak frequency and zero crossings increase with muscle activity, but then plateau at about 70% and 60% MVC respectively (NIOSH, 1992). Neither zero crossings nor peak frequency will be used in the current study.

The power spectrum measures most often used are MPF and MnPF (Krivickas et al, 1998; NIOSH, 1992). The MnPF is the average of all frequencies within the power spectrum and the MPF is the frequency at which 50% of the frequencies are distributed

on either side. Because the MPF is not an average, but the middle frequency, it is less sensitive to noise compared to MnPF (Jurell, 1998; NIOSH 1992) and is usually smaller in magnitude (Krivickas et al, 1998). MnPF is considered by some studies to be more reliable than MPF (Hary et al, 1982). As the high frequency components are reduced in the power spectrum, the MnPF and MPF shift towards the lower end of the spectrum and can be graphed over time to measure fatigue (Bilodeau et al, 2003; Elfving et al, 1999). The slope of the graph shift is usually linear (Pease and Elinski, 2003) with intensity of exertion being the dominant factor for the rate of change (Lowery et al, 2002; NIOSH, 1992) and thus more intense exertions have a steeper slope than less intensive exertions.

The intrasubject reliability for MPF has been called “excellent,” but the intersubject reliability contains more variability (Krivickas et al, 1998). Inter subject variability may be in part caused by different muscle fiber type contents. Muscles with more type II (fast twitch) muscle fibers have a higher initial median power frequency and decrease more rapidly than type I (slow twitch) muscle fibers (Bilodeau et al, 2003). Even though spectrum analysis allows investigators to study LMF, the recovery of the spectrum does not coincide with the physiological recovery of the muscle (NIOSH, 1992).

MnPF slope values were calculated immediately following each treatment during a final sustained 100% MVC contraction. MnPF was graphed against time to calculate the slope of the fatiguing exertions.

The initial mean power frequency (IMnPF) will be calculated as the y-intercept of the regression line used to calculate the slope of the MnPF during the normalization session immediately preceding each treatment (Krivickas et al, 1998). It should be noted

that IMnPF is an estimation of the starting MnPF value and thus would not be affected by the treatments. Comparing pre treatment IMnPF provides an internal validity check because there should not be a significant difference between IMnPF values for different treatments. IMnPF values calculated at the beginning of each treatment were also compared to IMnPF values calculated immediately following the treatments to compare any significant loss in IMnPF value.

RMS

Each experimental treatment (see Treatment section for a further description) contained two different contractions of varying intensity and duration. Treatments 1 through 3 have a primary exertion of 10% MVC (textured exertion in Figures 1 through 3) held for three seconds once during every ten second cycle. Treatments 4 through 6 have a primary exertion of 40% MVC (textured exertion in Figures 4 through 6) held for three seconds once during every ten second cycle. For each treatment, RMS values will be calculated for all contractions (RMS_a) and also individually for the primary (RMS_p) and secondary (RMS_s) contractions, as well as the resting periods (RMS_r).

METHODS: PART II – STRAIN INDEX METHODS

Comparison Calculations and Complex Strain Index Methodology

Peak and Minimum Values

The calculations for the Complex Strain Index score using the extreme values method are straightforward. The Strain Index score for the peak method was calculated using the peak hand force as the intensity for all task exertions making the complex task a mono-task job.

The Strain Index score was also calculated using the minimum hand force for all exertions. Again, the intensity transformation makes the complex task job into a mono-task job that could be analyzed by the traditional method.

Average and Time-Weighted Averages

A Complex Strain Index score will be calculated by using an average of the individual mono-task Strain Index scores. Because the treatments consist of two different tasks, the two individual Strain Index scores were calculated independent of each other. The two scores were added together and divided by two (two tasks in the complex job) to give a Complex Strain Index score.

For the TWA method, a Strain Index score was calculated for each task and then weighted for the duration of time that the worker performs the tasks. As will be demonstrated below, time weighting presents a problem for Complex tasks analysis. With a complex tasked job, a worker performs several different tasks for the duration of

the workday. A worker will perform task A for eight hours and also perform task B and C during those same eight hours. In this case, the total time (τ_T) is equal to eight hours, but so are the total exertion times of task 1 (τ_1), task 2 (τ_2), and task 3 (τ_3) because each task is performed for the whole eight hours. Equation 1 shows the method of calculating the TWA Complex Strain Index score.

Equation 1 TWA Complex Strain Index score Calculation

$$SI_{TWA} = \frac{SI_1 * t_1}{t_T} + \frac{SI_2 * t_2}{t_T} + \dots + \frac{SI_N * t_N}{t_T}$$

Since $\tau_T = \tau_1 = \tau_2 = \dots = \tau_N$

Then

$$SI_{TWA} = SI_1 + SI_2 + \dots + SI_N$$

Because the task times are all equal to each other as well as to the total time, the “time weighting” actually drops out of the equation and the TWA method is reduced to a simple summation. Because the time weighting is removed from the equation, the current method will be referred to as the unadjusted sum.

Duration Adjusted Sum

The unadjusted sum does not take into account the loss of recovery time from the first task and is removed when the second task is added to the job. Suppose a worker’s job contains two tasks, A and B. Task A is performed once every ten seconds and lasts for three seconds (30 percent duration). Task B is also performed once every ten

seconds, but lasts for two seconds (20 percent duration). If these two tasks were combined, then the Duration of Exertion task variable would be equal to 50 percent. Since the Duration of Exertion task variable relies on recovery time (the amount of time the worker is not performing any tasks) to help the worker recover from the previous exertion, any additional work performed reduces recovery time. By introducing task B into a job containing task A, the recovery time for task A has been reduced by 20 percent. This example does not grant task B any recovery time, which normally would have to be considered. The Duration of Exertion task variable can be adjusted to take into account the loss of recovery time to task A, as well as to task B. The standard method of calculating an unadjusted sum also does not account for the increased frequency of adding additional tasks. There are numerous ways to incorporate the loss of recovery time and frequency into the Strain Index calculation, but the following method was used in calculation of the Complex Strain Index score and will be referenced as the duration adjusted sum. If the job in the current example were a mono task job, the calculation for Duration of Exertions would be $(t_A + t_B) / t_T$ where t_A is the total time of the exertions in Task A, t_B is the total time of the exertions in Task B, and t_T is the total amount of time in the job cycle. In order to integrate the loss of recovery time into the individual Strain Index score, each task's Strain Index score was calculated using a reduced total time. It was assumed that each task receives an equal amount of recovery time, so the total time, t_T , was divided by the number of tasks within the job. The individual or mono-task Duration of Exertions were calculated using the reduced time (t_R). The proposed method of calculating the Duration of Exertion Task Variable would be t_A / t_R and t_B / t_R . Using the example job above, the Duration of Exertion for task A would be 60 percent (three

seconds divided by five seconds ($\tau_R = 10$ seconds divided by two tasks)) and the Duration of Exertion for task B would be 40 percent (two seconds divided by five seconds). The modified Duration of Exertions was used to calculate the individual Strain Index scores for both task A and task B. Equation 1 was then used to calculate the adjusted sum Complex Strain Index score.

Complex Strain Index Equations

In order to calculate a Complex Strain Index score, new equations are needed to account for the additional stress placed on the DUE by the additional work. Not only must the equations reflect this additional stress, but they must be internally consistent. If the Complex Strain Index equations calculate a score for a job containing two different tasks that can be combined into a single mono-task job, the score for the combined mono-task job should be the same as the complex job. A method for calculating a Complex Strain Index score was developed by one of the original Strain Index authors that meet these criteria (referenced as the Complex method), but the equations have never been published or validated. It should be pointed out that the Complex method was based on the Composite Lifting Index in the Revised NIOSH Lifting Equation. The variables for the equation are defined as the following:

SI_j	=	Strain Index score for jth task
SI_R	=	Complex Strain Index Redundancy
D_j	=	Percent Duration of Exertion for the jth task
F_j	=	Frequency of Exertion for the jth task
MI_j	=	Intensity of Exertion Multiplier for the jth task

MD _j	=	Duration of Exertion Multiplier for the jth task
MF _j	=	Frequency of Exertion Multiplier for the jth task
MP _j	=	Hand/Wrist Posture Multiplier for the jth task
MS _j	=	Speed of Exertion Multiplier for the jth task
MH	=	Duration of Job (hours/day) Multiplier

The preliminary Complex Strain Index method uses several steps to calculate the score. The first step involves calculating the Strain Index scores for each task separately and independently of any other tasks in the job using the original published method or one of the above mentioned continuous methods. Once calculated the Strain Index scores are rank ordered by highest score. The highest Strain Index score is the base score. The Complex Strain Index score must be greater than the base score because any additional tasks only add to the strain of the DUE. Once the base score has been established, the additional strain must be calculated. The second Strain Index score in the rank order (the second largest Strain Index score) is recalculated using Equation 2.

Equation 2

$$SI_{2C} = MI_2 * MD_c * MF_c * MP_2 * MS_2 * MH_2$$

Where:

$$MD_C = \text{Multiplier for } (D_1 + D_2)$$

$$MF_C = \text{Multiplier for } (F_1 + F_2)$$

The second step involves calculating the Strain Index Redundancy (SI_R). The new calculation for the second Strain Index score counts some of the strain applied to the

DUE twice and must be removed from the Composite Strain Index score. SI_R is calculated by Equation 3.

Equation 3

$$SI_R = MI_2 * MD_1 * MF_1 * MP_1 * MS_1 * MH_1$$

The third and final step involves calculating the Complex Strain Index score, which is calculated by Equation 4.

Equation 4

$$SI_C = SI_1 + SI_{2C} - SI_R$$

Continuous Strain Index

As with all good tools, the Strain Index is continuously evolving to become a better analysis tool. The current project is an example of this evolution. Another project that will aid in the evolution of the Strain Index is finding a way to calculate the Strain Index using continuous variables as opposed to the current categorical variables. Under the current method of calculating the Strain Index, if a worker performs a task with a Duration of Exertion of 12 percent, then that worker has the same Strain Index score as a person who does the identical job, but performs the task with a Duration of Exertion of 25 percent. Physiologically and biomechanically, these two tasks apply different levels of stress to the DUE and the Strain Index should reflect the difference in the Strain Index score. The original authors of the Strain Index have hypothesized several different methods of calculating a continuous Strain Index score, but no method has been officially adopted, published, or validated. For the purpose of the current experiment, two different

methods will be used to calculate a continuous Strain Index score and then used to calculate a Complex Strain Index score. The first formula, called SI_A , was calculated by Equations 5 through Equation 9. The task variables Speed of Work and Hand/Wrist Posture will remain categorical and calculated according to the published guidelines (Moore and Garg, 1995).

Equation 5 Intensity of Exertion calculation for SI_A

$$I_A = 0.0006 * (\%MVC)^2 + 0.092 * (\%MVC) + 0.2582$$

Equation 6 Duration of Exertion calculation for SI_A

$$D_A = 0.029 * (\% \text{ Duration}) + 0.41$$

Equation 7 Frequency of Exertion calculation for SI_A

$$F_A = 0.1 * (\text{Efforts per minute}) + 0.3$$

Equation 8 Duration of Task per Day calculation for SI_A

$$DT_A = 0.0014 (\text{hours worked})^3 - 0.033 (\text{hours worked})^2 + 0.3 (\text{hours worked})$$

Equation 9 Continuous Strain Index score calculation for SI_A

$$SI_A = I_A * D_A * F_A * DT_A * \text{Posture Multiplier} * \text{Speed of Work Multiplier}$$

The second method that was used to calculate a continuous Strain Index score, SI_B , is listed in Equations 10 through Equations 14. Once again, Hand/Wrist Posture and Speed of Work were calculated according to the published guidelines (Moore and Garg, 1995).

Equation 10 Intensity of Exertion calculation for SI_B

$$I_B = (\%MVC / 20)^{1.6}$$

Equation 11 Duration of Exertion calculation for SI_B

$$D_B = 0.033 * (\% \text{ Duration})$$

Equation 12 Frequency of Exertion calculation for SI_B

$$F_B = (\text{Efforts per minute}) / 8$$

Equation 13 Duration of Task per Day calculation for SI_B

$$DT_B = 0.361 * LN(2 * \text{hours worked})$$

Equation 14 Continuous Strain Index score calculation for SI_B

$$SI_B = I_B * D_B * F_B * DT_B * \text{Posture Multiplier} * \text{Speed of Work Multiplier}$$

Variable Selection

Once the treatments were administered and the results calculated, variables must be selected for inclusion in Part II of the study that would help evaluate the method of calculating a Complex Strain Index. Variables included showed a treatment effect and made rational sense. For example, IMnPF could show a treatment effect by random chance, but since IMnPF was recorded before the treatments were administered, they could not be influenced by the treatments and thus would not make sense for inclusion. If variables are highly correlated with each other, only one was selected to compare with the Strain Index models.

Comparison of Methods

Table 2 lists each method of calculating the Complex Strain Index score and the expected score for each experimental treatment. To calculate the Strain Index score, Table 2 uses the categorical method the Strain Index, which involves using the multipliers outlined in the original Strain Index article (Moore and Garg, 1995). Table 3 and Table 4 use the SI_A and SI_B methods, respectively, to calculate the continuous Strain Index score. The Strain Index methods were correlated with the subject variables to determine how well each method fit the data.

For a Complex Strain Index method to be considered an acceptable fit: (1) the method must have a high correlation with the subject variables (R^2 above a 0.7), (2) the Complex Strain Index score for a job with several tasks of varying intensity must not exceed the Strain Index score of the same job if it were calculated as a mono-task job with the intensities for each task were set to the peak values, (3) a Complex Strain Index score can not be lower than the highest mono-task Strain Index Score calculated independent of the other tasks in the job, and (4) the Complex Strain Index score must be equal to the mono-task Strain Index score for mono-task jobs.

Table 2 Experimental treatments and the expected value of the Complex Strain Index score using the categorical method

Treatment						
Method	T1	T2	T3	T4	T5	T6
SI Average	0.32	0.38	0.94	1.25	1.32	1.88
Unadjusted Sum	0.63	0.76	1.88	2.5	2.63	3.75
Adjusted Sum	0.75	1.00	2.00	3.25	3.50	4.50
SI Peak	0.56	0.75	3.38	3.38	4.50	3.38
SI Minimum	0.56	0.75	0.56	0.56	0.75	3.38
SI _c Complex	0.56	0.75	1.06	2.43	2.62	3.38

Table 3 Experimental treatments and the expected value of the Complex Strain Index score using the SI_A continuous method

Treatment						
Method	T1	T2	T3	T4	T5	T6
SI Average	0.30	0.38	0.61	0.86	0.95	1.17
Unadjusted Sum	0.59	0.64	1.21	1.72	1.89	2.34
Adjusted Sum	0.94	1.28	1.81	2.84	3.18	3.71
SI Peak	0.78	1.07	3.10	3.10	4.24	3.10
SI Minimum	0.78	1.07	0.78	0.78	1.07	3.10
SI _A Complex	0.78	1.07	1.40	1.91	2.20	3.10

Table 4 Experimental treatments and the expected value of the Complex Strain Index score using the SI_B continuous method

Treatment						
Method	T1	T2	T3	T4	T5	T6
SI Average	0.04	0.06	0.13	0.29	0.31	0.38
Unadjusted Sum	0.08	0.12	0.25	0.75	0.62	0.75
Adjusted Sum	0.16	0.24	0.50	1.17	1.26	1.51
SI Peak	0.16	0.25	1.50	1.50	2.25	1.50
SI Min	0.16	0.25	0.16	0.16	0.25	1.50
SI _B Complex	0.16	0.25	0.33	0.66	0.75	1.50

STATISTICS

The first phase of the study was to collect data on subjects' responses to DUE stress caused by hand gripping tasks. By varying the duration and intensity of exertions, the treatments simulate complex jobs and the data obtained can be used to examine how increasing the stress on the DUE affects the measured and subjective variables. The effects will be used during the second phase of the experiment to evaluate previously mentioned methods of incorporating complex tasks into the Strain Index score calculation.

By interlacing mono-task jobs and complex task jobs into the treatment scheme, the baseline subjective and measured variable values can be established for Strain Index scores that are known (mono-tasks) and then compare them to the data results from complex task jobs. Once the difference between the data in the complex jobs and mono-task jobs is known, the impact of the addition stress to the DUE can be established and used to evaluate different methods of incorporating the additional stress of the complex task into the Strain Index score.

Descriptive Statistics and Data Testing

The independent variables are Treatment (derived from Duration of Exertion and Intensity of Exertion) and Gender. The dependent variables MVC, percent strength loss, subjective measures (RPEs, fatigue, discomfort, and difficulty ratings), and EMG

measures (MnPF slopes, RMS, and IMnPF). To test if MVC varied by treatment session, an intra-subject ICC(2, 1) absolute agreement was performed.

Descriptive statistics on the raw data will be calculated including the mean, median, and mode values, and the standard deviation. This information can be used to inspect intrasubject variability and consistency, but most data, including MVC, RPE, and all EMG data will have to be normalized before it can be used for intersubject analysis. Calibration measurements will be taken at the beginning of each treatment session and used in the normalization process. For RPE, the subjects will perform a random series of exertions as a percentage of their MVC and asked to report the RPE for the random exertion. With the subject blind to the real MVC value, the RPE calibration measurement could be evaluated for inter-subject and intra-subject reliability using ICC(2,1) absolute agreement. If the ICC reliability coefficient was above 0.80 for both inter-subject and intra-subject reliability, it was assumed that the raw RPEs did not need to be normalized and could be used in the analysis phase of this experiment. For subjective data, descriptive statistics as well as linear trend lines and R^2 values were calculated.

EMG Statistics

The EMG signals was checked for ergodicity using the Runs Test to determine the appropriate window size (the time span for each observation) for the spectral analysis. Spectral analysis of the EMG signal was used to calculate the MnPF. Once the MPF was calculated, it was plotted against time and a least-squares regression was used to calculate the slope and y-intercept (Krivickas et al. 1998; Rainoldi et al, 1999). The y-intercept of

the MnPF represents the IMnPF and the slope of the MnPF represents the rate of decline, also known as the fatigue rate measured in hertz per second. A paired t-test was used to determine if there is a significant difference between pre and post treatment MnPF signifying if subjects fatigued during all treatments.

Experimental Design

The experiment used MANOVA to analyze gender, treatment and their interaction, with the null hypothesis of mean equivalence. The null hypothesis for gender was expected to be accepted, while rejected for treatment. Post hoc testing (Fisher's LSD) was used to determine treatment differences and these differences were then used to determine which model best describes the strain caused by the Complex Tasks. Contrast testing will be used to evaluate the two extreme calculation methods.

Each of the Complex Strain Index model correlated with the dependent variables. Each model was then evaluated on how it fits each dependent variable. The experimental design, with a significance difference level of alpha equal to 0.05, has a row effect Power of 1, a column effect Power of 1, and an interaction effect power of 1 based on the Root Mean Sum of Squares Estimate calculated using data collected in a previous experiment.

PRELIMINARY DATA

In order to insure that the proposed experiment provided the results needed to answer the research questions, preliminary data was gathered. The first question that was answered was “is the equipment working correctly?” This includes proper calibration of the hand dynamometer and the EMG leads, stability of the acquisition software, checking the data storage, as well as verifying that the data analysis programs are providing accurate and precise results.

Hand Dynamometer

The first step was to calibrate the hand dynamometer. A work bench was constructed to hold the hand dynamometer such that calibrated weights could be hung from the gripping handle. The analog pressure gauge was adjusted to reflect the correct amount of pressure corresponding to the weights added to the handle (i.e. if 20 pounds of weight was added to the dynamometer, then the gauge read 20 pounds of pressure). Once the analog pressure gauge was calibrated, the voltage created by the pressure transducer was measured and graphed against the weight applied to the dynamometer. Figure 8 shows a graph of the calibration curves of the dynamometer over several days.

