EFFECT OF UPPER EXTREMITY INJURY ON GRIP STRENGTH EFFORT

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2007

To my parents, for their countless prayers.

ACKNOWLEDGMENTS

I would like to thank my supervisory committee. First and foremost, I thank Dr. Orit Shechtman, my mentor and chair of my graduate study committee. Thank you for your vision, support, and encouragement. I am especially thankful for the moments when you lifted my spirits with your simple gestures of kindness. Thank you for polishing my research and teaching skills and thank you for helping me become a better person. I am lucky to have you as a mentor. I would also like to say a special thanks to Dr. Paul Davenport, the external member on my graduate committee. Thank you for always helping me in anyway you could, and for challenging and guiding my thought process. Working in your lab was an enriching experience. Dr. John Rosenbek, I am grateful to you for teaching me the meaning of being a rehabilitation scientist. Dr. Mark Bishop, I am very grateful for all your help with the analysis of EMG data. I thank you all for opening your hearts to me, for taking me under your wings, and for sharing your knowledge with me.

I would also like to thank Thought Technology Ltd. and the American Society of Hand Therapists (ASHT) for supporting this research project. I am grateful to Thought Technology Ltd. for loaning their equipment and for providing technical support. I am also grateful to the ASHT for partially funding this research project. I could not have completed this project without your support.

I am grateful to the faculty and staff in the Department of Occupational Therapy at University of Florida for their support and encouragement. I am especially grateful to

Wendy Holt for always being there to help, support, encourage and advise me. Wendy, you have taught me so much. It has been a pleasure working with you and sharing an office with you.

I am also very grateful to my fellow graduate students: Leigh, Rick, Patricia, Jessica, Inga, Megan, Pey-Shan, Jia-hwa, Eric, Michelle, Cristina, Sandy, Swathy, and Kezia. Thank you all for being so helpful and supportive at various stages of my graduate study. Without your friendship I could not have survived the last six years in the RSD program.

Last, but not the least, I would like to thank my grandmother, parents, aunts and uncles, sister and brother-in-law, and my cousins for their love and support. Thank you all for your guidance at each and every step. You inspired and motivated me to work hard. You have dreamed of and prayed for my success. I am not sure what I would have done without you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

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December 2007

Chair: Orit Shechtman
Major: Rehabilitation Science

Force-time curve (F-T curve) and electromyographic (EMG) measures have been used to differentiate between maximal and submaximal grip efforts. The Force-Time Curve Test (F-T Curve Test), which uses the slopes of the force-generation phase and the force-decay phase to detect submaximal effort, has been shown to be valid in healthy people. However, the validity of the F-T Curve Test has not been examined in people with UEMDs.

The primary purpose of this study was to examine if the F-T Curve Test is valid in people with UEMDs. Another purpose of this study was to examine if other F-T Curve characteristics and EMG properties are valid sincerity of effort measures in people with UEMDs.

Forty subjects participated in the study. Each subject performed 2 sessions of 2 maximal and 4 submaximal grip efforts with each hand. Each grip lasted 6-seconds. The order of the efforts (maximal versus submaximal) was randomized and the test administrator was blinded to the level of effort exerted by the subject. The force-time

curve and EMG signal of each contraction were recorded and following dependent variables were measured: peak force, time-to-peak force, slopes of the force-generation phase and the force-decay phase, as well as forearm flexor and extensor EMG amplitude and MF-ratio.

The dependent variable scores were subjected to the following analyses: Repeated-measures ANOVA were used to compare the dependent variables with effort, injury, and session as the within-subject variables and gender as between subject variable. Test-retest reliability was analyzed using the ICC. Sensitivity and specificity values were calculated and ROC curves were plotted to find the optimal slope cutoff values.

All dependent variables identified differences between maximal and submaximal efforts. The test-retest reliability ranged from 0.3 to 0.96. The slope of the force-generation phase was the most effective in distinguishing between maximal and submaximal efforts but yielded overall error rates 55% for women and 60% for men.