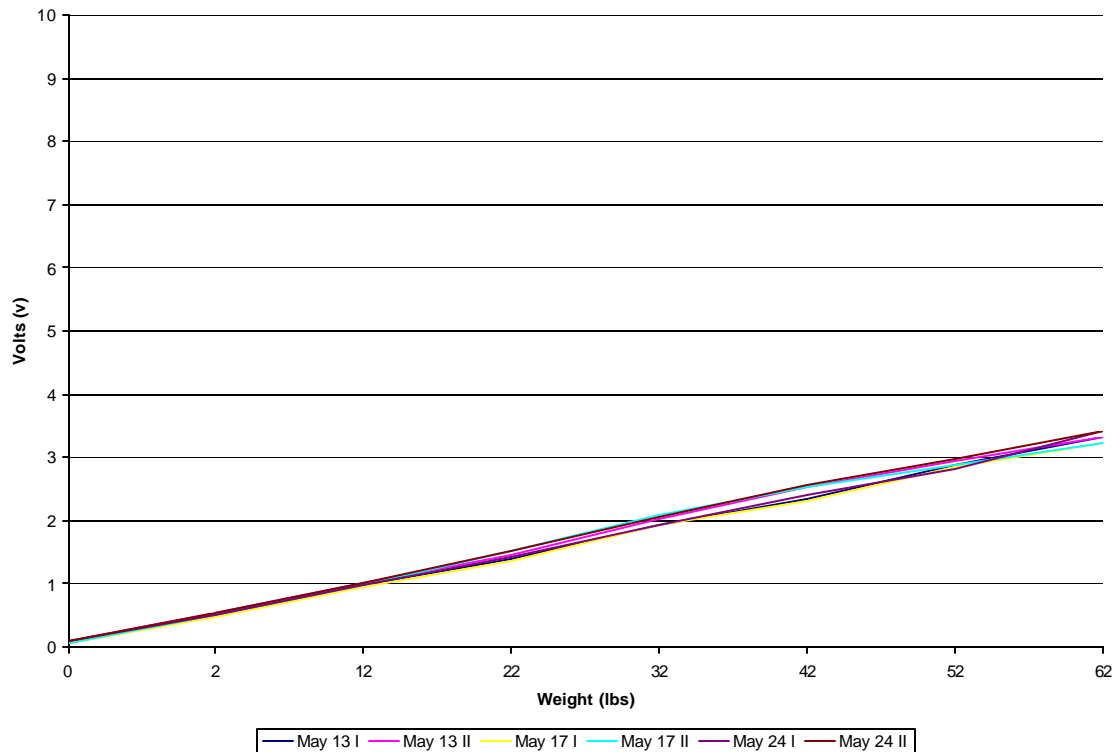


Figure 8 Dynamometer voltage calibration curves measured two times daily for three days over a period of 11 days

All of the sampled calibration curves are linear with R-squared values above 0.99. The graph is scaled to 10 volts because the National Instruments (NI) data acquisition card (daq) has a resolution of plus or minus 10 volts. Because negative pressure cannot exist on the dynamometer, the graph is only scaled in the positive direction. The gain cannot be increased to take advantage of a larger percentage of the scale because of saturation problems (the voltage exceeds the maximum of ten volts).

Even though the dynamometer has shown stability over 11 days, the dynamometer was recalibrated before each subject to ensure accuracy. In a previous experiment, years prior, the dynamometer developed a slow leak due to improper maintenance. This leak was not discovered for several days. Two subject sessions had to

be repeated due to the error introduced by the leak in pressure. The leak previously experienced is an example of reasons why the dynamometer was calibrated before each subject session.

EMG Gain Settings

The EMG signals were tested to determine the proper gain settings as well as the proper filter settings. Several different gain settings were tested Figure 9 and Figure 10 show gain settings of “1000” and “2000” respectively. The gain settings are in quotations because, at the moment, the equipment to verify the accuracy of the labeled gain states on the amplifiers has not been found. It is believed, due to previous research that the gain states listed above are overestimating the true value of the gain states they represent.

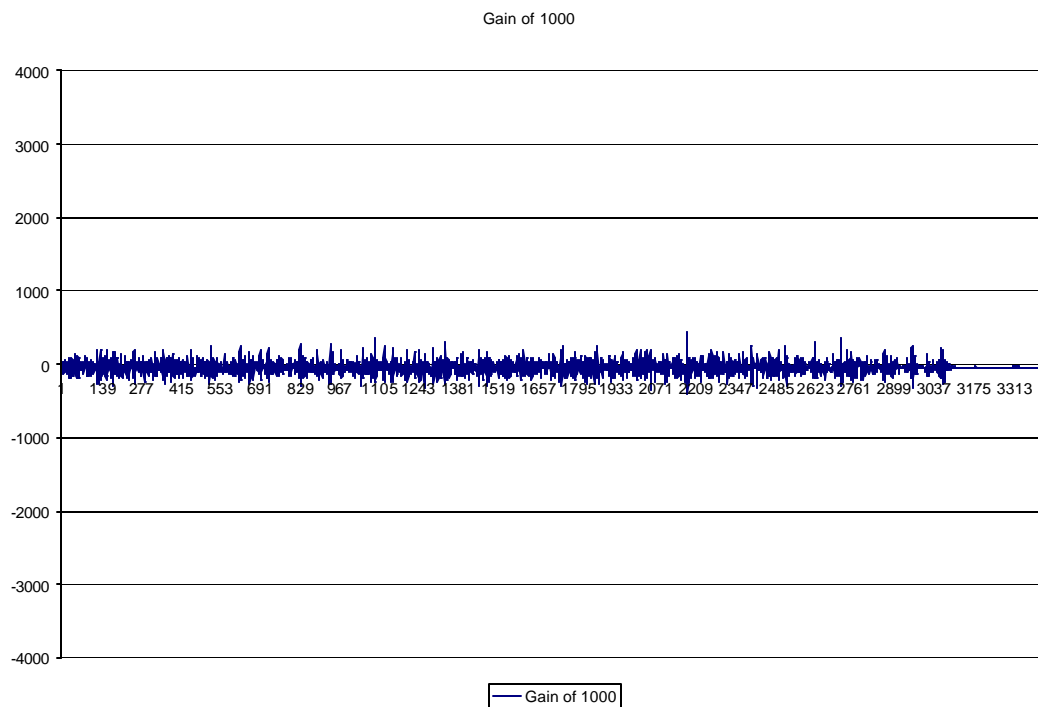


Figure 9 A 100 percent MVC hold for three seconds using 1000 times gain of the extensors.

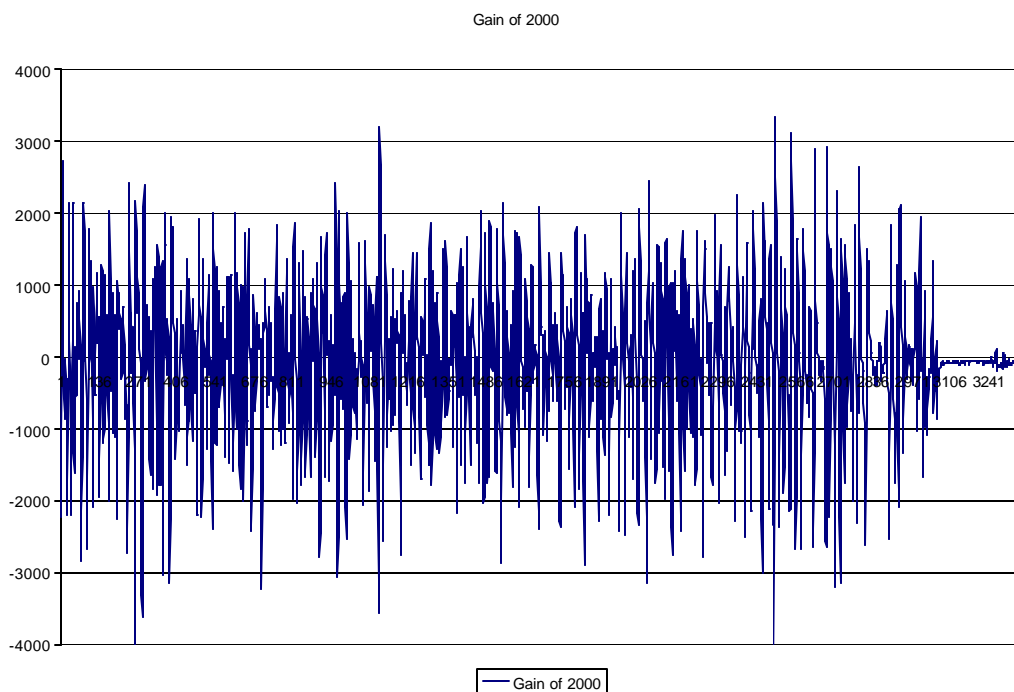


Figure 10 A 100 percent MVC hold for three seconds using 2000 times gain of the extensors.

Figures 9 and 10 are scaled between +/- 4000 because a 12-bit daq card is being used to acquire the data. This means that the resolution of the card is +/- 2^{12} or +/- 4096. To get meaning out of what the y-axis means (the correct voltage), the proper scaling factor must be known. For the moment, the y-axis is primarily being used for magnitude of change and not to gather the precise muscle voltage changes. The difference between Figure 9 and 10 is the gain setting. Figure 10 uses much more of the y-axis with no points of saturation. Other options for gain settings are 5000, which has major saturation issues and 500, which has a smaller resolution than the gain of 1000 (Figure 9). As seen in Figure 10, a gain state of 2000 was selected for this experiment.

Expected Results

A test subject performed a 100% MVC exertion for ten seconds. The results were analyzed using the DaDiSP software. Figure 11 shows the graphed spectral shift from the first second of the hold to the tenth second.

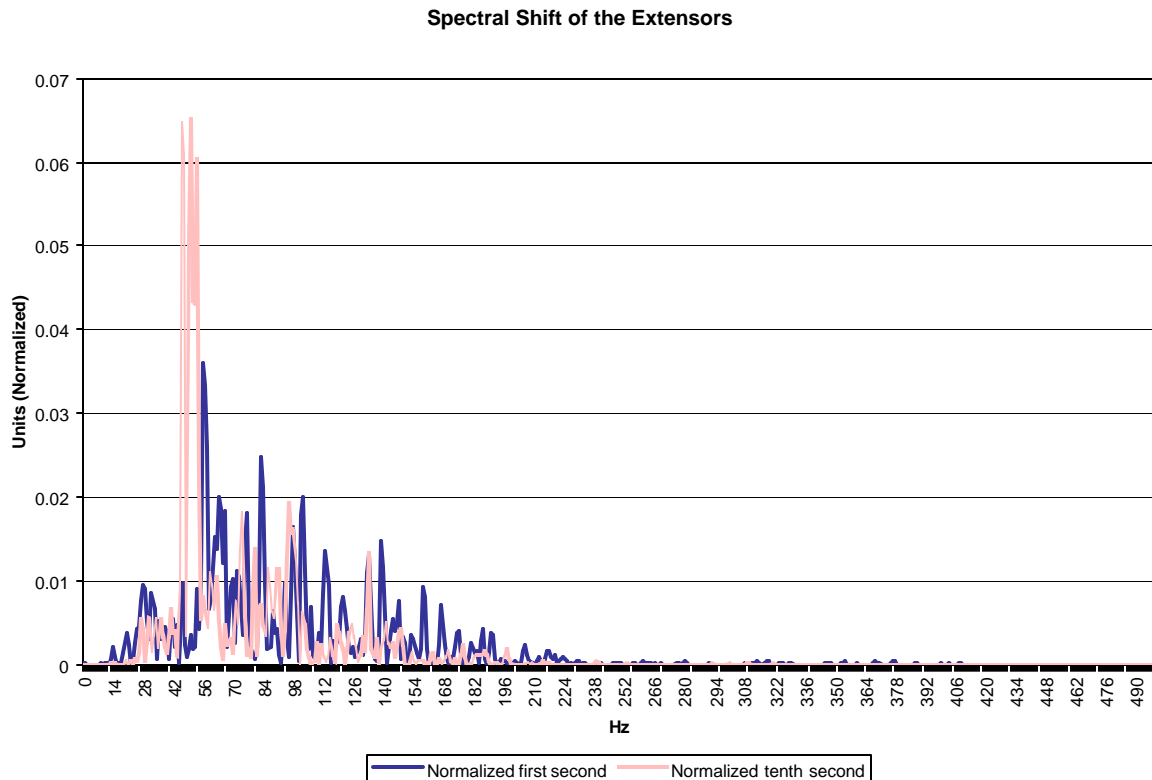


Figure 11 The spectral shift from the first second of a 100% MVC hold to the tenth second.

As can be seen in Figure 11, the tenth second shows an increased amount of energy in the lower frequency bands compared to the first second, which is what is expected from literature (Bilodeau et al, 2003; Elfving et al, 1999). Literature also states that the MnPF can be graphed over time and the slope should be close to linear (Lowery et al, 2002; Moritani et al, 1986a; NIOSH, 1992; Pease and Elinski, 2003). As Figure 12 shows, this is the case in the current study.

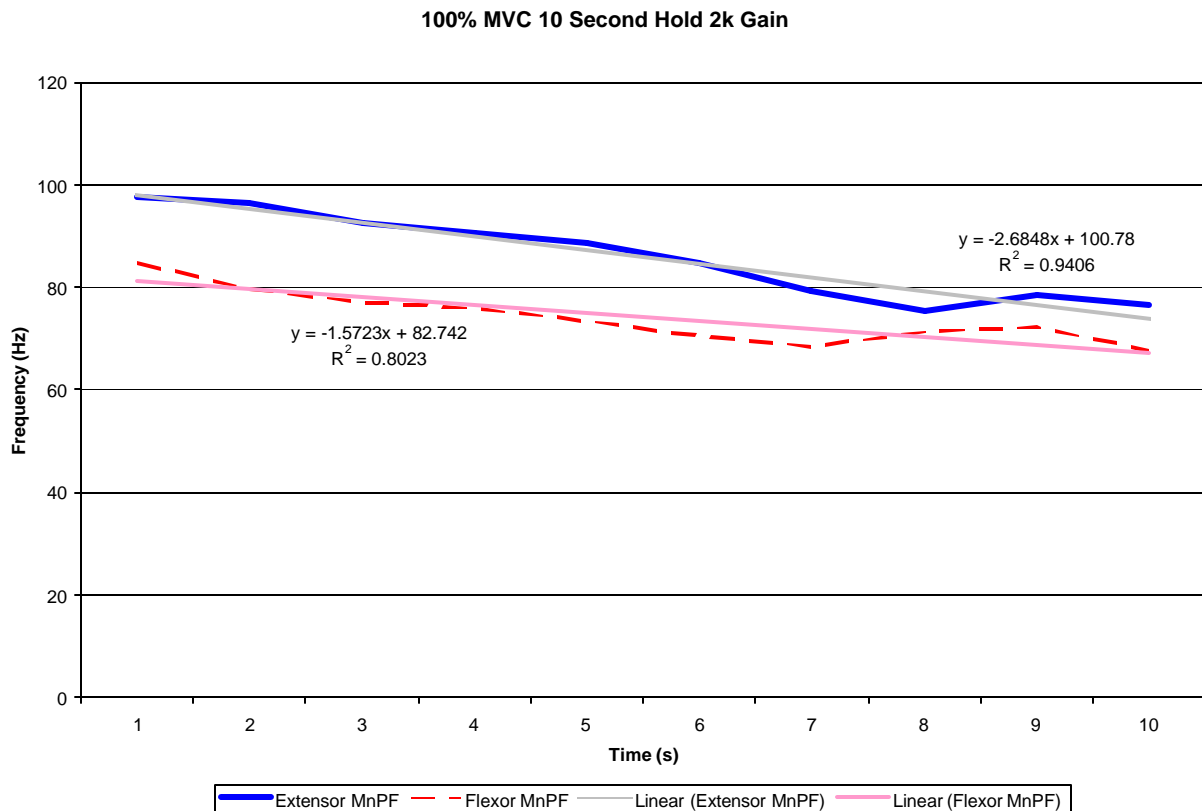


Figure 12 The MnPF for extensors and flexors are graphed for a ten second 100% MVC hold.

The testing protocol calls for subjects to use intermittent holds for durations of one or three seconds with a testing period of an hour. A preliminary test was performed with a subject performing a one second 60% MVC hold, four second rest, three second 60% MVC hold, and rest for two seconds. The subject could only perform this task for thirty minutes. Another subject was asked to perform a one second 60% MVC hold, four second rest, three second 40% MVC hold, and two second rest. The test was completed by repeating the hold and rest cycle for an hour. The MnPF data from the first test was compared to the second test. Since the first test could not be completed (run the complete

60 minutes), the second test was truncated down to thirty minutes. Figure 13 shows a comparison between the MnPF of the flexors in test one and test two.

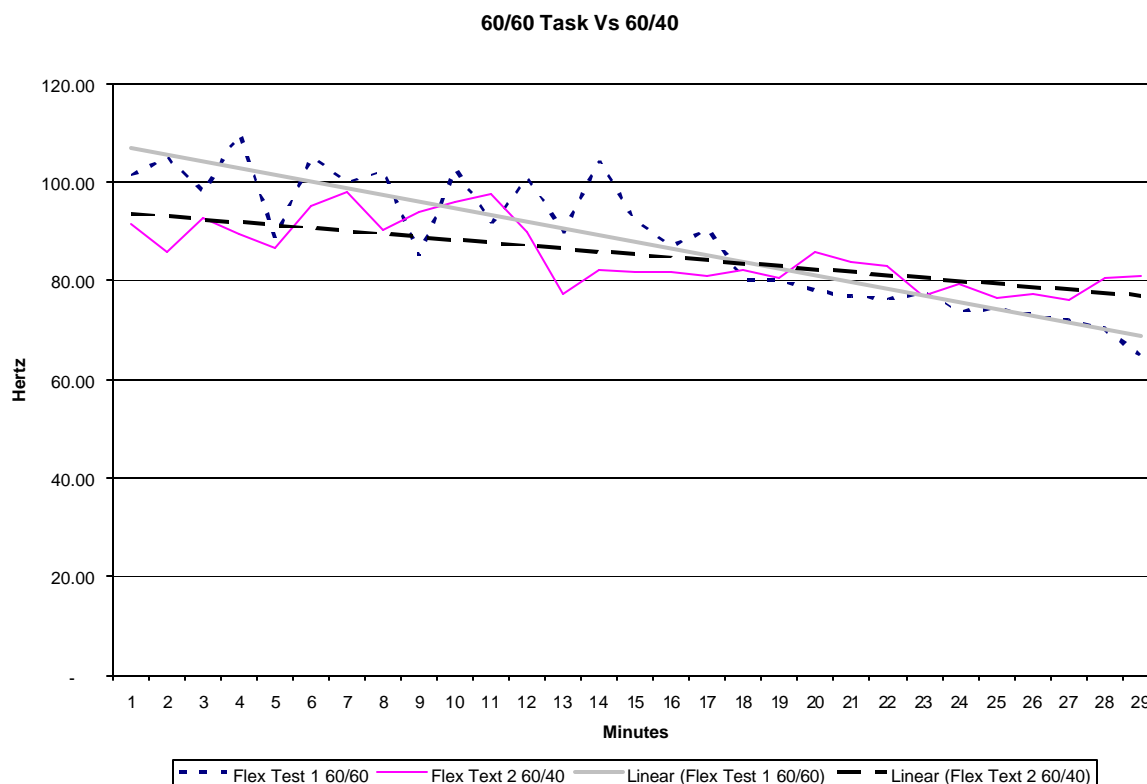


Figure 13 A comparison between the flexor MnPF of test one and test two.

As one would expect, the slope of the harder test (test one) is steeper than the slope of the easier test (test two).

RESULTS: PART I

Subject Data

All 24 subjects (12 men and 12 women) completed each of the six treatments for a total of 144 treatment sessions. Subjective data for all 144 treatment sessions were recorded and analyzed. Due to unexpected noise and filter problems, three EMG treatment records could not be completely analyzed. Some EMG data was available for each of these three records and was included in the analysis.

The mean age of male subjects was 26.8 (22 – 37) years and 24.6 (23 – 28) for females. Table 5 further describes the study population.

Table 5 Information on study population

	Male		Female		Total	Total Percent
	Number	Percent	Number	Percent		
Subjects	12	100%	12	100%	24	100%
Minority	4	33%	3	25%	7	29%
Left Handed	2	17%	1	8%	3	13%
College Graduates	10	83%	12	100%	22	92%

MVCs and Percent Strength Loss

Pre treatment MVCs are shown in Table 6 by gender. Intra-subject pre treatment MVC had a correlation coefficient of 0.94. Percent strength loss by gender and treatment can be seen in Figure 14 and is further broken out in Table 7. Treatment 1 had a negative average percent strength loss for males. This means that the male subjects gained strength (had a higher 100% MVC) at the end of the treatment as compared to the start of

the treatment. Percent strength loss was the only variable that saw an interaction effect between gender and treatment ($p < 0.05$). Because no other variable had a significant gender effect, gender was dropped as a factor from the analyses of all other dependent variables.

Table 6 Descriptive statistics of pre and post treatment MVCs.

	Male					
	Mean	Median	Mode	Max	Min	Stdev
Pre MVC (kg)	43.2	42.1	40.6	66.6	32.6	7.5
	Female					
	Mean	Median	Mode	Max	Min	Stdev
Pre MVC (kg)	26.2	24.8	22.3	48.5	14.6	8.2

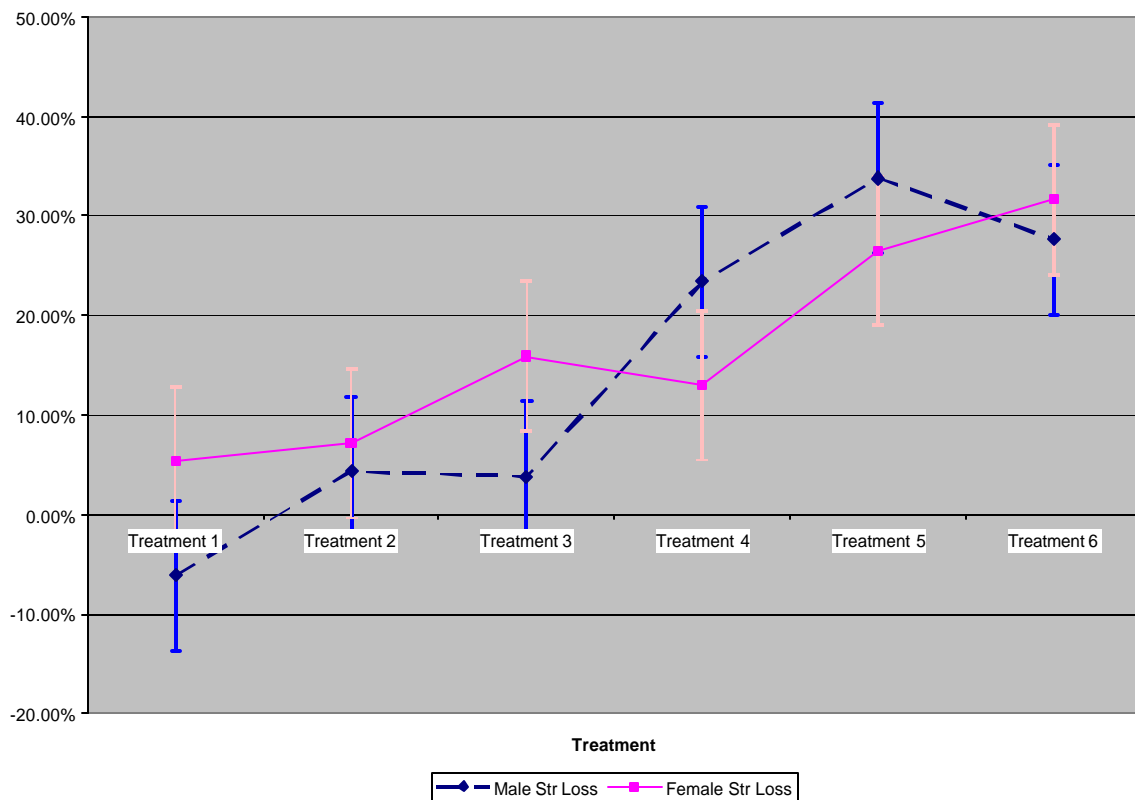


Figure 14 Strength loss by gender and treatment.

Table 7 Percent strength loss by treatment separated by gender

	Male			
	Average	Max	Min	CI 95%
Treatment 1	-6.10%	7.90%	-16.10%	(-13.7%, 1.4%)
Treatment 2	4.30%	21.00%	-11.80%	(-3.2%, 11.8%)
Treatment 3	3.80%	21.40%	-18.30%	(-3.7%, 11.3%)
Treatment 4	23.40%	53.90%	0.30%	(15.9%, 30.9%)
Treatment 5	33.80%	53.00%	8.80%	(26.3%, 41.3%)
Treatment 6	27.60%	48.50%	6.20%	(20.1%, 35.1)
	Female			
	Average	Max	Min	CI 95%
Treatment 1	5.40%	27.10%	-18.90%	(-2.2%, 12.9%)
Treatment 2	7.10%	38.90%	-16.50%	(-0.4%, 14.6%)
Treatment 3	15.90%	36.40%	-8.20%	(8.4%, 23.4%)
Treatment 4	13.00%	31.10%	-0.40%	(5.5%, 20.5%)
Treatment 5	26.50%	45.50%	4.20%	(19.0%, 34.0%)
Treatment 6	31.60%	50.70%	7.20%	(24.1%, 39.2%)

Subjective Measures

Figures 15 - 19 show the average RPE, hand and forearm fatigue, and hand and forearm discomfort for each five minute interval by treatment.

R^2 values of the RPEs show a linear increase for RPE throughout the hour of each treatment. Treatments 1 – 3 have very similar slopes as do treatments 4 – 6. These groupings are important because treatments 1 – 3 and 4 – 6 have the same primary exertion and vary due to their secondary exertion.

Table 8 presents the results from the RPE inter and intra-subject normalization ICCs. Because the results show a correlation coefficient above 0.80 for both inter and intra-subject variability, it is assumed that the raw RPE scores recorded are representative of the actual RPE scores and do not need to be normalized.

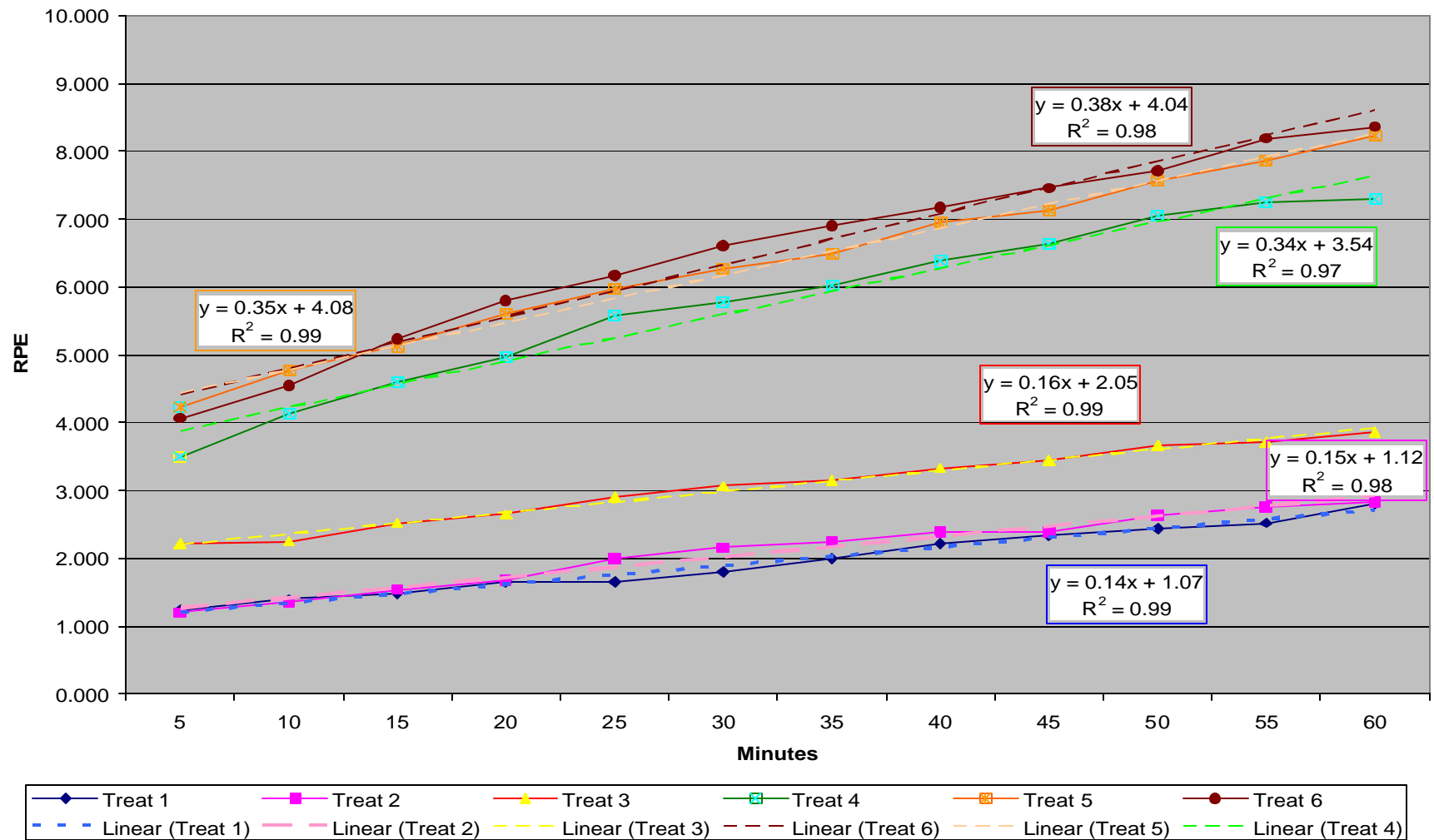


Figure 15 Average RPE in five minute intervals by treatment.

Table 8 ICC scores for inter and intra-subject variability in RPEs.

	ICC	Lower CI	Upper CI
Inter Subject			
Consistency	0.92	0.90	0.94
Absolute Agreement	0.88	0.84	0.91
Intra-subject			
Consistency	0.93	0.92	0.94
Absolute Agreement	0.93	0.92	0.94

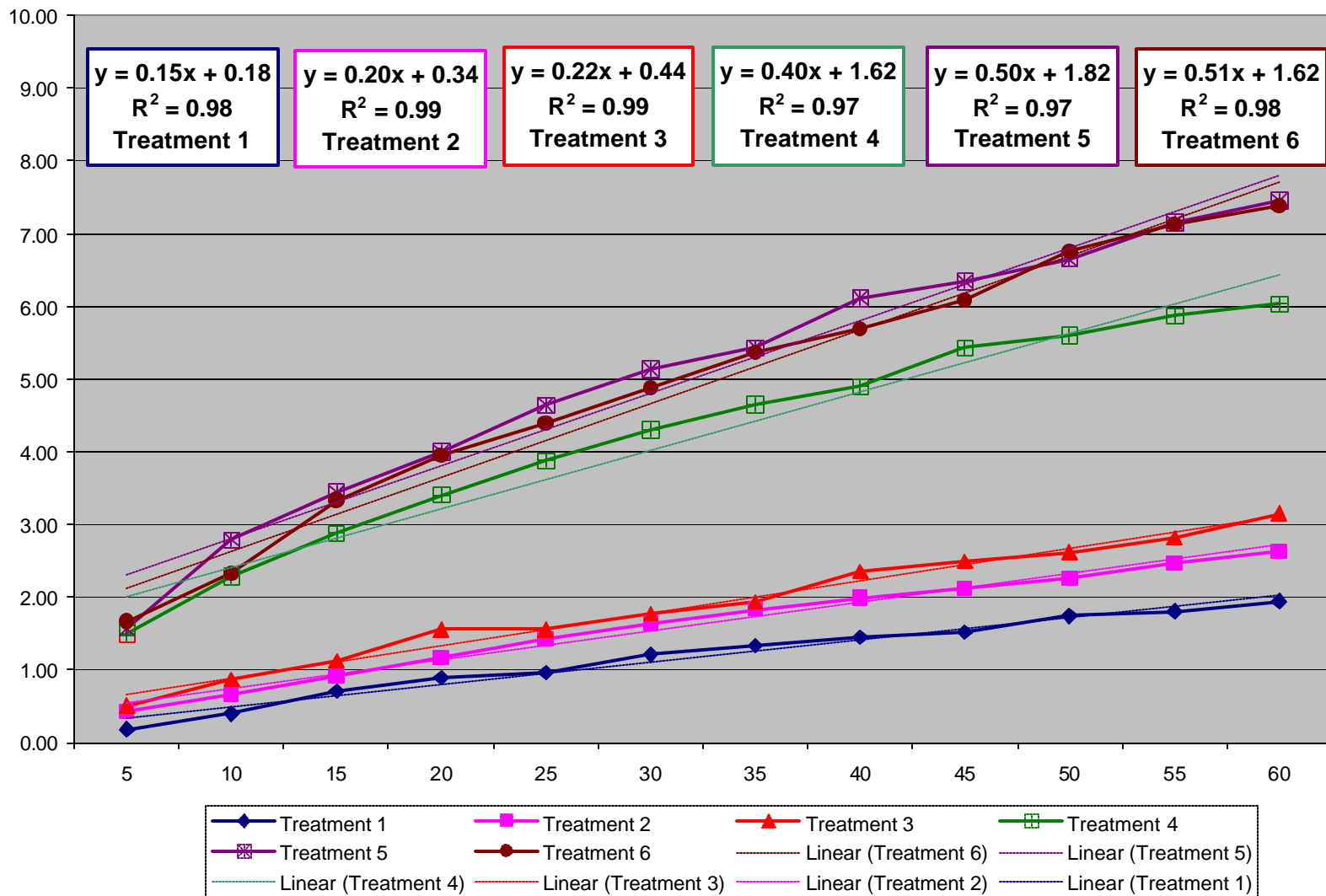


Figure 16 Average hand fatigue in five minute intervals by treatment

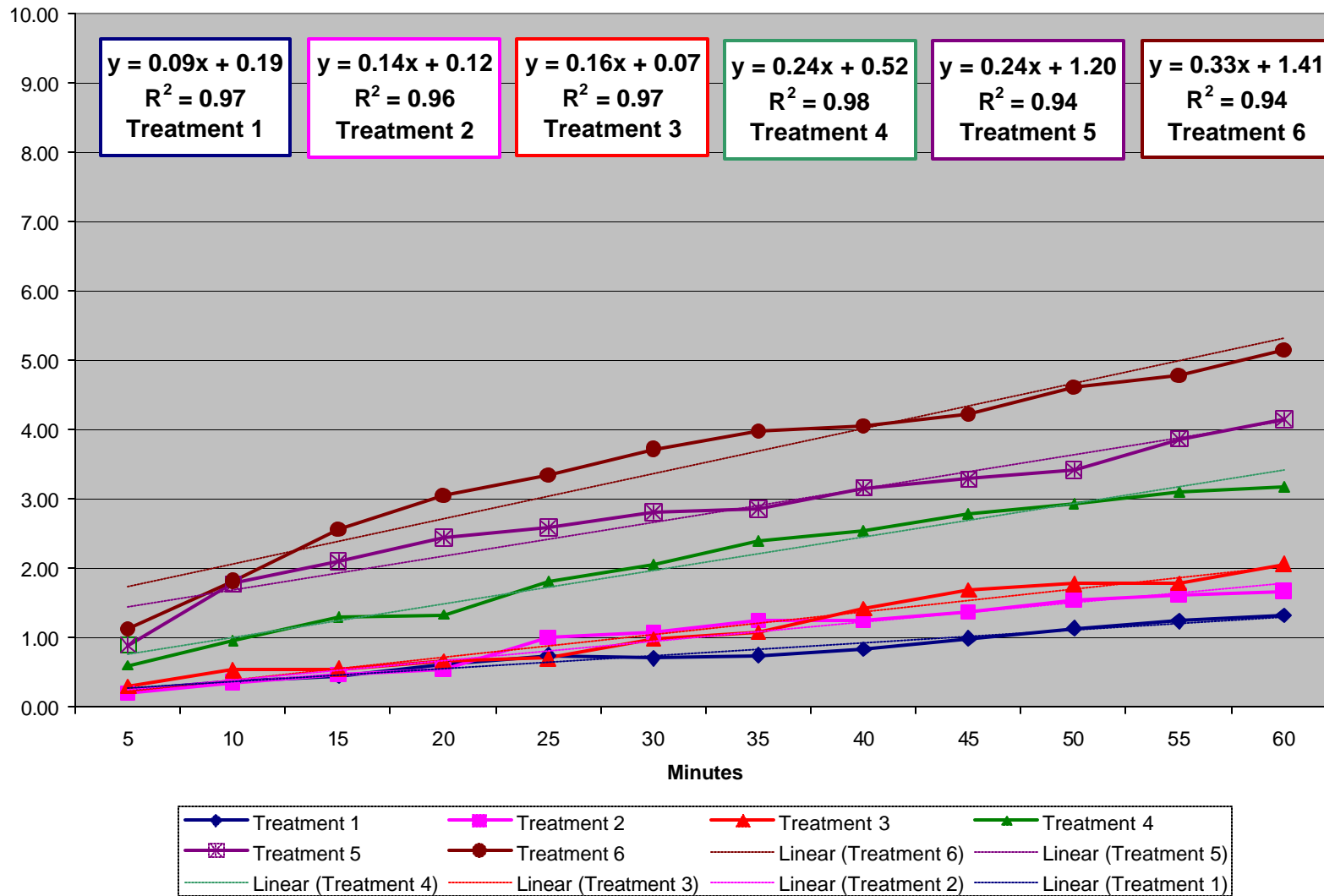


Figure 17 Average forearm fatigue in five minute intervals by treatment.

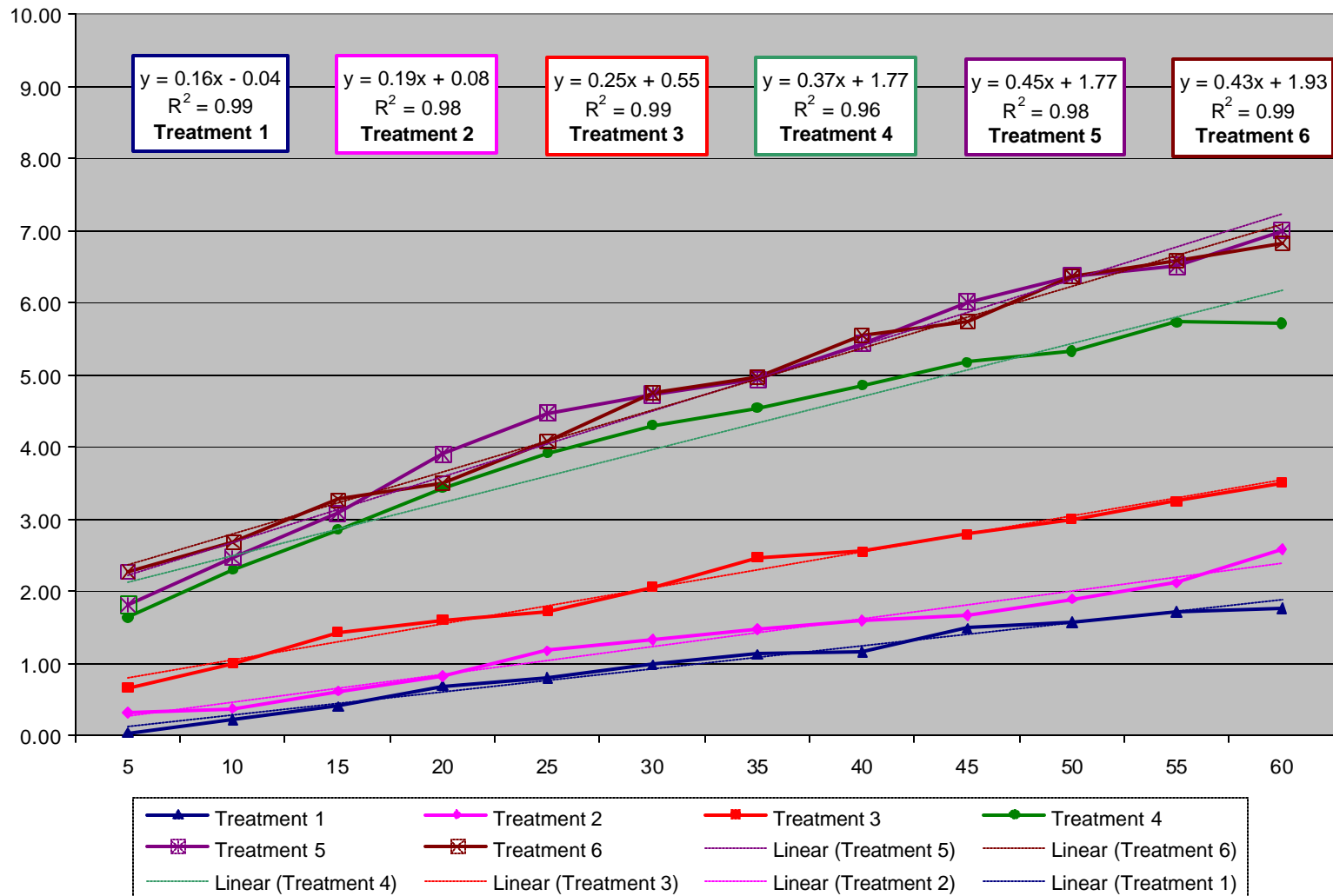


Figure 18 Average hand discomfort in five minute intervals by treatment.