Despite the significant differences between maximal and submaximal efforts, we did not find acceptable combinations of sensitivity and specificity for detecting sincerity of effort. Therefore, the F-T curve and EMG measures may not be clinically valid.

CHAPTER 1
INTRODUCTION

Problem Statement

Upper extremity musculoskeletal disorders and injuries (UEMDs) may result in compromised grip strength.[1] Grip strength depends on the type, rate and number of contracting muscle fibers.[2] Reduced grip strength (weakness of grip) brought about by injury may be due to either a reduction in the rate and number of contracting muscle fibers[3], changes in muscle-fiber-type[3-7], or pain.[8-10] Pain has been associated with decreases in: voluntary muscle activity[11-17], electromyographic (EMG) activity[11, 12], motor unit discharge rates[14, 15], γ-motor neuron activity[16], speed of force generation[17], and endurance time.[13]

Maximal voluntary grip strength scores of people with UEMDs are used by clinicians[18] to determine the extent of injury[19], disease process[20], and progress in rehabilitation.[21] Grip strength is a valid indicator of musculoskeletal pathology and recovery from such pathology only when people exert a sincere, maximal voluntary effort.[22-27] Weakness of grip strength may be brought about by an injury but could also be due to exertion of submaximal effort. Submaximal effort may be exerted during evaluation and treatment for a variety of reasons, either unintentional or intentional. Unintentional submaximal effort may be exerted as a result of pain, fear of pain and fear of re-injury. Intentional submaximal effort may be exerted for secondary gain (such as money, benefits, or attention). To improve rehabilitative care, clinicians need to be able

to distinguish between a maximal voluntary grip effort (exerted by a client with true weakness of grip) and a submaximal grip effort.

Force-time curve (F-T curve) characteristics and electromyographic (EMG) properties generated during isometric grip contraction have shown promise in differentiating between maximal and submaximal efforts.[28] The F-T curve is generated by plotting force generated by a contracting muscle over a period of time during a single strength trial.[29] The F-T curve characteristics include the slope of the force-generation phase, the slope of the force-decay phase, and the time-to-peak force[28], whereas, the EMG properties include its amplitude and frequency.[30-32] So far, these F-T curve characteristics and EMG properties have been described in healthy people.[28, 30-32] However, little evidence exists regarding the effects of UEMDs on the nature of maximal voluntary grip contraction as expressed by the F-T curve characteristics and EMG properties. The purpose of this research proposal was to identify if selected F-T curve characteristics and EMG properties can form valid sincerity of effort tests in people with UEMDs. As part of this study we examined 4 force and 2 EMG measures: peak force, time-to-peak force, slope of force-generation phase, slope of force-decay phase, EMG amplitude, and median frequency ratio.

Specific Aims

The purpose of the study was three-fold: (1) to compare the force-time curve characteristics of maximal and submaximal grip effort exerted by the injured versus uninjured hand, (2) to compare the electromyographic properties of maximal and submaximal grip effort exerted by the injured versus uninjured hand, and (3) to examine the reliability and validity of the force-time curve test in distinguishing between maximal and submaximal grip efforts.

Specific Aim 1

To examine the difference in force-time curve (F-T curve) characteristics between the injured and uninjured hands as well as between maximal and submaximal efforts. The characteristics that we examined were:

1. Peak force
2. Time-to-peak force
3. Slope of the force-generation phase
4. Slope of the force-decay phase

Hypothesis 1a. The peak force will be significantly greater, time-to-peak force will be significantly faster, and slope of the force-generation phase will be significantly steeper for the uninjured hand than for the injured hand, whereas, the slope of the force-decay phase will be significantly steeper for the injured hand than for the uninjured hand.

Hypothesis 1b. The peak force will be significantly greater, time-to-peak force will be significantly slower, and the slope of the force-generation phase and the force-decay phase will be significantly steeper for maximal effort than for submaximal effort.