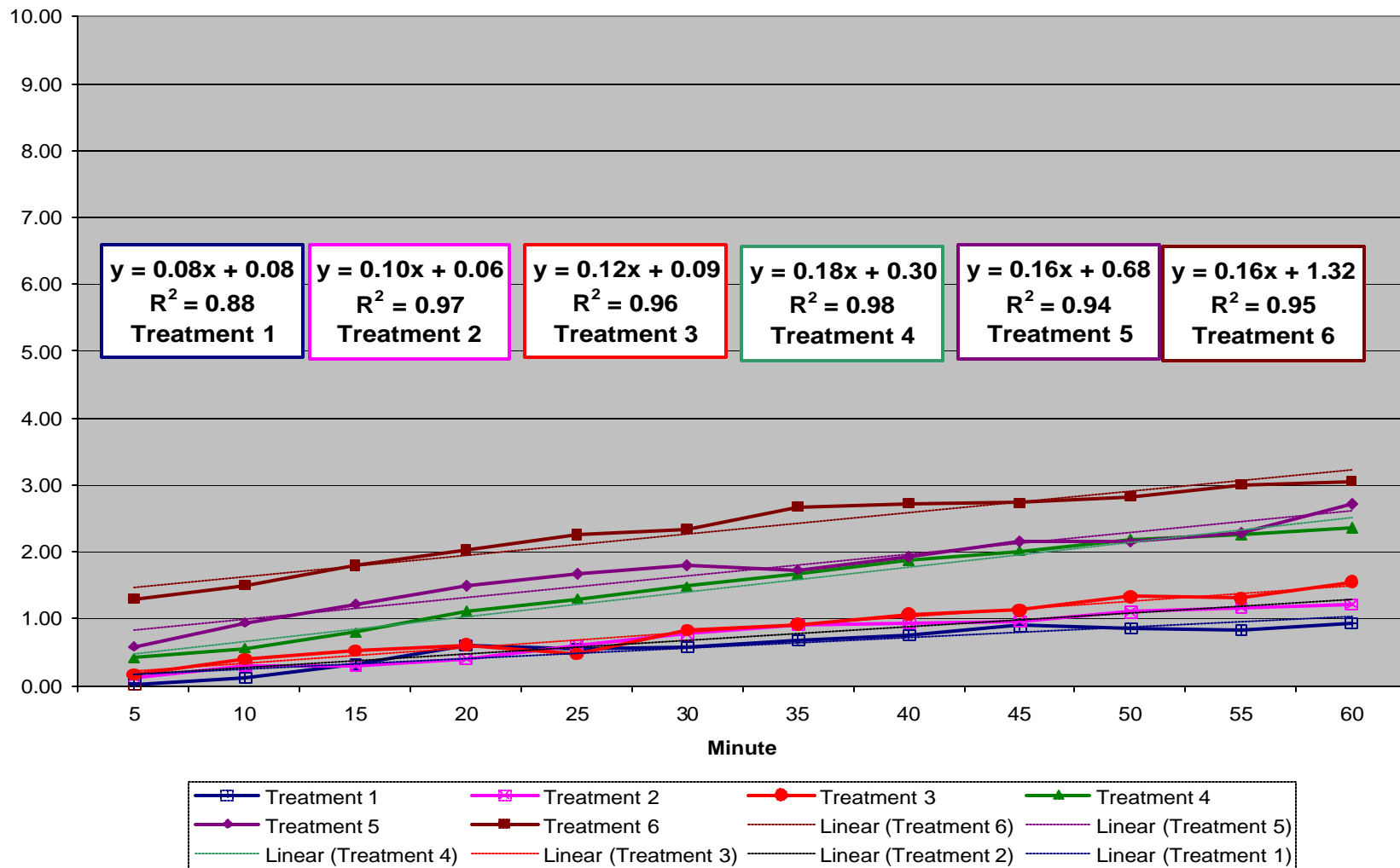


Figure 19 Average forearm discomfort in five minute intervals by treatment.

Fatigue and discomfort subjective measures also show a linear increase over time. Hand fatigue and hand discomfort parallel RPE's slope grouping of the primary exertions. Significant differences between treatments were found for all subjective measures ($p < 0.01$).

Figures 20 - 24 show the average maximum and minimum RPE, hand and forearm fatigue, and hand and forearm discomfort values by treatment. The max and min average values are displayed on the graphs so the average change for each treatment can be seen. Solid lines mark the Fisher's LSD homogeneous subsets for maximum values. The minimum value Fisher's LSD homogeneous subsets are designated by dotted lines.

During each hour-long treatment, if a subject reported fatigue/discomfort at any time interval, it was counted as a response for that time interval for that subjective variable (hand fatigue, forearm fatigue, hand discomfort, or forearm discomfort). The maximum number of intervals was 288 per-treatment per-variable (24 Subjects x 12 five-minute intervals). Subjects could report several locations of fatigue or discomfort within the same interval, so the total number of reports per treatment could be greater than the maximum number of intervals. Tables 9 and 10 show the frequency and location of fatigue in the hand and forearm respectively, as reported by subjects. Tables 11 and 12 show the frequency and location of discomfort in the hand and forearm respectively, as reported by subjects.

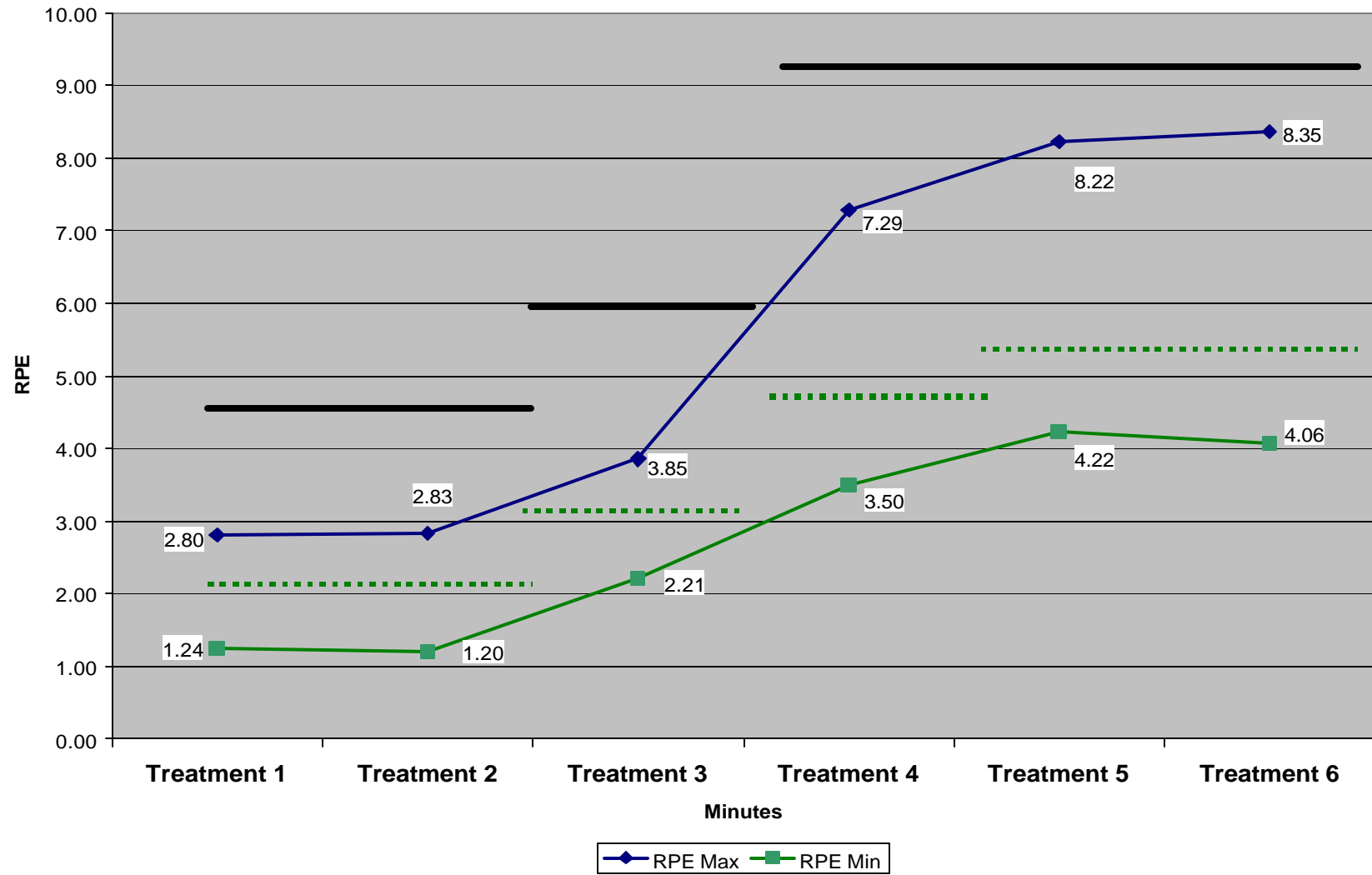


Figure 20 Max and Min RPEs averaged by treatment. Fisher's LSD homogeneous subgroups also displayed.

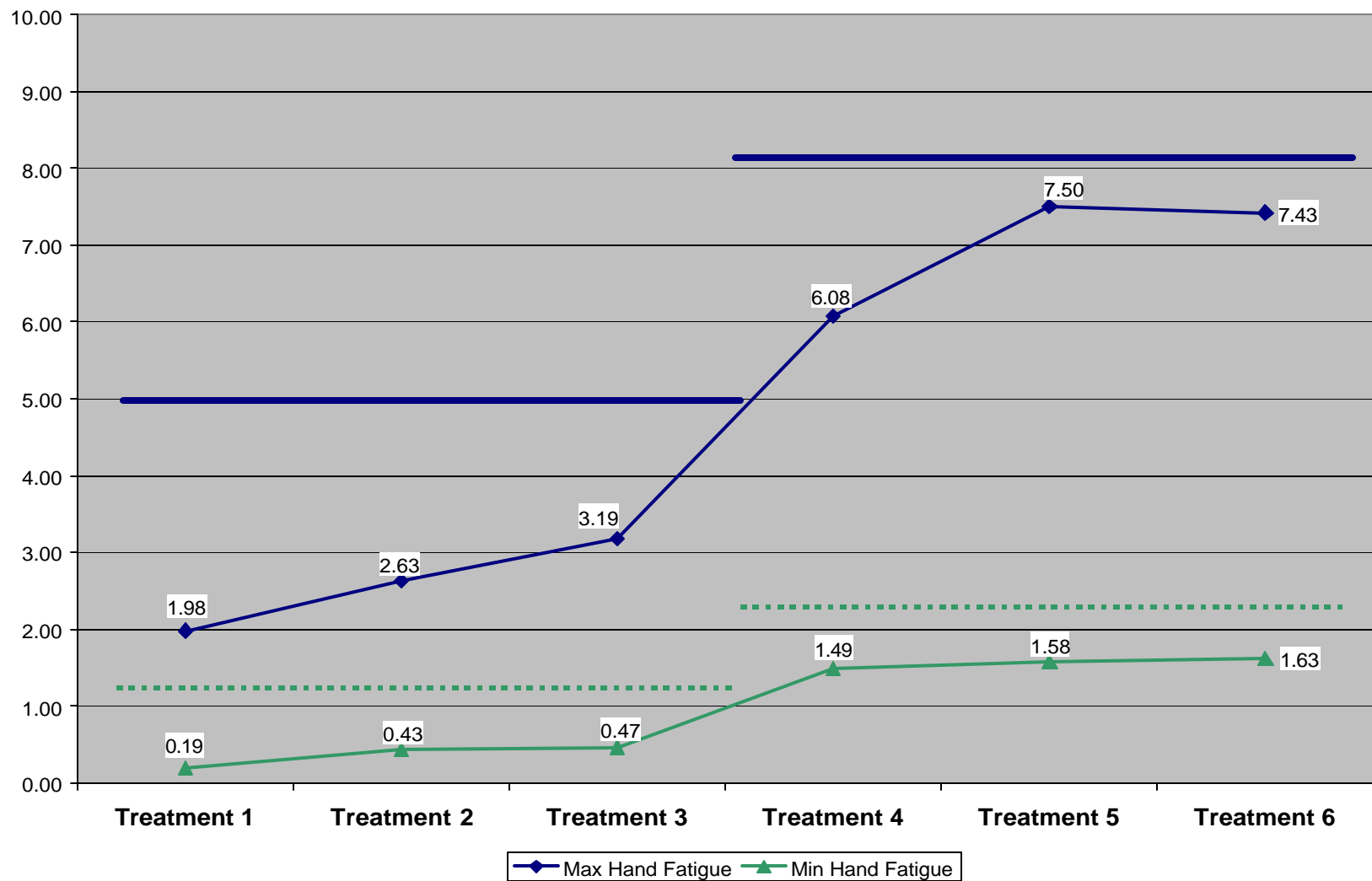


Figure 21 Max and Min hand fatigue averaged by treatment. Fisher's LSD homogeneous subgroups also displayed.

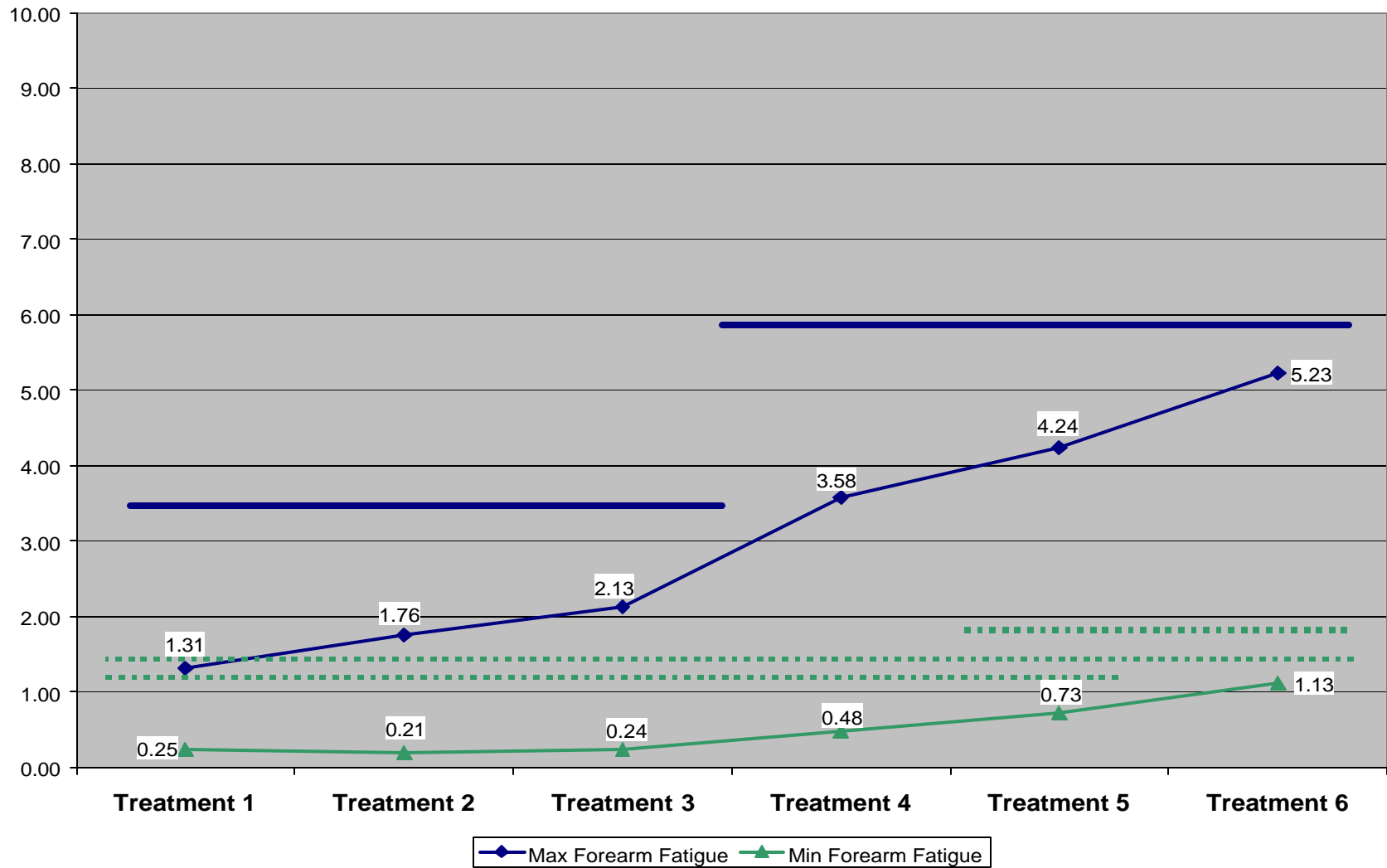


Figure 22 Max and Min forearm fatigue averaged by treatment. Fisher's LSD homogeneous subgroups also displayed.

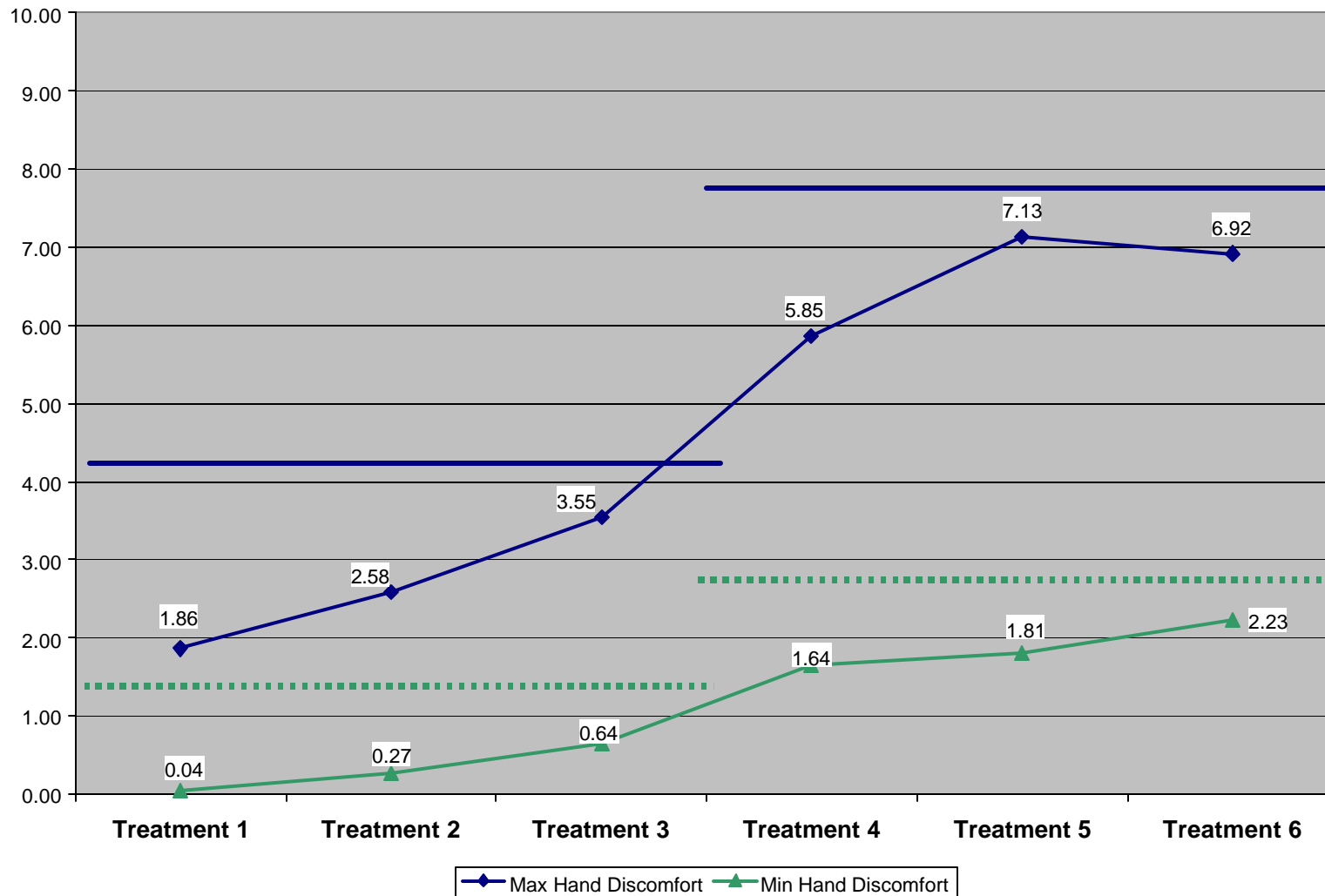


Figure 23 Max and Min hand discomfort averaged by treatment. Fisher's LSD homogeneous subgroups also displayed.

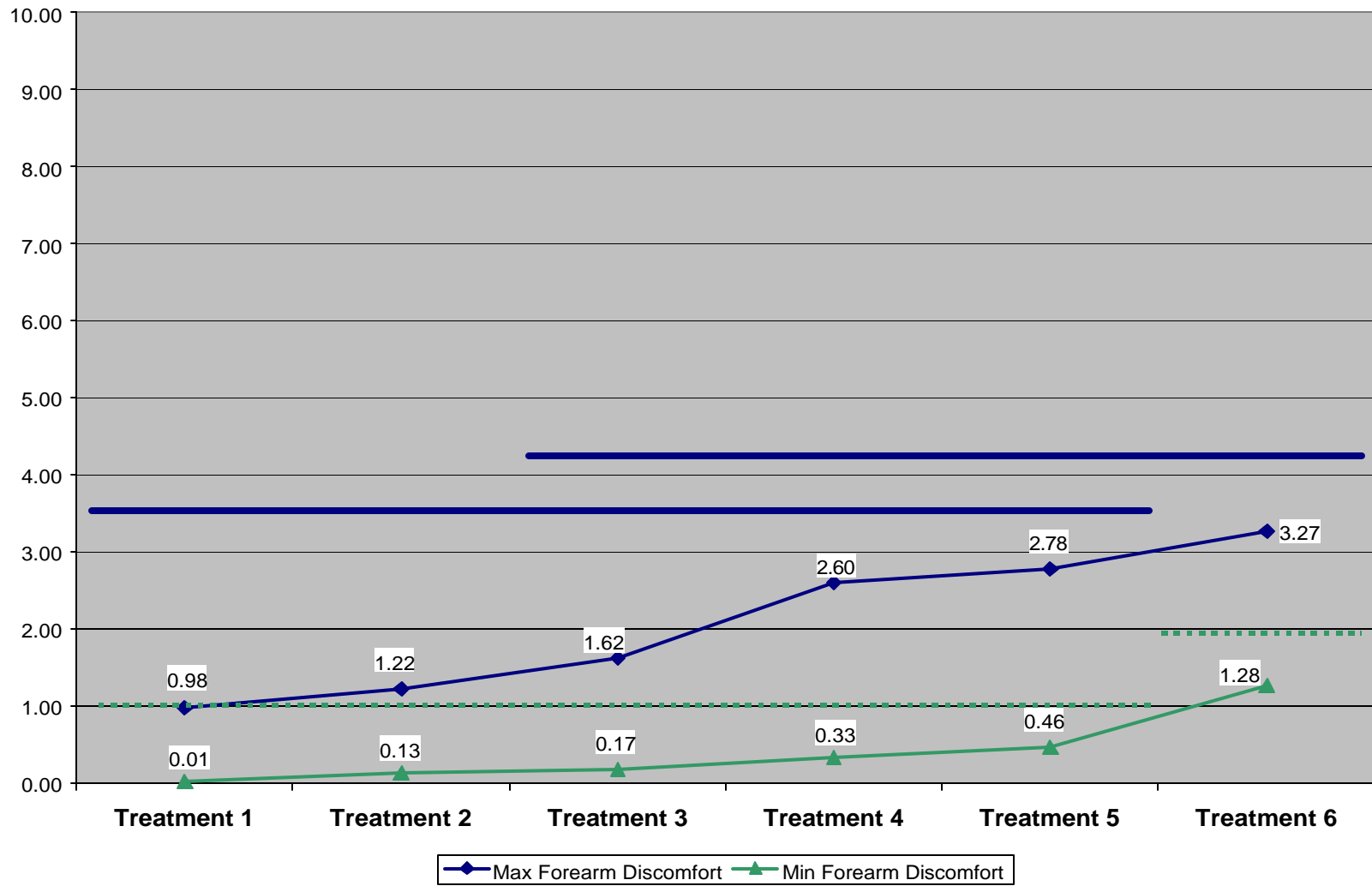


Figure 24 Max and Min forearm discomfort averaged by treatment. Fisher's LSD homogeneous subgroups also displayed.