Specific Aim 2

To examine the difference in electromyographic (EMG) properties between the injured and uninjured hand as well as between maximal and submaximal effort. The characteristics that we examined were:

1. The amplitude of forearm muscle EMG
2. The median frequency ratio of last to first second

Hypothesis 2a. The forearm muscle EMG amplitude will be significantly greater for the uninjured hand than for the injured hand, whereas, the median frequency ratio will be significantly smaller for injured hand than for the uninjured hand.

Hypothesis 2b. The forearm muscle EMG amplitude will be significantly greater, whereas, the median frequency ratio will be significantly smaller for maximal effort than for submaximal effort.

Specific Aim 3

To examine the reliability and validity of the force-time curve characteristics and EMG properties in distinguishing between maximal and submaximal grip efforts. The psychometric properties that we tested were:

1. The reliability assessed by identifying test-retest reliability
2. The validity assessed by identifying the effectiveness

Hypothesis 3a. The F-T curve characteristics and EMG properties will consistently measure grip efforts as expressed by high test-retest reliability ($r \geq 0.9$).

Hypothesis 3b. The F-T curve characteristics and EMG properties is valid for measuring of grip efforts, i.e. effective in differentiating between maximal and submaximal grip efforts, as expressed by a combined optimal value of 80% sensitivity and 90% specificity.

Background

Musculoskeletal disorders and injuries have an enormous and growing impact on American society.[33] In 1996, 53.9 million Americans, or 1 in 5 Americans, reported having at least 1 musculoskeletal condition.[34] Scientists have predicted a substantial increase in the prevalence of musculoskeletal conditions. By 2020, arthritis alone will affect an estimated 59.4 million Americans.[35] The prevalence of physical disabilities caused by musculoskeletal conditions has been estimated at 4-5% of the population.[36] Musculoskeletal impairments have been ranked number one among impairments due to chronic conditions.[33, 37] Musculoskeletal and connective tissue disorders also represent

17.2% of all activity limiting conditions.[38] Besides the obvious physical effects, musculoskeletal conditions significantly affect the psychosocial status of the people with these conditions as well as their families and caregivers.[33] The economic burden of musculoskeletal conditions is substantial: the total cost amounts to more than $250 billion per year[39] and the medical care expenditure for people with musculoskeletal conditions is 50% higher than for people with non-musculoskeletal chronic conditions.[34] Specifically, work-related musculoskeletal disorders (WMSDs) cost over $20 billion every year.[40] Therefore, people with musculoskeletal disorders and injuries use a sizeable amount of health and social care resources.[41]

Musculoskeletal disorders (MSDs) are caused by different pathophysiological mechanisms[42, 43] and form a diverse category of conditions.[44] Among the pathophysiological mechanisms, repeated or awkward movements have been reported to cause or aggravate MSDs.[45] MSDs encompass over 150 different diseases and syndromes because of their anatomical links as well as by their association with pain and impaired physical function.[42] Gradually developing pain and discomfort in soft tissue structures including nerves, muscles, tendons, blood vessels, and their related connective tissues represents a common clinical feature of the MSDs. Moreover, MSDs that have been associated with work activities commonly affect the upper extremities.[45]

Work-related musculoskeletal disorders (WMSDs) represent a cluster of conditions that are diagnosed by symptoms of pain, numbness, and/or tingling lasting more than a week or occurring more than 20 times in a year, without evidence of acute traumatic onset or systemic disease.[45] A large proportion of WMSDs affect the upper extremity. In 2003, 23% of the non-fatal work related injuries and illnesses affected the upper

extremity.[46] The upper extremity musculoskeletal conditions that are frequently associated with WMSDs include lateral epicondylitis (a tendon/muscle disorder) and carpal tunnel syndrome (a nerve compression disorder).[43] The muscle groups commonly affected by the upper extremity musculoskeletal disorders and injuries (UEMDs) include the neck and shoulder muscles[47-49] as well as the extensor muscles of the forearm and the hand musculature.[50] The affected muscles generally present with fatigue and stiffness, radiating pain, increased muscle tone during passive movement, painful locations and/or trigger points, which are defined as "palpable discrete, focal, and/or hyperirritable spots."[43]

Among people with UEMDs, grip strength has been used as a measure that indicates musculoskeletal pathology and documents recovery from such pathology.[18] Grip strength scores have been frequently used to determine the extent of disability and the amount of financial compensation for an injury, estimate physical work capacity, match job requirements to work capacity, and assess ability to return to work after injury.[51-57] Clinicians commonly use a dynamometer to measure grip strength. Objective measurement of grip strength is possible due to the availability of standardized testing procedures, normative values and accurate instruments.[18] A grip strength score, however, is objective, reliable and valid only when a patient exerts a maximal voluntary effort.[22-25]

Some people with UEMDs may exert a less than maximal voluntary effort during evaluation and treatment for a variety of reasons, either intentional (such as secondary gain of money, benefits, or attention)[58-61] or unintentional (such as pain, fear of pain, or fear of re-injury).[8, 9, 62] A less than maximal effort has been termed as insincere, low, submaximal, or less than honest effort.[25, 27, 28, 63-67] From this point on, an intentional low

effort will be referred as an insincere effort and an unintentional low effort will be referred as a submaximal effort. An insincere effort is a component of disability exaggeration. Disability exaggeration has been defined as "intentional production of false or grossly exaggerated physical or psychological symptoms, motivated by external incentives such as avoiding military duty, avoiding work, obtaining financial compensation, evading criminal prosecution, or obtaining drugs" (p. 245).[58] The rate of disability exaggeration is estimated to be between 25 and 30% of all personal injury litigation, worker's compensation, or disability claims.[59-61]

A submaximal effort may be exerted when the person is in pain or has fear of pain. Pain is one of the most commonly reported symptom by people with MSDs [43] and the most significant symptom for the majority of people with MSDs.[68] Pain signals originate in the periphery as a result of an injury or a disease. The central nervous system (CNS) then selects, abstracts, and synthesizes pain signals with other sensory signals.[69, 70] The force exerted by a muscle decreases as the level of pain increases. Several studies have reported this inverse relationship including region specific studies (involving a certain area of the body)[71], diagnosis specific studies (involving certain medical conditions)[8, 72], and studies involving chronic pain.[9, 62] However, people respond to pain differently as their pain experience is influenced by factors such as attitude, culture, past experiences, meaning of a situation, and other psychological variables like anxiety, stress and depression.[69, 70] Therefore, pain may cause people with UEMDs to exert submaximal grip efforts.

People with UEMDs may also develop a fear of pain. Fear of pain has been shown to impact people with chronic musculoskeletal conditions[73-75] as well as people with

acute pain.[76] An elevated fear of pain has been hypothesized to induce an avoidance behavior[76-78], which includes avoidance of movement, daily activity, leisure activity and social interaction.[79] In turn, the avoidance behavior may lead to disuse syndrome, chronic disability and exaggerated pain perception.[76-78] Therefore, through the mechanism of avoidance behavior, fear of pain may prevent people with UEMDs from exerting maximal voluntary grip effort.

Detecting a submaximal grip effort is essential as a person cannot be effectively rehabilitated without putting forth full effort, even on applying the most advanced technology, equipment and therapies. Different methods based on the grip strength have been used in the clinic to detect submaximal efforts.[80-82] These methods include the five rung grip (5R) test, the rapid exchange grip (REG) test and the coefficient of variation (CV).[27, 28, 64-67, 83, 84] The 5R-test uses variability in grip strength scores across the 5 handle positions of a Jamar dynamometer to identify a submaximal effort. A greater variability in grip strength scores across the 5 handles increases the likelihood of maximal effort.[22, 25, 31, 32, 85-89] The REG-test requires a patient to grip a dynamometer in rapid succession. The highest score resulting from this rapid succession has been termed as the REG-score. The REG-score is then compared to the peak score generated during a static grip (SG) test, which has been termed as the SG-score. The REG-test score is calculated by subtracting the REG-score from the SG-score. A negative REG-test score (i.e. the SG-score is greater than the REG-score) increases the likelihood of a maximal effort.[62, 90, 91] The CV, which measures relative dispersion, expresses the standard deviation (SD) of multiple grip strength trials as a percentage of their mean score.[53, 64-66, 92] The premise of the CV is that a set of submaximal effort trials would result in a greater