Table 9 Subject reported hand fatigue by location

Treatment	Total Number of Intervals with a Response ^a	Location of Response					Total Number of Responses
		Whole Hand	Palm	Thumb & Thenar	Fingers	Extensor Side	
1	149	25	63	25	35	21	169
2	168	34	76	28	58	20	216
3	175	28	72	59	76	8	243
4	241	20	120	62	129	5	336
5	276	51	124	53	139	24	391
6	248	34	115	65	140	41	395

a Each treatment contains 12 intervals per subject for a maximum of 288 per treatment.

Table 10 Subject reported forearm fatigue by location

Treatment	Total Number of Intervals with a Response	Location of Response		Total number of Responses
		Flexors	Extensors	
1	108	87	52	139
2	157	85	72	157
3	129	100	83	183
4	181	133	132	265
5	217	177	125	302
6	241	166	162	328

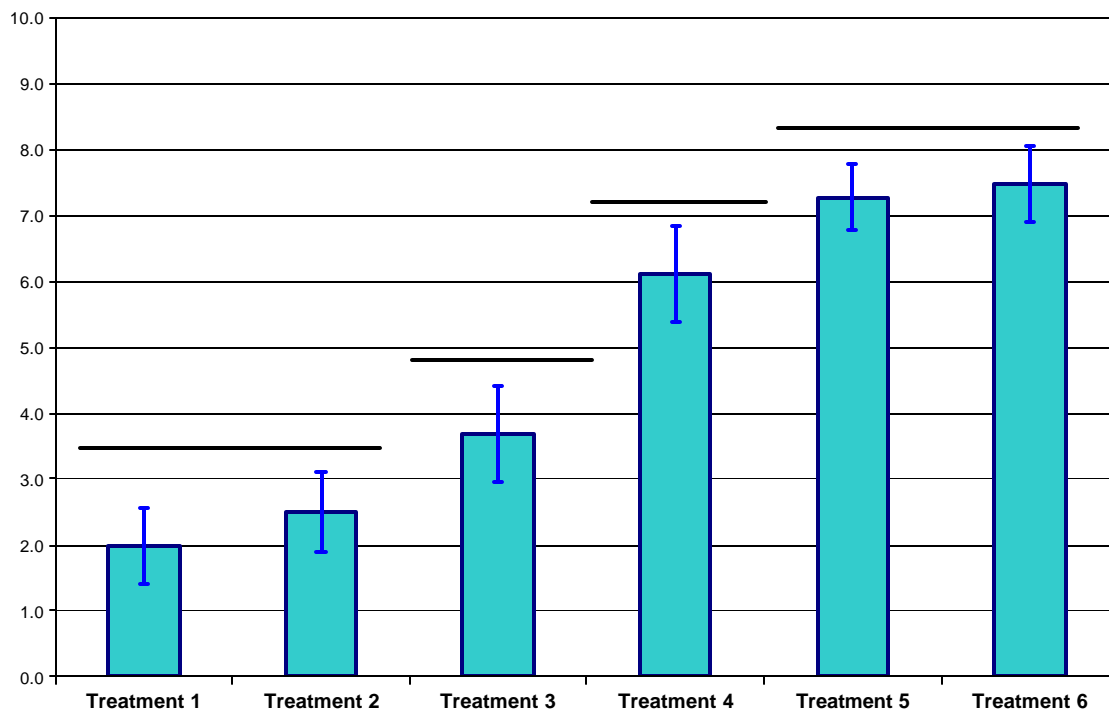
Table 11 Subject reported hand discomfort by location

Treatment	Total Number of Intervals with Responses	Location of Response					Total Number of Responses
		Whole Hand	Palm	Thumb & Thenar	Fingers	Extensors Side	
1	138	2	68	39	73	22	204
2	140	0	45	55	106	29	235
3	210	18	48	82	87	41	276
4	241	18	87	75	182	51	413
5	260	24	73	97	158	37	389
6	262	8	108	134	185	21	456

Table 12 Subject reported forearm discomfort by location

Treatment	Total Number of Intervals with a Response	Location of Responses		Total number of Responses
		Flexors	Extensors	
1	90	54	53	107
2	78	44	61	105
3	111	75	84	159
4	140	98	95	193
5	165	113	108	221
6	160	81	123	204

The average Difficulty Rating and its confidence interval (95%) for each treatment is shown in Figure 25 along with Fisher's LSD homogeneous subsets. Figure 26 shows average RPE, Difficulty Rating and maximum RPE per treatment.

**Figure 25** Average Difficulty Rating for each treatment with Fisher's LSD homogeneous subsets.

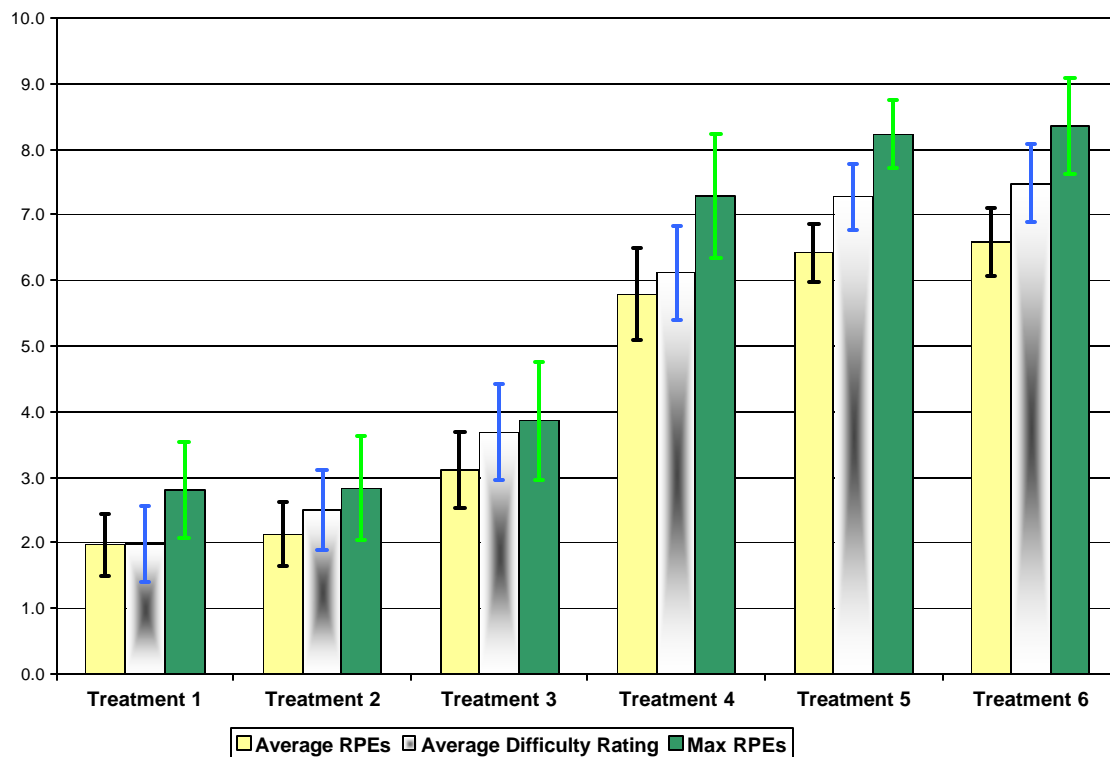


Figure 26 Difficulty Rating and RPEs averaged over each treatment

EMG Measures

Table 13 shows the results from the Runs Test. Because the observed values do not significantly differ from the expected values, a one second window was used. The Runs Test demonstrates ergodicity and thus the EMG signals were assumed to be independent and stationary. Figure 27 shows the MnPF slope and 95% confidence intervals for the pre treatment normalization session. For the pre treatment session, MnPF slope was not significantly different between treatments ($p > 0.05$) for either the flexors or extensors, which was expected since the treatments had not been administered at this point. Figure 28 shows the MnPF slopes and 95% confidence intervals for the post

treatment session for each treatment. Differences in MnPF were not significant between treatments ($p > 0.05$) for either the flexors or extensors during the post treatment sessions, but a paired t-test showed a significant difference between pre and post MnPF slope ($p < 0.01$) demonstrating fatigue had occurred.

Table 13 Runs Test results from a random sample of treatments

One Second Window											
Subject #	Sample n	n/2	$\alpha = 0.975$	Number of Runs in Treatment ^a						$\alpha = 0.025$	
				T1	T2	T3	T4	T5	T6		
2	10	5	2	5	5	4	5	7	5	9	
7	10	5	2	5	4	5	5	5	5	9	
12	10	5	2	3	5	5	5	5	5	9	
16	10	5	2	5	6	5	5	5	5	9	
20	10	5	2	5	7	7	5	5	5	9	
24	10	5	2	5	4	5	5	5	5	9	

^a Number of runs for all samples for all treatments are between the values for $\alpha_{0.975}$ and $\alpha_{0.025}$. Results demonstrate ergodicity for a one second window.

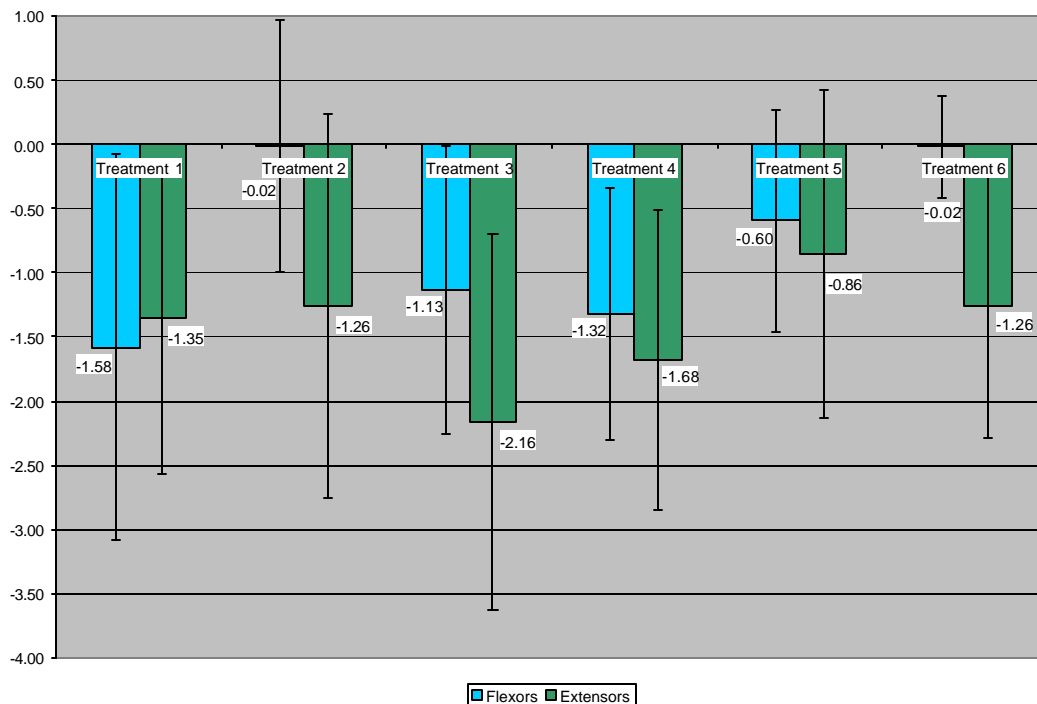


Figure 27 Pre treatment MnPF slope with confidence intervals.

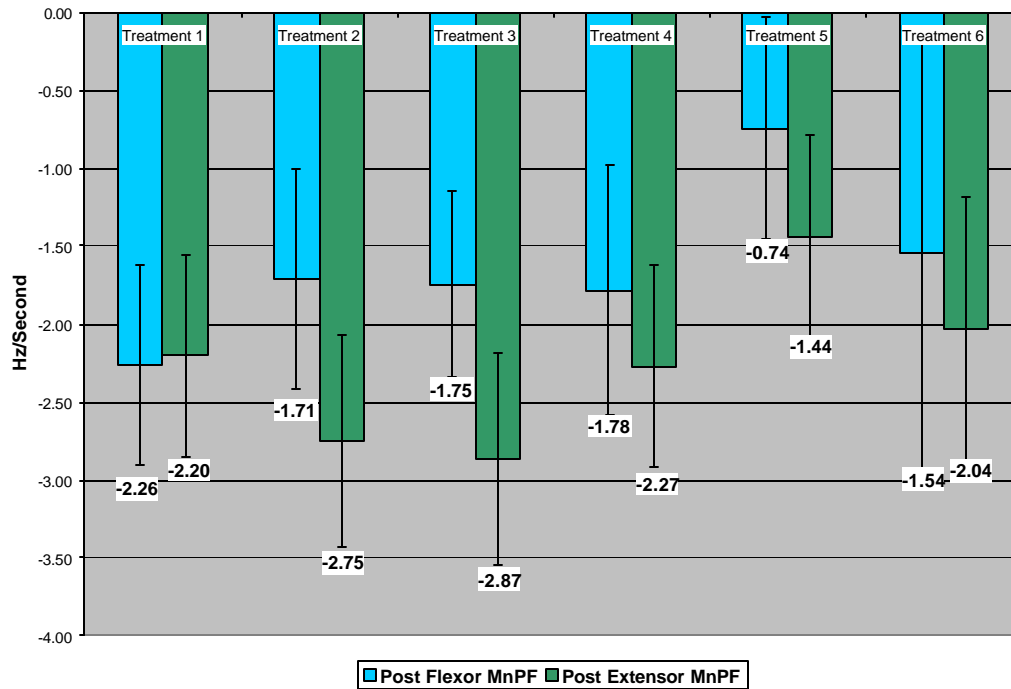


Figure 28 Post treatment MnPF slopes and confidence intervals for the flexors and extensors.

IMnPF values recorded in the pre and post treatment normalization sessions are shown in Figures 29 and 30 for the flexors and extensors respectively. The IMnPF values are not significantly different between treatments ($p > 0.05$) for either the pre or post treatment sessions. Figure 31 shows an example of the average post and pre treatment IMnPF values for Treatments 2 and 6 with their respective MnPF slopes. The graph visually demonstrates the lack of significant difference in treatment, but shows the increase in slope due to fatigue.