value of the CV when compared to a set of maximal effort trials.[82] The CV, 5R-test and REG-test, however, lack standardized testing protocols, reliability and validity values, and empirical support.[27, 28, 64-66, 80, 83, 89, 93, 94] Each of these tests has been shown to have a high error rate for the combined sensitivity and specificity values. High error rates indicate that using these tests inaccurately classifies a large number of people exerting maximal effort as exerting submaximal effort, and large number of people exerting submaximal effort as exerting maximal effort. Such high error rates deem these tests inadequate in detecting submaximal effort in a clinical setting.[26-28, 58, 64-66, 82, 83, 93]

Physiologically based measures, which take into consideration muscle activity over a period of time, such as the force-time curve and electromyography, may provide better detection of maximal versus submaximal efforts. The force-time curve (F-T curve) graphically represents the force generated by a contracting muscle over a period of time during a single strength trial.[29] The vertical axis (Y-axis) represents change in force of muscular contraction and the horizontal axis (X-axis) represents change in time. The typical isometric F-T curve consists of an initial rapid rise of force (the force-generation phase or the initiation phase), followed by a relatively smooth peak curve (the initiation peak), and a subsequent gradual decrease in force over time (the force-decay phase or the maintenance phase).[95, 96] Various F-T curve characteristics have been used in athletics for evaluating neuromuscular adaptations to strength-training programs. These characteristics have been used to identify maximal effort in a variety of muscle groups.[97-99] Several characteristics have been found to be consistent for portraying age-related changes[100] as well as fatigue-related changes[95] in grip strength. Submaximal grip effort was also identified in the 1980's using the variability of force during the plateau phase of the F-T

curve.[29, 55, 101] However, the F-T curve is not commonly used in the clinic to evaluate sincerity of effort because it requires specialized equipment and software, which are currently not available commercially.

In a previous study we found that the slopes of the two phases of the F-T curve (the force-generation phase and the force-decay phase) successfully differentiated between maximal and submaximal grip effort in healthy subjects. The Receiver operating characteristic (ROC) curves identified the best combinations of sensitivity and specificity values for the slopes. We found excellent sensitivity and specificity values for the slopes, with sensitivity values ranging from 0.8 to 0.93 and the specificity values ranging from 0.93 to 1.0. Also, the lowest overall error rates ranged between 7% and 33%.[102] These error rates are excellent when compared to the error rates of the five-rung test, rapid exchange grip test and the coefficient of variation, which range from 47% to 69%.[27, 65, 93] The grip efforts in the pilot study lasted for 5-seconds. Two studies have evaluated sustained maximal grip efforts over 10-seconds (s).[96, 103]

Kamimura and Ikuta[96] compared the reliability of a maximal isometric grip lasting 6-s with that lasting 10-s. Fifty healthy subjects continuously gripped a modified Jamar dynamometer that was set at the second handle position. Subjects performed grip efforts on two occasions separated by 2-7 days. On each occasion, subjects performed one trial of the 6-s grip followed by the 10-s grip. Subjects rested for a minute between the two grips. Test-retest reliability was compared for peak grip strength, time-to-peak strength, and the momentary strength (strength at every second during a trial). The peak grip strength and time-to-peak strength were found to have high reliability coefficients for both grips. However, the coefficients of momentary strength were found to be higher for

the 6-s grip than the 10-s grip. Consequently, the 6-s grip was identified to be more consistent than the 10-s grip. The study also identified that in both tests maximal strength was achieved in the first two seconds. After achieving maximal strength, a gradual decline in strength was observed.[96]