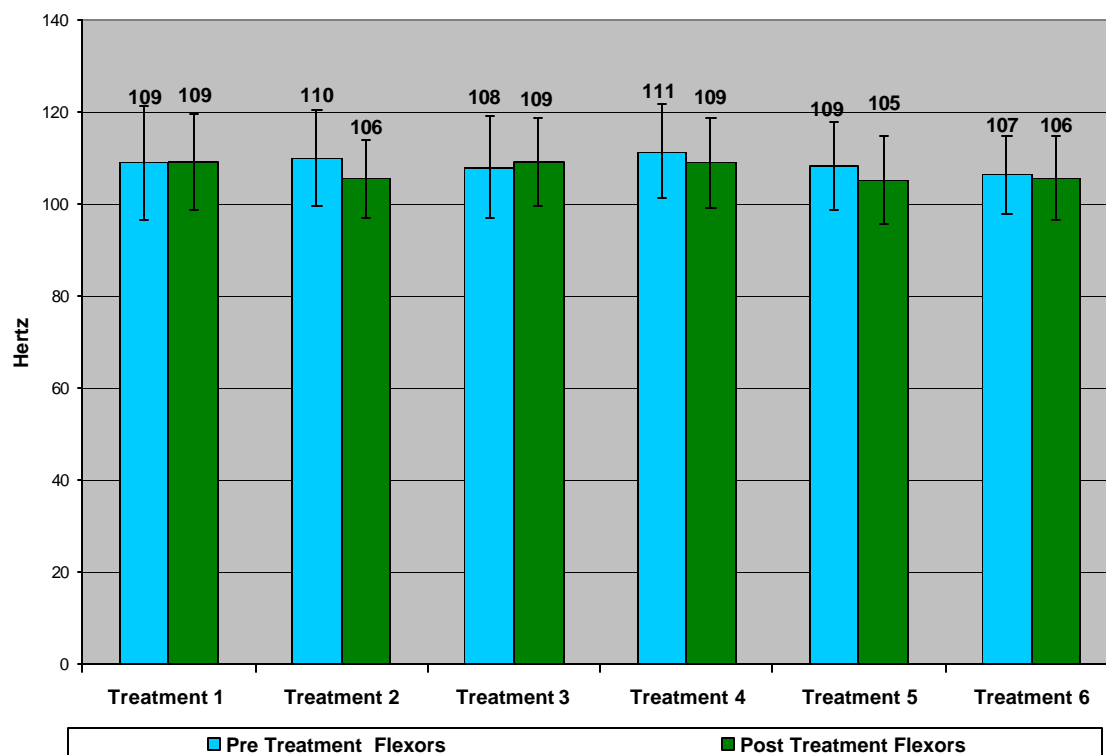


Figure 29 IMnPF pre and post treatment values for the flexors

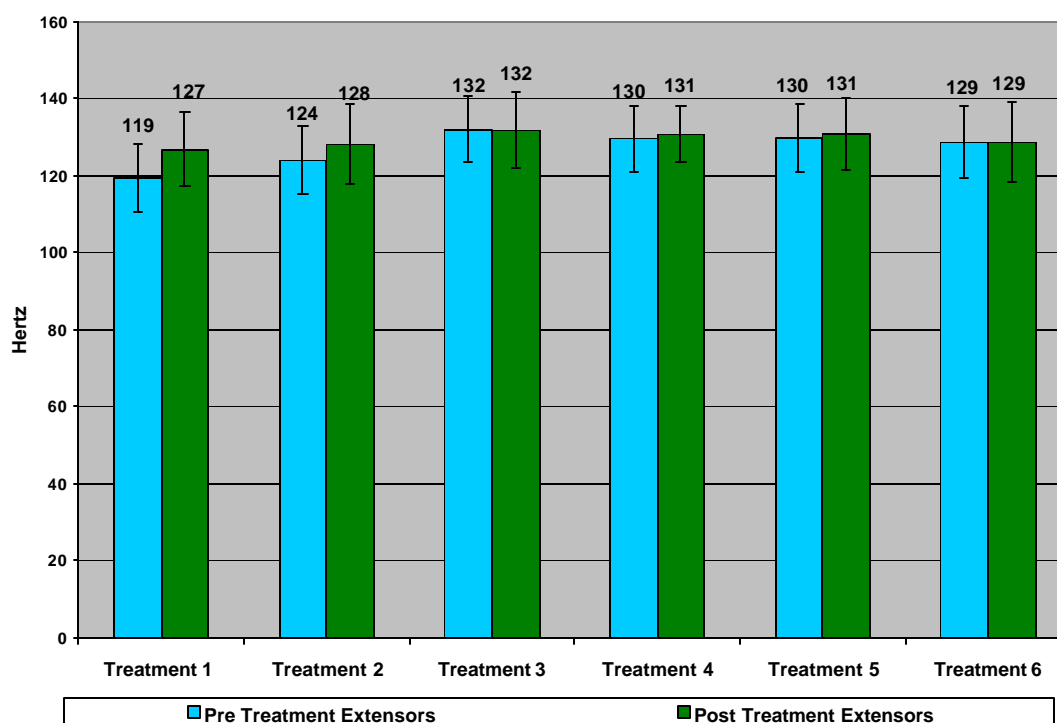


Figure 30 IMnPF pre and post treatment values for the extensors

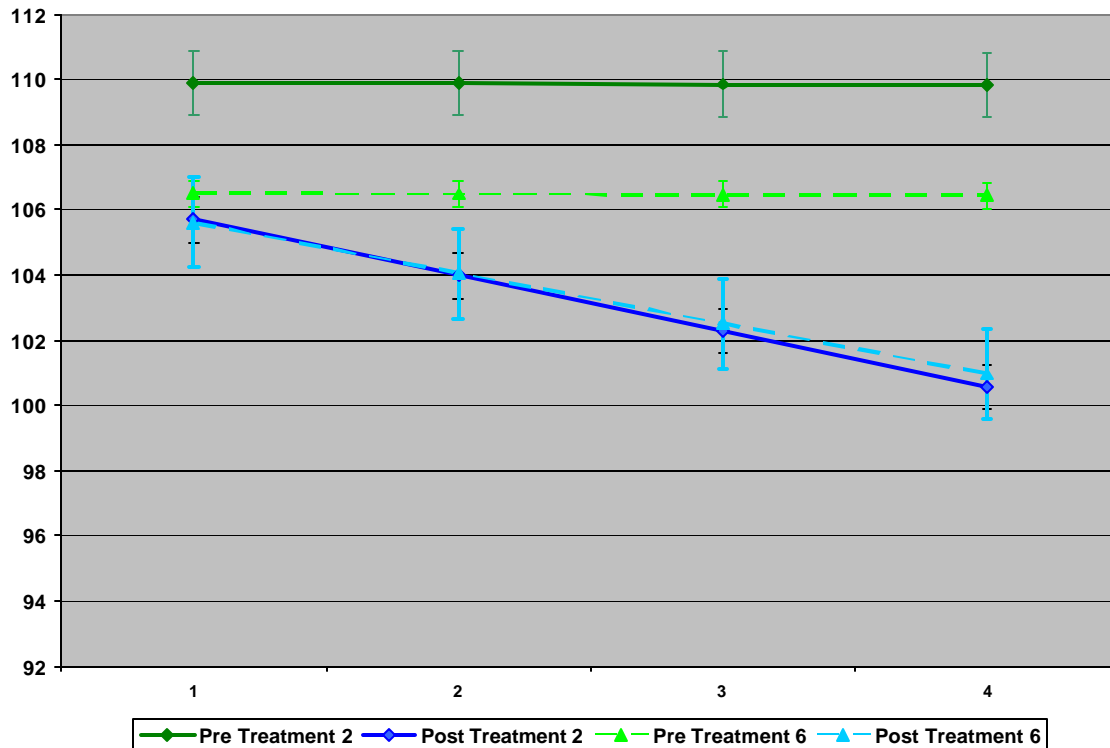


Figure 31 The IMnPF and MnPF slopes of Treatments 2 and 6

Normalized RMS values were calculated for all contractions (mixed primary and secondary), primary and secondary contractions (independently), and during the rest period for the flexors and extensors. No RMS values significantly differed ($p > 0.05$) over time indicating that RMS did not show fatigue. RMS_a flexor and extensor values for the fifth and sixtieth minutes are shown in Figures 32 and 33 respectively. Treatment 4 is higher than Treatment 5 which shows the drawback of using RMS_a . Treatment 5 has a 10% MVC intensity exertion every seven seconds that lasts for three seconds where Treatment 4 only has a 10% MVC intensity exertion every nine seconds that lasts for one second. The extra two seconds per ten second cycle heavily skews Treatment 5's average because contraction time is equal for the greater intensity primary exertion and the lighter intensity secondary exertion. Treatment 4's average sees a 3 to 1 ratio of high intensity

contractions (40% MVC) to light exertions (10%), which is one reason the primary and secondary exertions are analyzed separately in the following pages. This same problem is not seen in Treatments 1 and 2 because the primary and secondary exertions are of the same intensity.

RMS_P flexor and extensor values by treatment are shown in Figures 34 and 35 respectively. Figures 36 and 37 show flexor and extensor values by treatment for RMS_S. Figure 38 shows the average RMS_R values.

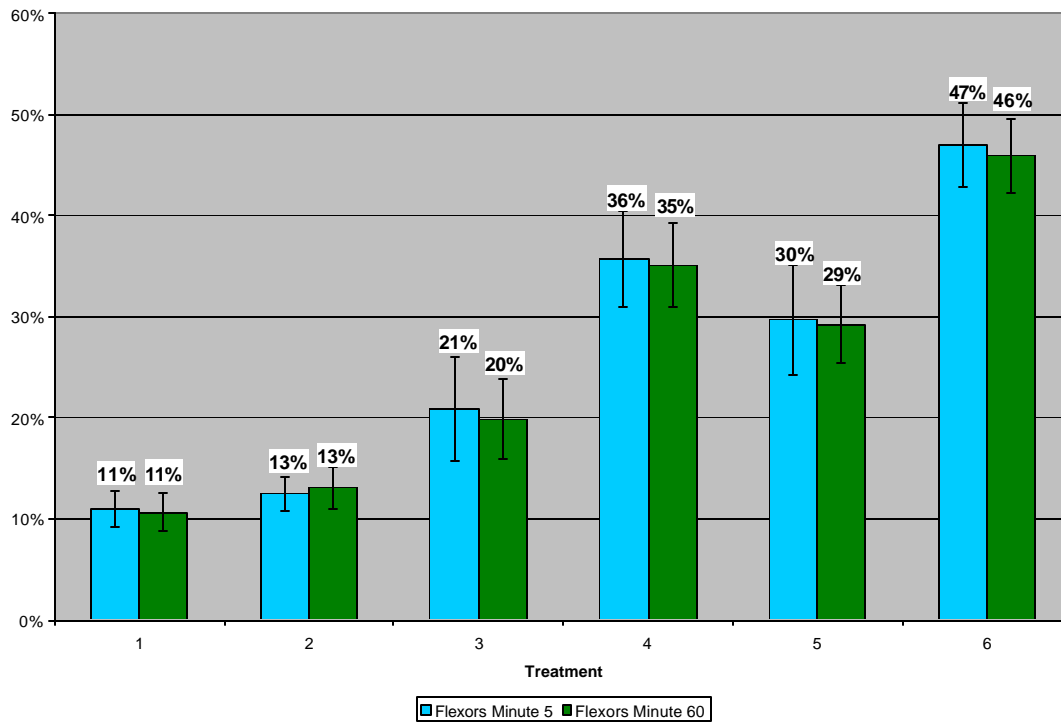


Figure 32 RMS_a flexor values for the fifth and sixtieth minutes

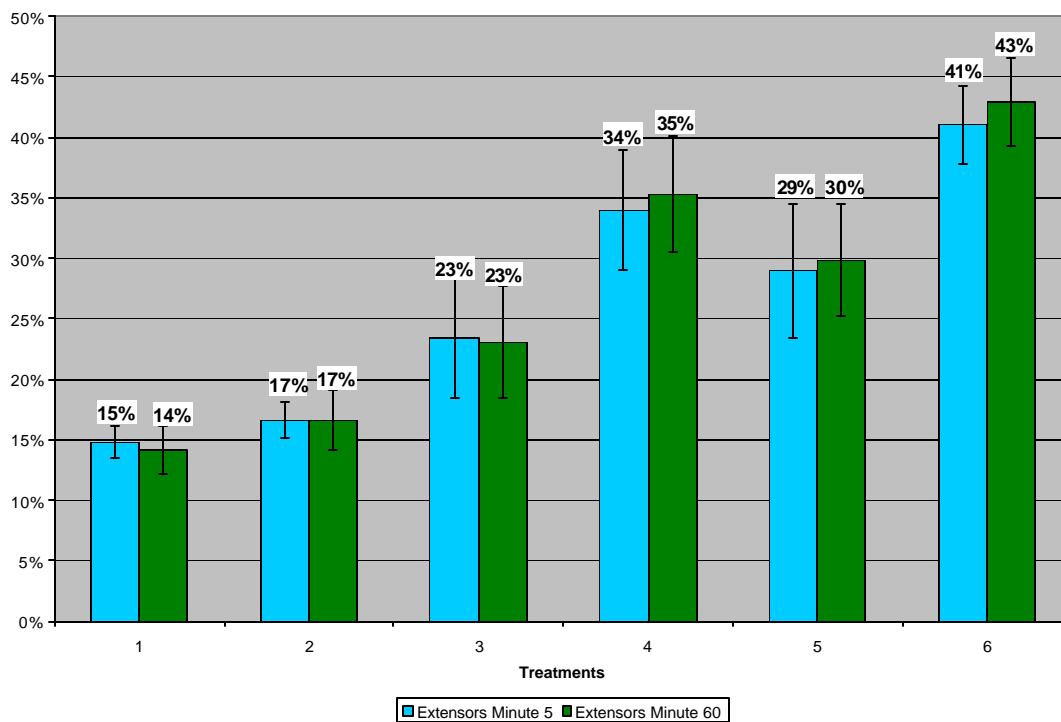


Figure 33 RMS_a extensor values for the fifth and sixtieth minutes

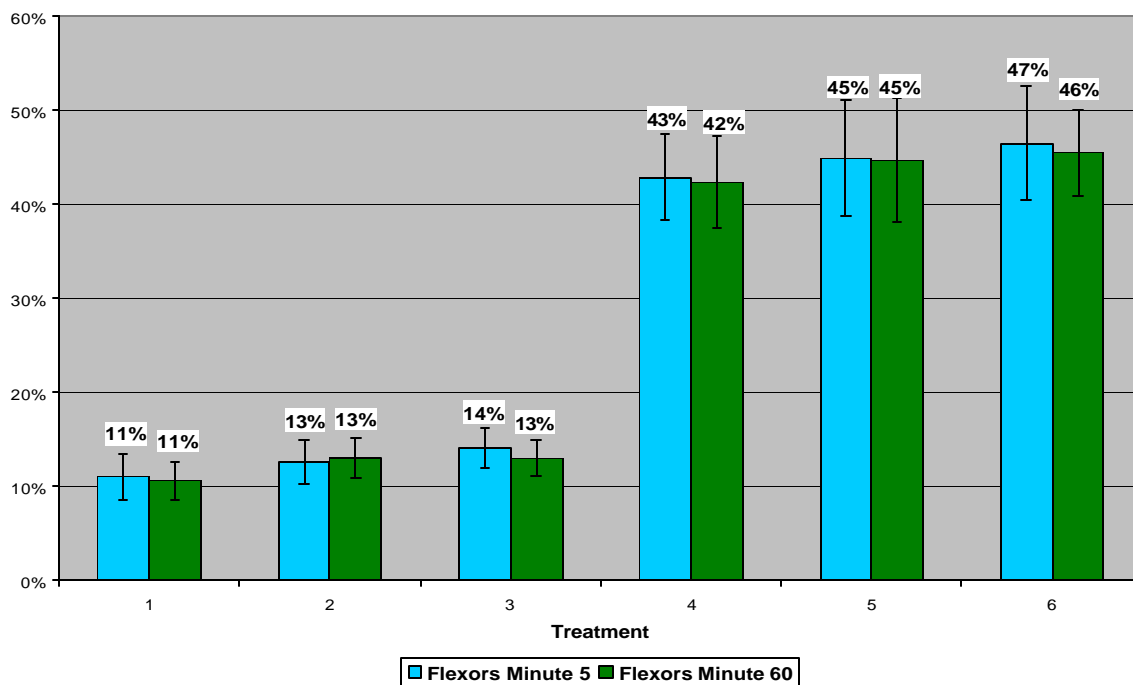


Figure 34 RMS primary contraction for the fifth and sixtieth minute for the flexors by treatment

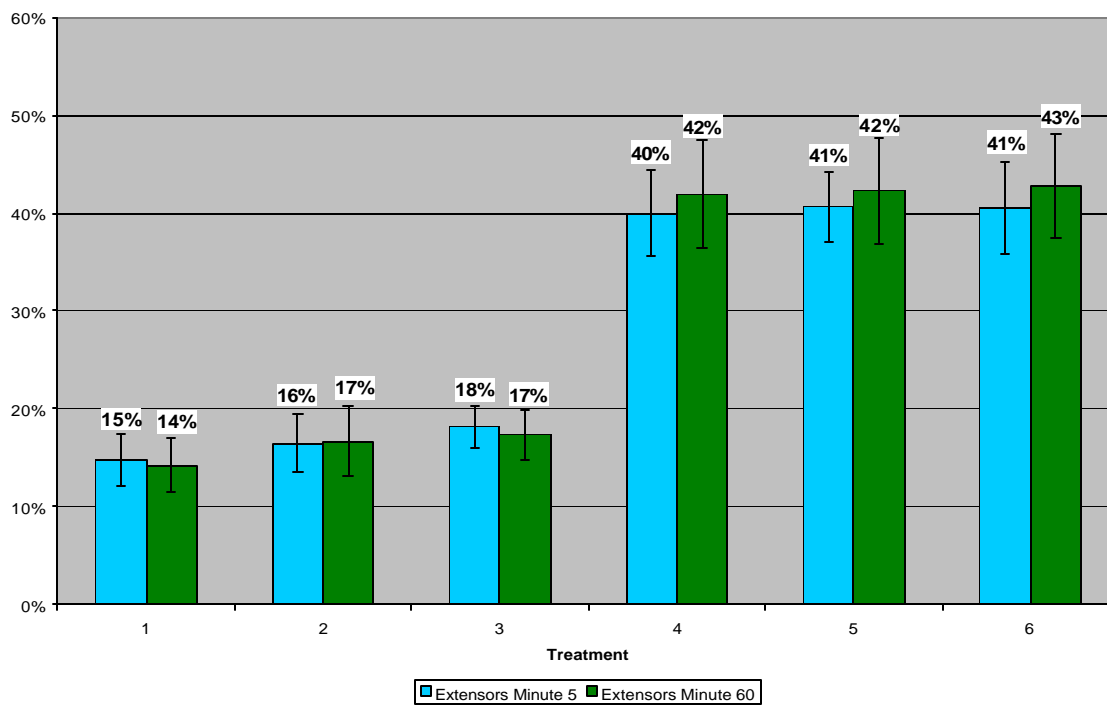


Figure 35 RMS primary extensor contractions for the fifth and sixtieth minute by treatment

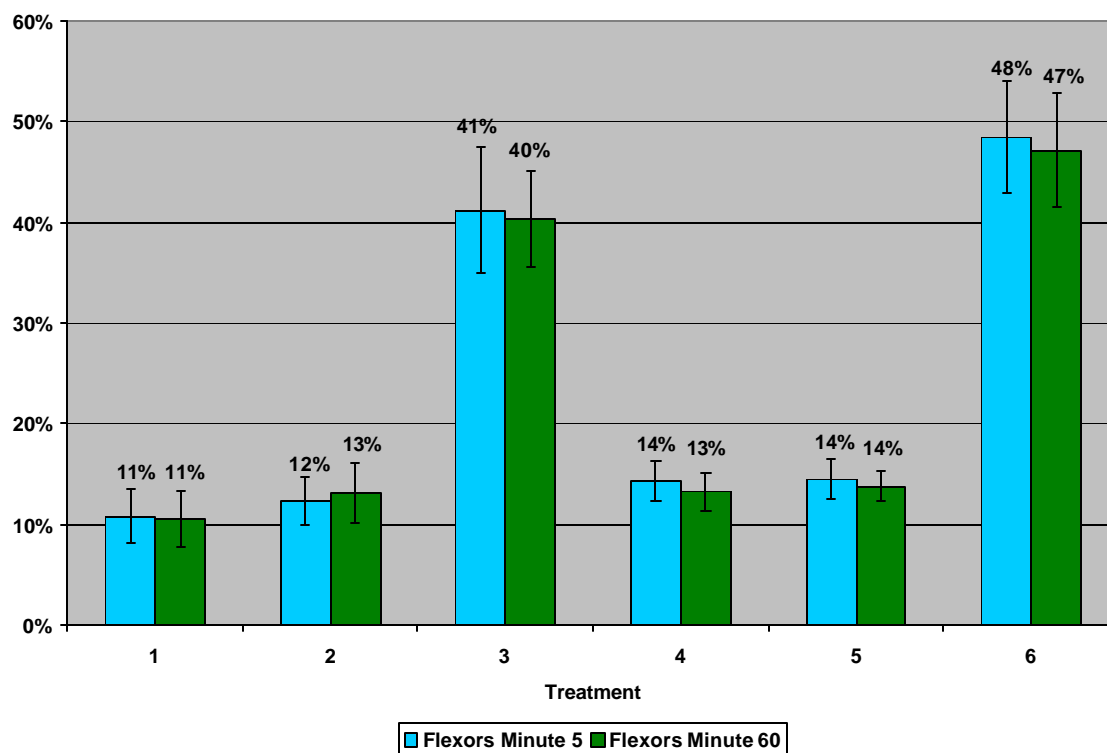


Figure 36 RMS_s flexor contractions for the fifth and sixtieth minute by treatment

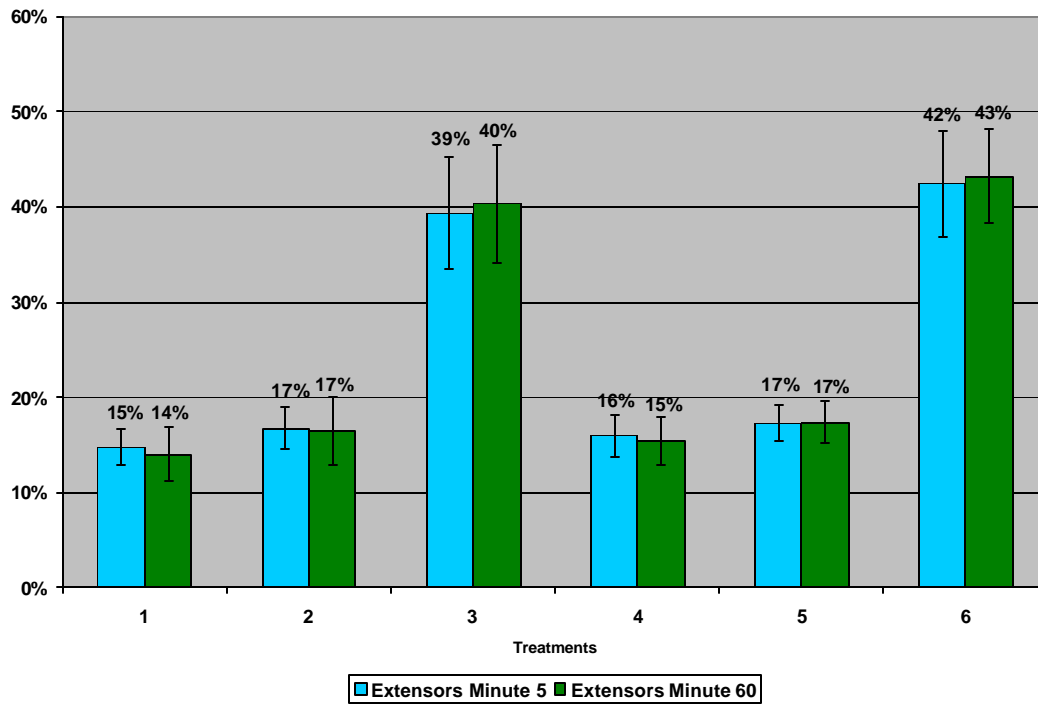


Figure 37 RMS_s extensors contractions for the fifth and sixtieth minute by treatment

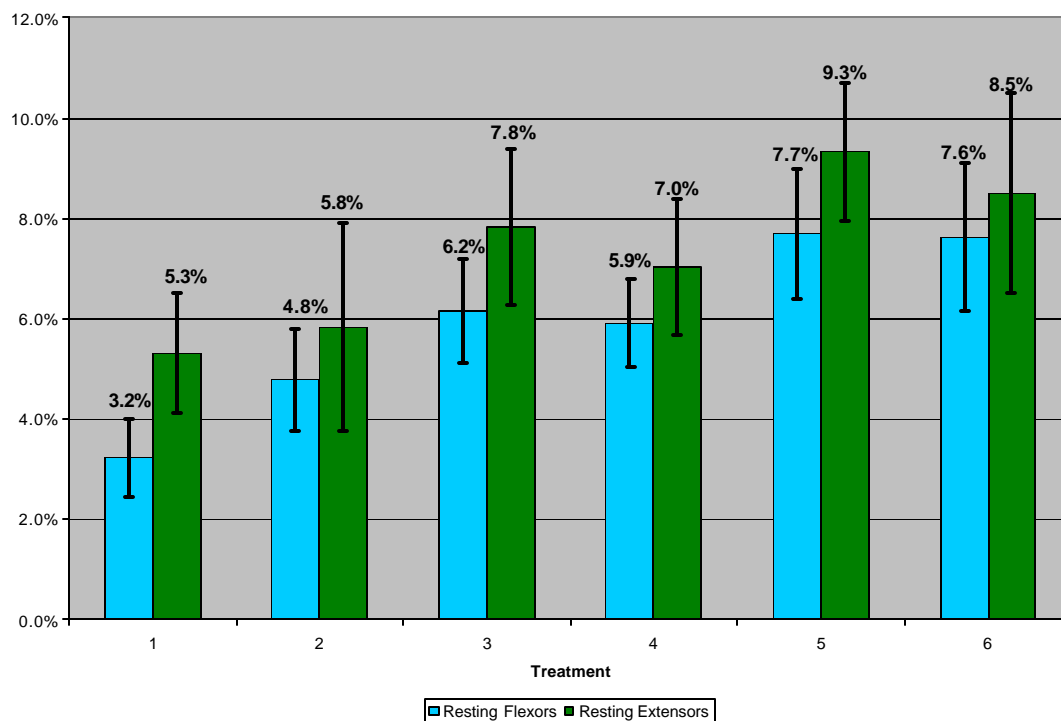


Figure 38 Average normalized RMS values for the Rest periods for the flexors and extensors.

RESULTS: PART II

Variable Selection

Table 14 shows the correlation matrix of the subjective variables and percent strength loss. As evident in the correlation significance, all subjective variables and percent strength loss are significantly correlated. Figure 39 further demonstrates the correlation of the subjective variables by plotting Difficulty Rating, max RPE, hand and forearm fatigue, and hand discomfort by treatment. Because of the high correlation values and the desire not to duplicate results, only Difficulty Rating was used in the comparisons of the Strain Index Methods. Difficulty Rating was chosen because it represents the whole hour of the treatment and instead of a single point.

MnPF and IMnPF for the post treatment sessions did not show statistically significant differences ($p > 0.05$) between treatments and were not used to evaluate the proposed Strain Index Methods. The RMS varied between treatments, but not over time, signifying fatigue. Force differences were expected between treatments because the percent MVCs changed between treatments. Because the RMS values did not show a change in fatigue levels between treatments, RMS was not used to evaluate the Complex Strain Index methods.

Table 14 The Correlation matrix of subjective variables and percent strength loss

Variable	Strength Loss	Difficulty Rating	Hand Discomfort	Hand Fatigue	Forearm Discomfort	Forearm Fatigue	Max RPE
Strength Loss	1	0.637	0.617	0.526	0.274	0.608	0.660
Sig	-	<.01	<.01	<.01	<.01	<.01	<.01
Difficulty Rating	0.637	1	0.696	0.592	0.397	0.708	0.912
Sig	.000	-	<.01	<.01	<.01	<.01	<.01
Hand Discomfort	0.617	0.696	1	0.677	0.537	0.956	0.739
Sig	<.01	<.01	-	<.01	<.01	<.01	<.01
Hand Fatigue	0.526	0.592	0.677	1	0.560	0.655	0.595
Sig	<.01	<.01	<.01	-	<.01	<.01	<.01
Forearm Discomfort	0.274	0.397	0.537	0.560	1	0.543	0.356
Sig	<.01	<.01	<.01	<.01	-	<.01	<.01
Forearm Fatigue	0.608	0.708	0.956	0.655	0.543	1	0.724
Sig	<.01	<.01	<.01	<.01	<.01	-	<.01
Max RPE	0.660	0.912	0.739	0.595	0.356	0.724	1
Sig	<.01	<.01	<.01	<.01	<.01	<.01	-

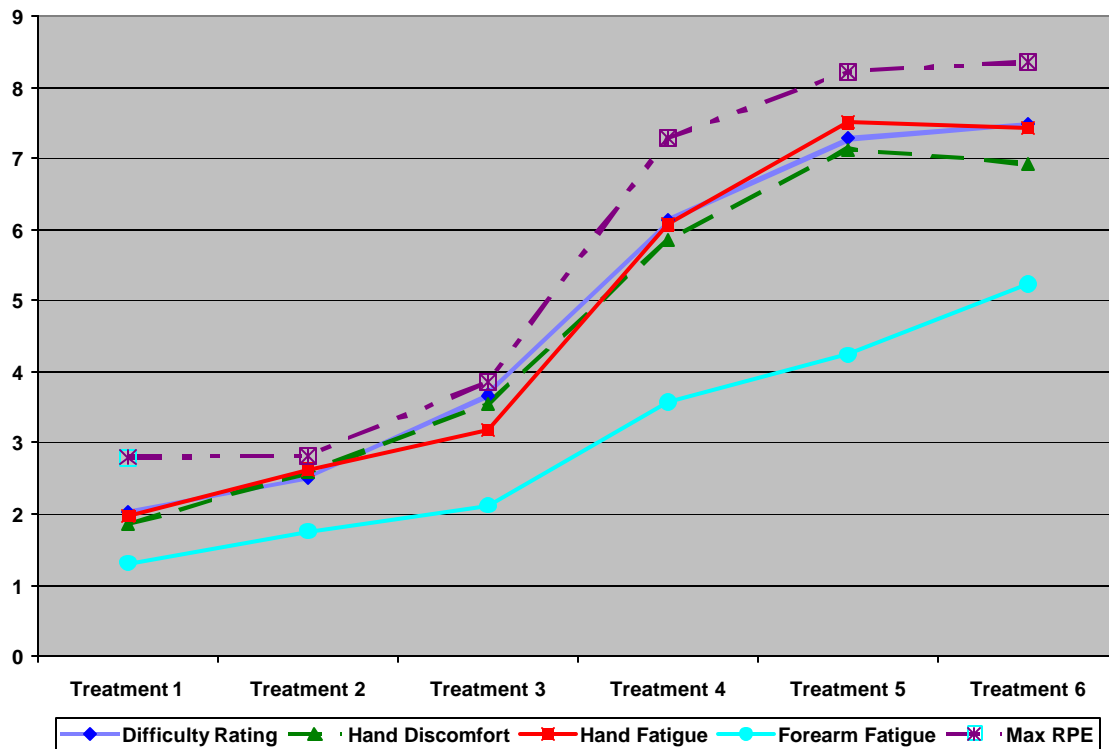


Figure 39 Difficulty Rating, max RPE, hand and forearm fatigue, hand discomfort by treatment

Comparison of Complex Strain Index Methodology

Categorical Method

Figure 40 shows the Difficulty Rating graphed against the Complex Strain Index Score of the treatments using the average method. For Figure 40 and the following graphs, the x-axis has been set to five, which is the critical value for the Strain Index Hazard Classification. Values below five are considered safe and hazardous above five. The reported correlation value for the average method is high, but the average method does not have a good distribution of Strain Index Scores. With RPE exertions above seven or “very strong” on the CR-10, a Strain Index score above three is expected. A

majority of subjects stated they did not think they could complete Treatments 5 and 6 for a two hour period. Using the average method, Treatment 5 and 6 are considered safe even though subjects could not physically complete the tasks. The average method also violates the requirement that a Complex Strain Index score for a mono-task job must be equal the Strain Index score calculated as a mono-task (as published in Moore and Garg, 1995). For the reasons listed above, the average method proved inadequate as a possible method for calculating a Complex Strain Index score.

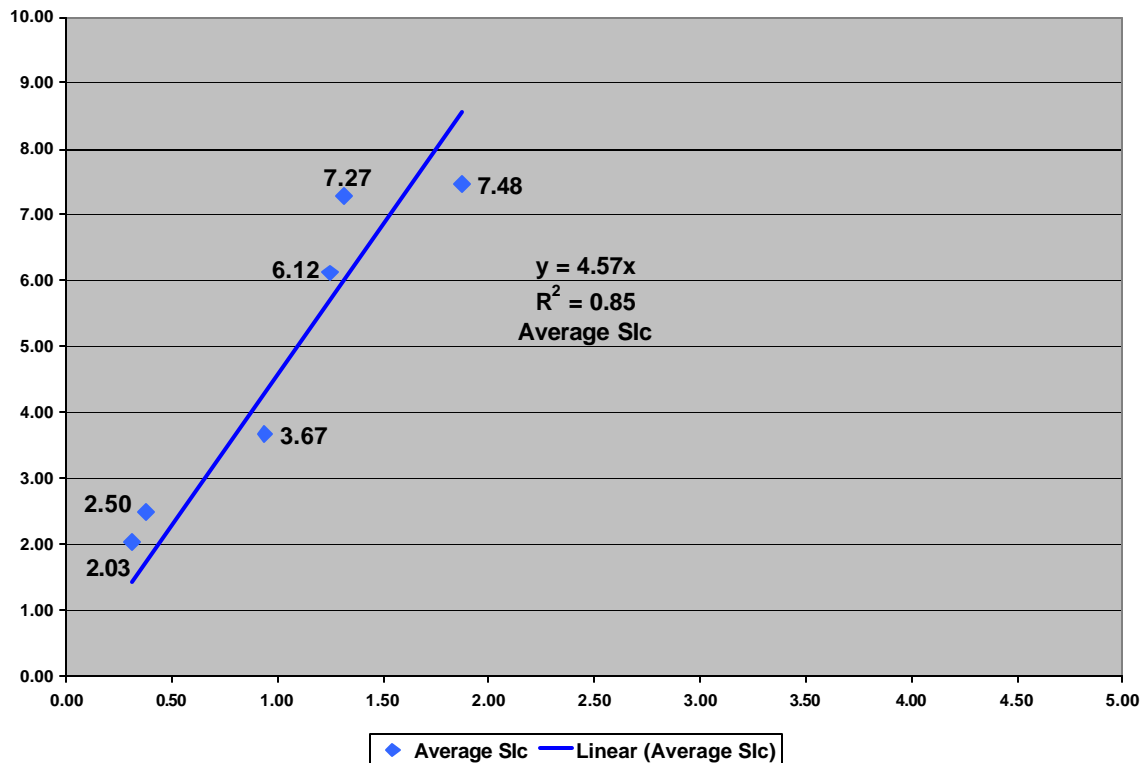


Figure 40 Difficulty Rating correlated with the categorical Complex Strain Index score using the average method

Figure 41 shows the Difficulty Rating graphed against the Complex Strain Index Score of the treatments using the minimum method. The minimum method has many of the same problems as the average method. The Strain Index score for Treatment 5 is 0.75. Under the minimum method, a worker could perform a job with the same attributes as Treatment 5 all day, every day, and the job would be considered safe. As mentioned above, performing this task for two hours is not possible (given subjective responses), let alone for eight hours. The minimum method has the same Strain Index score for Treatments 1, 3, and 4, which have very different Difficulty Ratings. For the aforementioned reasons, plus a negative correlation value, the minimum method was dropped from further analysis of Strain Index methods.

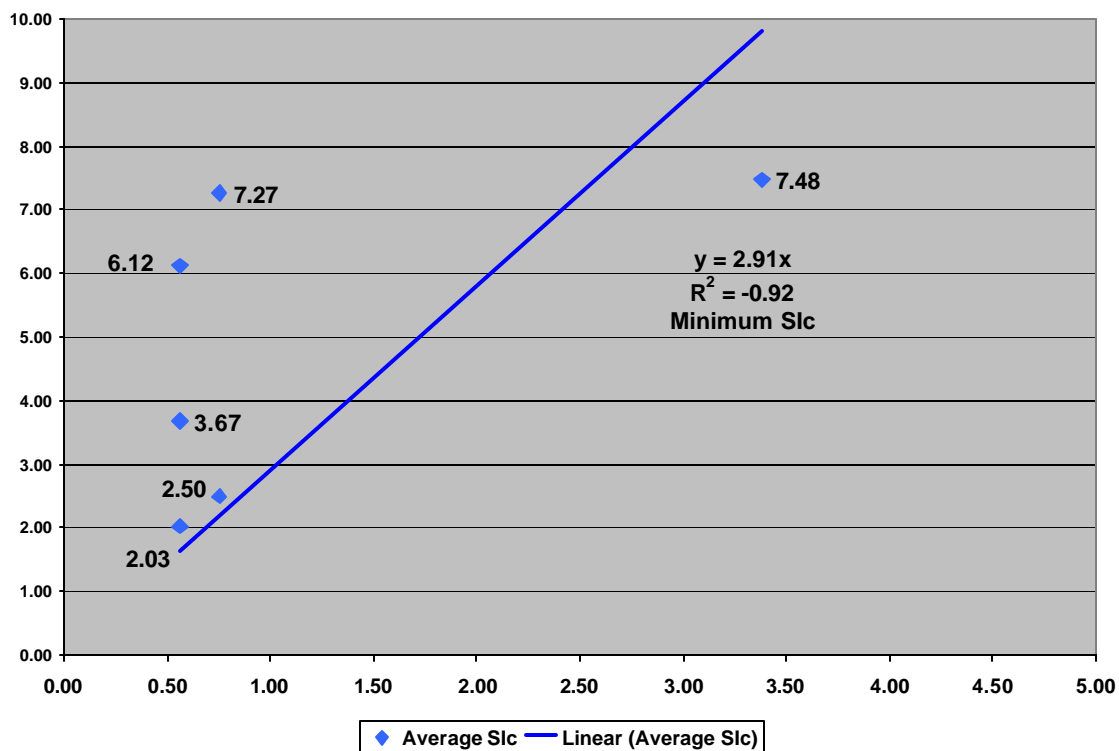


Figure 41 Difficulty Rating correlated with the categorical Complex Strain Index score using the minimum method

Figure 42 shows the Difficulty Rating graphed against the Complex Strain Index Score of the treatments using the peak method. The Peak method has the same Strain Index score for Treatments 3, 4, and 6, which have very different Difficulty Ratings. The correlation value of 0.65 does not meet the criteria of 0.70. For previously mentioned reasons, the peak method was dropped from further analysis.

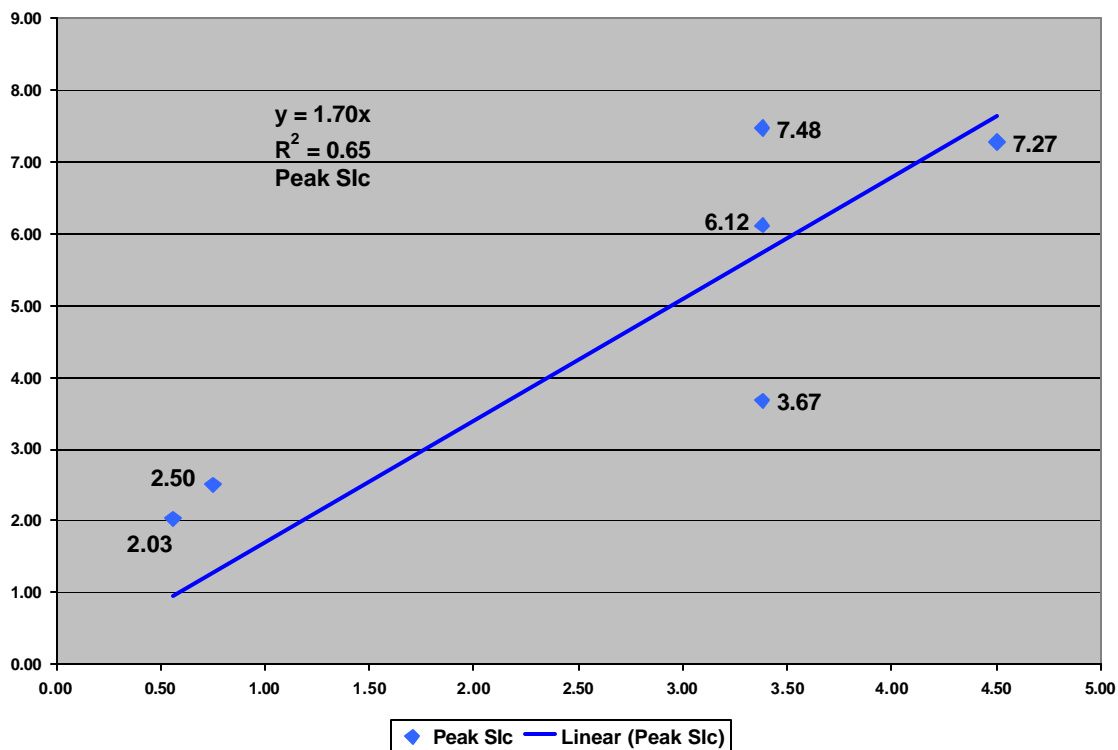


Figure 42 Difficulty Rating correlated with the categorical Complex Strain Index score using the peak method

Figure 43 shows the Difficulty Rating graphed against the Complex Strain Index Score of the treatments using the unadjusted sum method. The unadjusted method has a high correlation value and a good variation in Strain Index Scores. The unadjusted sum method violates two of the necessary criteria previously set forth for an acceptable

Complex Strain Index method. The unadjusted sum method's Strain Index score exceeds the peak value (when the highest intensity of all tasks is used as intensity for all tasks) and the unadjusted sum method does not equal the mono-task method for mono-task jobs. For previously mentioned reasons, the peak method was dropped from further analysis.

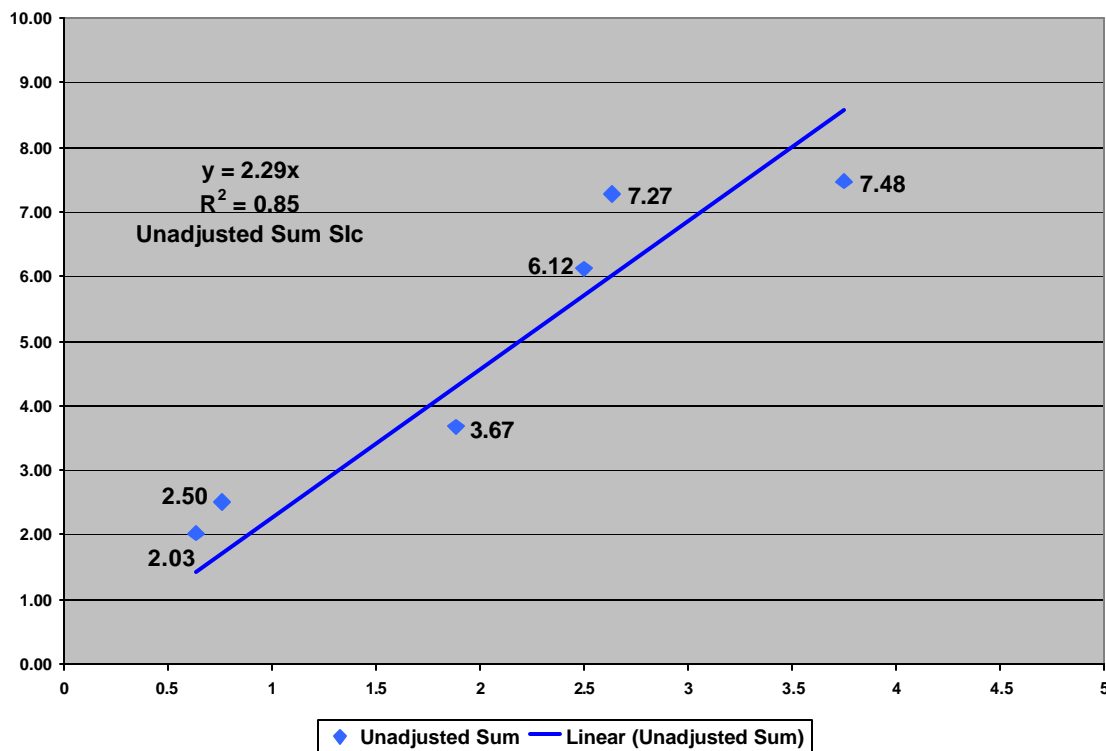


Figure 43 Difficulty Rating correlated with the categorical Complex Strain Index score using the unadjusted sum method

Figure 44 shows the Difficulty Rating graphed against the Complex Strain Index Score of the treatments using the adjusted sum method. The adjusted method has a high correlation value and good variation in Strain Index scores. As with the unadjusted sum method, the adjusted sum method violates the same criteria previously

set forth for being an acceptable Complex Strain Index method. For previously mentioned reasons, the peak method was dropped from further analysis.

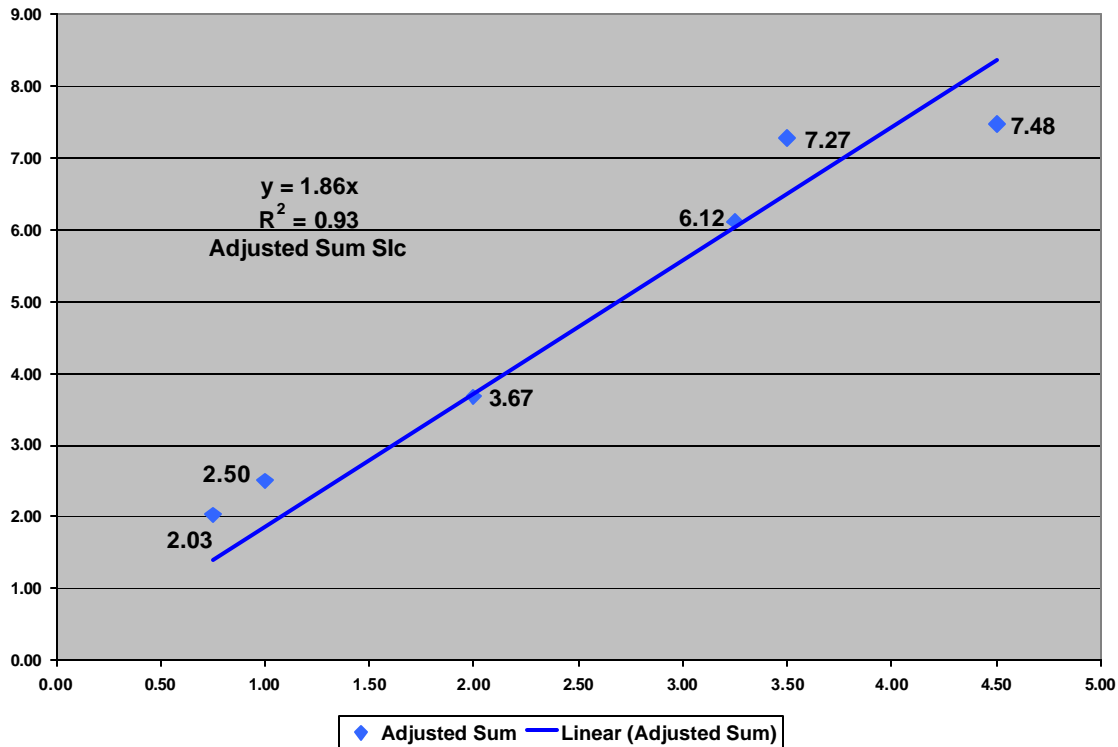


Figure 44 Difficulty Rating correlated with the categorical Complex Strain Index score using the adjusted sum method

Figure 45 shows the Difficulty Rating graphed against the Complex Strain Index score of the treatments using the complex equation method. The complex method has a high correlation value and good variation in Strain Index scores. The complex method also meets all the criteria previously set forth. The complex method is accepted as a possible method of calculating a Complex Strain Index score and will be used to evaluate the SI_A and SI_B methods.

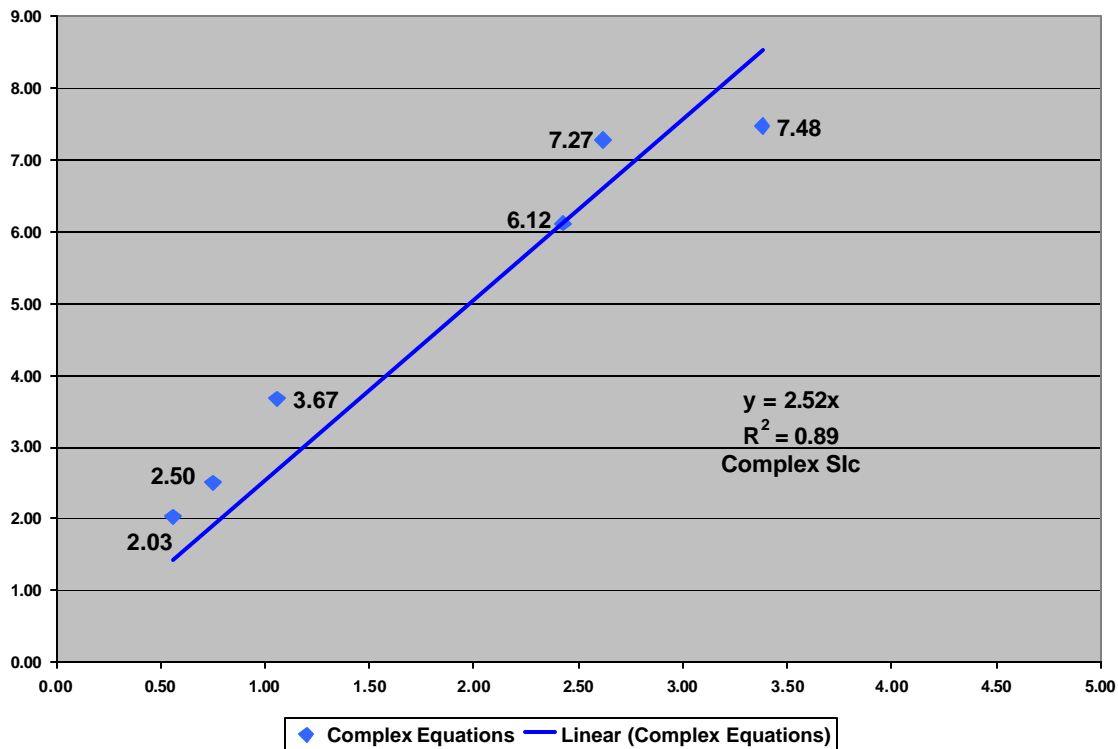


Figure 45 Difficulty Rating correlated with the categorical Complex Strain Index score using the Complex method

Continuous Strain Index Methods

Figure 46 shows the Difficulty Rating graphed against the Complex Strain Index Scores of the treatments using the complex equation method and the two proposed methods for calculating a continuous Strain Index score. Unlike the previous methods which use the categorical method, the continuous Strain Index scores are not necessarily bound by the critical value of five for the Hazard Classification. Since neither continuous calculation methods have been validated and are both still theoretical, the appropriate critical value is unknown. For this reason, the fact that SI_B does not have a wide variation of Strain Index Score values does not immediately dismiss SI_A as a suitable

method for calculating a continuous Strain Index score. SI_A has a higher correlation value than does SI_B and thus seems to fit the data better than does SI_B .

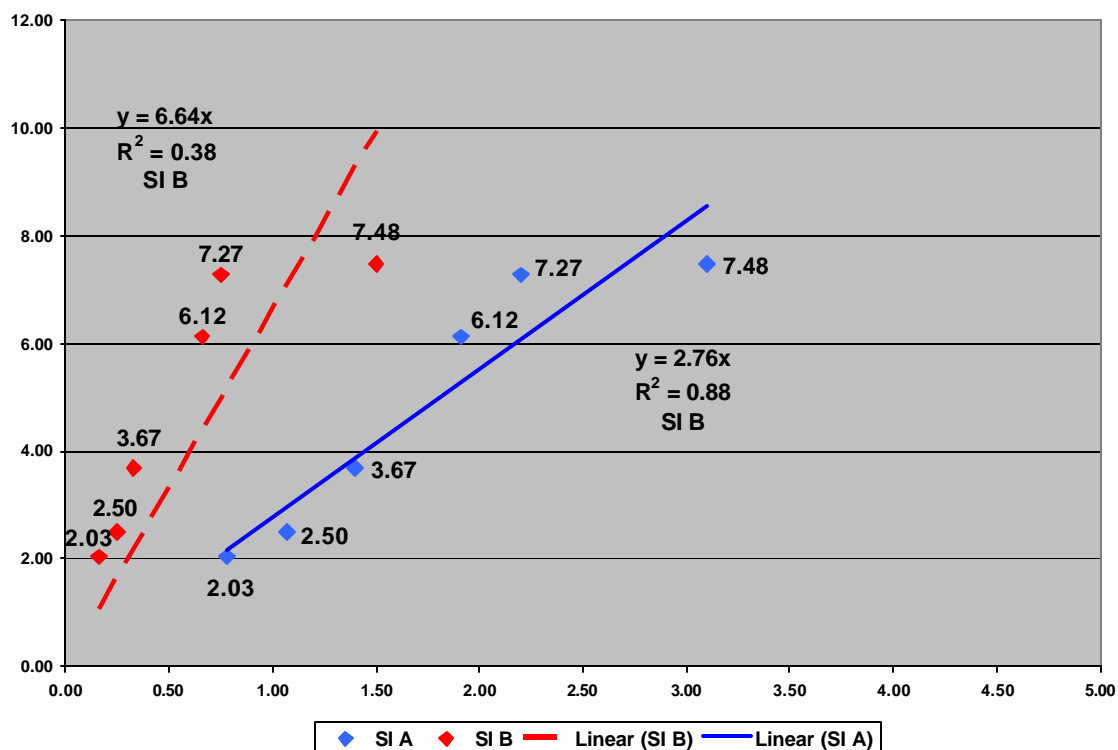


Figure 46 SI_A and SI_B compared by correlating Strain Index values with the Difficulty Rating

DISCUSSION

Part I

Subjects

One of the strengths of this study was the subject size. The 12 male and 12 female subjects provided good statistical power for mean effects as well as testing for gender interaction. A drawback of the study population was the narrow age distribution, especially for females. A broader range in age would help in the generalizability of the results.

Signal Analysis

Of the 144 EMG records, only two were corrupted with noise and one normalization record was physically lost. The two records that were corrupted contained large amounts of low frequency noise (below 30 Hz) as well as a very large 60-cycle spike. The pre-amp analog filters should have removed much of this noise, but did not for these two records. No other records contained 60-cycle noise, but a few contained low frequency noise (possibly noise artifacts) less than 10 Hz. These signals were refiltered using a digital high-pass filter with a frequency cutoff of 10 Hz.

The bipolar surface electrodes were consistently placed a fixed distance of 2 cm apart, but the physical placement of the surface electrodes varied a little between treatments and subjects. Other studies have commented on increased variability between day studies due to the reapplication of electrodes (Elfving et al, 1999). Blackwell et al's

(1999) method for finding the FDS was used, along with signal verification, but this method might have been one of the sources of variance in the EMG signal variables. Temporary marks (inks or dyes) to indicate electrode placement could have been used to reduce variance between treatments where electrodes are removed.

Measured Outcomes

As reported in the results section, the intra-subject MVC's had an ICC(2,1) absolute agreement coefficient of 0.94. This agrees with the 1995 West et al study findings that found there is not a significant difference in intra-subject MVC between testing periods. The correlation between percent MVC and RPE during the normalization sessions were also very high (0.88 for inter and 0.93 for intra-subject). Subjects seem, initially, able to report accurately the force they are exerting for a hang gripping task. As seen by the linear increase in RPEs, this discernment may be lost once fatigue and discomfort start to occur.

Some studies have shown decreased MVC, as a measure of fatigue, in intermittent contractions as low as 10% exertion (Søgaard et al, 2003). In the current study, males actually gained strength during Treatment 1. This particular treatment might have served as a “warm up” for the muscles, which could account for the higher post treatment MVC. Both males and females showed a decrease between pre and post MVC measurements for Treatment 2, which is also an intermittent 10% intensity contraction. The difference between Treatment 1 and 2 was the duration of recovery time (or rest time) and inversely, the duration of exertion. Either one may impact the fatigue rate of a muscle. It should be noted that the confidence interval for the male's percent strength loss for the treatments

containing a primary contraction of 10% MVC (Treatments 1 – 3) all included negative values (MVC increased from pre to post treatment values). Females also had negative values in their percent strength loss confidence intervals for Treatments 1 – 2, which have a maximum intensity of 10%. When gender is not considered a factor, as seen in Graph 30, there is not a significant difference (as seen in the Fisher's LSD homogeneous subsets) in percent strength loss between the treatments whose primary exertion is 10% MVC.

Subjective Outcomes

As seen with percent strength loss, there was not a significant difference between Treatments 1 and 2 for any of the subjective measures (RPE, hand and forearm fatigue, hand and forearm discomfort, and Difficulty Rating). The results raise a question of how much impact low intensity exertions have on fatigue and the overall stress placed on the DUE.

In the calculation of the Strain Index (Moore and Garg, 1995), the Intensity of Exertion task variable drives the Strain Index score and is the only Task Variable where the multiplier value is a power increase between rating categories. Treatments 5 and 6 have different secondary exertions that differ in intensity and duration. The results of this study show that there is not a significant difference between the two treatments for most variables analyzed. The secondary exertion of Treatment 5 is 10% MVC for three seconds compared to the one second exertion of 40% MVC of Treatment 6. Many of the calculation methods evaluated considered the percent change between Treatments 4 and 5 to be smaller than the percent change between Treatments 5 and 6, which is contrary to

what the study variables reported (Table 22). Rest and recovery time (absent from Treatment 5) may be a larger factor in the strain placed on the DUE than is accounted for using current Strain Index methods.

One of the most interesting findings in the current study is the linearity of the subjective outcome variables, especially RPE. Figure 14 seems to indicate a relationship between the primary exertion and slope. It was expected that all subjective variables would plateau over time, but they remained linear. If longer treatments had been used, a plateau might have occurred. At least for RPE and the hand variables, a deviation from linearity would be expected in a second hour (if administered) as to the fact subjects would hit the maximum values of the rating scales. Several subjects did achieve the maximum scale values for RPE and hand discomfort for Treatments 5 and 6.

EMG Outcomes

Since gender was not found to be a significant factor, it was dropped in the analysis of EMG parameters in the current study. Literature is mixed on a gender effect with some studies showing an effect (Hunter et al, 2004) and others that do not (Elfving et al, 1999; Krivickas et al, 1998).

It was expected that the MnPF slope would differ between treatments, but this was not the result. However, a difference was found between the pre and post treatments, just not between the treatments themselves. This shows that fatigue occurred, but there was not a significant difference in the amount of fatigue that occurred between treatments according to the MnPF slope. The method used to collect the MnPF during the pre and post treatment sessions might have also affected the results. Both pre and post treatment

sessions used a 100% MVC exertion to measure MnPF. It was assumed that each treatment would contribute a level of fatigue that would alter the fatigue rate seen in the end of session 100% MVC according to the intensity level of the treatment. The expected results did not occur and no treatment effect could be seen in the end of session fatigue rate.

Several differences exist between the majority of the EMG fatigue studies in literature and the current study. One difference was the built in rest within each treatment. The majority of fatigue studies reviewed consisted of treatments comprised of a single intensity exertion that was held for a given duration or until a requirement was met. For example subjects exert a given grip force for as long as they can maintain the force within 10% of the desired value. Once the requirement is met, the study ends. The current study was comprised of a series of exertions of different intensities and durations with built in rest periods. These rest periods provide time for the muscle to recover from fatigue. During these rest periods, blood flow removes cellular metabolism byproducts and re-oxygenates the muscle tissue. One question that arises is the impact of rest on the recovery rate of EMG parameters.

The treatments with a primary exertion of 10% MVC are below the intramuscular pressure threshold that causes ischemia. Rainoldi et al (1999) demonstrated EMG parameter fatigue at 10% MVC exertion, but other studies have not (Søgaard et al, 2003). Even though the muscles are active, the blood flow may be adequate to prevent the buildup of metabolism byproducts and to replenish energy supplies, which are two physiological factors in muscle fatigue (Dugan and Frontera, 2000). Duration of the treatment exertions may have contributed to the deviation of the findings of this study

from expected results. The longest contraction was three seconds for any exertion followed by a two second rest. Muscles have enough ATP to sustain a maximal contraction for a few seconds (Dugan and Frontera, 2000, Sherwood, 1993). If blood flow can provide enough O₂, the muscle fibers can rely on oxidative phosphorylation to supply the fuel requirement (aerobic activity) and may never have to convert to glycolysis and a buildup of lactic acid can be avoided.

MnPF recovery rate may also have been a factor in why significantly different spectral shifts were not seen in this study. One study of isometric sustained handgrip contractions (testing endurance times) showed that subjects returned to pre treatment values of MnPF before the end two minutes (Petrofsky, 1981). If MnPF recovers in less than two minutes for a sustained 40% MVC contraction lasting longer than 100 seconds, than how long does it take for MnPF to recover from a three second 40% MVC contraction? The Petrofsky study had two main similarities with the current study. Neither study showed a significant difference between MnPF and treatments, but did show a different in pre verses post treatment strength.

Many studies have shown an increase in RMS due to fatigue that was not seen in the current study (Blackwell et al, 1999; Dimitrova and Dimitrov, 2003; Elfving et al, 1999; Esposito et al, 1998; Jurell, 1998; Lowery et al, 2002; Moritani et al, 1986a; Moritani et al, 1986b; NIOSH, 1992; Petrofsky, 1981). Preliminary testing showed an increasing RMS values for 50% and 100% MVC sustained contractions (about ten seconds). Neither the primary (RMS_p) nor the secondary (RMS_s) contractions during any of the treatments adhered to this fatigue pattern. Subjects in the current study reported increased RPE and subjective fatigue values, but the increase was not reflected in the

RMS values. As with the MPF slope, this may have to do with the rest and recovery periods built into each treatment.

The RMS values were consistent with percent MVC or grip force, which also has been seen in other studies (Grant et al, 1994). At least in intermittent activities like the current study or similar industrial settings, RMS may be a valuable tool in determining how much force is being applied by a subject, but may have limited use in determining levels of fatigue.

The IMnPF values for the FDS are similar to the IMPF values shown by Blackwell et al. IMnPF tends to be a little higher than IMPF (Krivickas et al, 1998), as they are in this case. There was not a significant difference between treatments and pre treatment IMnPF, which is consistent with what was expected and other studies of IMPF and IMnPF have found (Elfving et al, 1999).

Part II - Strain Index Models

The adjusted sum method and the complex equations are the only two methods that account for recover time. Recovery time is accounted for in the published Strain Index score as a byproduct of the Duration of Exertion task variable. As in the original score, it was considered important for the Complex Strain Index models to account for recovery time lost due to additional exertions that were not accounted for in the individual Strain Index calculations.

Even though the peak and minimum methods were rejected, both methods are still useful in estimating Strain Index scores. By using the peak and minimum values,

estimation limits can be set to determine if further analysis needs to be performed. If the peak method is used and the job or task is determined to be safe, then since the peak method overestimates the actual stress, the task can be considered safe. If the minimum value method is used and the job Strain Index score is hazardous (above 5), then the job can be considered hazardous. If a job is deemed hazardous by the peak method and safe by the minimum method, further analysis is needed to determine if the job is actually safe or hazardous.

Of the three Strain Index calculation methods (SI_c , SI_A , and SI_B), only the categorical method (SI_c or original method) has ever been published (Moore and Garg, 1995) or tested for reliability and validity (Moore et al, 2001; Rucker and Moore, 2002; Stephens et al, 2006; Stevens et al, 2004). Before either of the continuous calculation methods can be used, they must first be validated. As can be seen in a comparison of Tables 2 – 4, SI_B seems to be smaller in magnitude than either of the other two methods of calculating the Strain Index score. For SI_B to be used properly, either a scaling factor needs to be used (which has not yet been determined) or possibly a different critical value for the Hazard Classification. Currently a Strain Index score above five is hazardous, but since SI_B 's scores are smaller in magnitude, the critical value may also have to decrease to keep the same predictive validity as the published version (SI_c). Further research is needed to determine the appropriate critical value for SI_B .

Future Research

One of the weaknesses of the study is the total duration of the treatments. Since a large number of jobs are performed for an eight hour day, a longer treatment cycle should be used to improve generalizability. Also only two Strain Index Task Variables were manipulated in the current study, Intensity of Exertion and Duration of Exertion. Further research is needed to determine the effects of changing other Strain Index Task Variables, such as frequency. Only two different intensities and durations were used in the current study. Further study is needed to examine the impact of different intensities and durations on the subjective measures of fatigue than those used in the current study.

The linear trends found in RPE should be examined in further detail to determine if plateaus exist beyond the limits of the current study. The linear trends can also be tested by using different intensities and duration than were used in the current study.

Additionally, more research needs to be conducted on the effects of rest breaks on EMG parameters. Are EMG fatigue parameters useful in an intermittent work environment? In such cases, would subjective measures more accurately describe the levels of localized muscle fatigue experienced?

As seen in the results of the current study, RMS highly correlates with percent MVC. RMS values were higher than their respective percent MVC values, but this could have been caused by the secondary exertion. If the correlation holds true for other percentage values of MVC, then RMS may be able to be used in industrial settings to gauge force applied by a worker without having to use a pressure gauge or other tool that can alter the way the worker performs the task. RMS may also be useful in determining

the force applied by specific muscles or muscle groups to perform a given task. To take full advantage of these findings, a non-intrusive portable EMG recording device that is economical needs to be developed.

Of the few methods proposed to calculate a Complex Strain Index score, only the complex equations met all the required criteria. This method needs to be further examined to determine its predictive validity and reliability using field data. Other methods may exist that have not been evaluated or considered by the current study.

CONCLUSION

The results of this study show that the Treatments can be separated by subjective reports of fatigue and strength loss. Fatigue was found using EMG parameters of MnPF slope, but no differences were found between treatments. This may be an indication that EMG parameters are not as sensitive to fatigue or certain types of fatiguing actives as subjective measures and physical strength loss.

According to the results shown in section II, the complex equations method (as calculated in the methods section) is effective for calculating a Complex Strain Index. Currently, the categorical calculation method is the best choice for calculating a Complex Strain Index score. There are two main reasons for this recommendation. The first is SI_c complex equation's correlation to the data as seen in Table 45. The second reason for this recommendation is the published reliability and validity of the categorical Strain Index calculation method (Knox and Moore, 2001; Moore et al, 2001; Rucker and Moore, 2002; Stephens et al, 2006; Stevens et al 2004). The SI_A and the SI_B have not been published nor have they been validated.

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VITA

JOHN-PAUL STEPHENS

Department of Interdisciplinary Engineering
c/o Dr. J. Steven Moore
Texas A&M University, MS-3127
College Station, TX 77840

EDUCATION

1999	BS	Industrial Engineering, Texas A&M University, College Station, TX
2003	MS	Safety Engineering, Texas A&M University, College Station, TX
2006	PhD	Interdisciplinary Engineering, Texas A&M University, College Station, TX

PREVIOUS EMPLOYMENT AND EXPERIENCE

1999-2001	Sawyer Crystal Systems, Conroe TX	Project Engineer
2001-present	Engineering Consultant, College Station TX	Consultant
2003-2004	Breakaway Ministries, College Station, TX	Intern
2001-present	Texas A&M University SRPH; Bryan, TX	Research Assistant

PEER-REVIEWED PAPERS

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