Massy-Westropp et al.[103] identify age and gender-specific reference values of a 10-s grip strength trial. The grip strengths of 476 healthy subjects were tested using the Grippit electronic dynamometer. Each subject performed one grip trial, which was used to calculate peak, average and final strength. The final strength was measured as an indicator of fatigue. Peak and average grip strengths were found to be the highest in the third and fourth decades of life, with women showing less strength than men for all age groups. The final strength indicated that left-hand dominant adults have more equal grip endurance between their hands than do right-hand dominant adults.[103]

Forearm muscle EMG properties have the potential of being a valuable adjunct for clinicians involved in identifying submaximal grip effort.[32] Surface EMG activity has been proposed to be the best measure of overall electrical activity that drives a muscle.[104] Surface EMG can also indicate the amount of voluntary effort perceived by a person.[104] The EMG activity of a submaximal grip effort was found to have smaller amplitude than that of a maximal voluntary effort.[31, 32, 89] This is not surprising because less motor units are active during submaximal compared to maximal effort resulting in lower EMG activity. However, conflicting findings have been reported for the mean power frequency (MPF). The MPF is the frequency of the EMG signal that represents the average power of a power spectrum. Also, the median power frequency has been defined as the frequency about which the power is distributed equally above and below.[105] The terms power and

power spectrum have been defined on page 18. The MPF of a submaximal grip effort has been reported to either be greater than maximal voluntary effort[31] or not to be different than that of maximal voluntary effort.[32, 89]

In general, it appears that F-T curve characteristics and EMG properties can be used to develop a dependable tool for determining whether a patient exerts maximal or submaximal effort.[31, 32] To date, studies investigating the potential of F-T curve[28] and EMG[31, 32, 89] to determine sincerity of effort have only included healthy participants. Furthermore, the nature of maximal voluntary effort (both F-T and EMG) has not been studied adequately in people with UEMDs.[106] Thus, there is a need to identify the nature of maximal grip efforts and submaximal grip efforts in people with UEMDs and to investigate the impact of current and imagined pain on grip effort.

Significance

MSDs present an enormous burden on today's society as they cost billions of dollars annually in medical and rehabilitative care as well as in lost work time.[34, 39, 40, 107, 108] This burden has increased the demands on health care professionals to correctly identify disability exaggeration.[84] One method of assessing disability exaggeration involves determining sincerity of effort in grip strength. Commercially available sincerity of effort tools are neither reliable nor valid.[26-28, 58, 64-66, 80, 82, 83, 89, 93, 94] A reliable and valid tool may assist in reducing the costs of misdiagnosis, rehabilitation, medical procedures, lost work-time, and lost productivity, and thus may be of great value to the society. Such a tool can be of benefit to rehabilitation specialists (such as occupational and physical therapists and rehabilitation counselors), insurance companies, worker compensation authorities, employers, and the workers themselves.

It is essential to have a reliable and valid assessment tool to identify sincerity of effort. A reliable instrument performs with predictable consistency under set conditions. An unreliable instrument cannot be valid as an inconsistent instrument cannot produce meaningful measurements. A valid measurement instrument collects data in an accurate and relevant manner.[109] A sincerity of effort instrument is a diagnostic tool that screens for the presence or absence of submaximal effort. A valid diagnostic tool has high sensitivity and specificity values.[110] An instrument with a low sensitivity value may misclassify a person who exerts submaximal effort as exerting maximal effort. Consequently, a person feigning disability may be mistakenly labeled as sincere. Low sensitivity can lead to seemingly ineffective treatment, increased unnecessary procedures, and elevated disability and health care costs.[27, 65, 82, 83, 93, 94] Conversely, an instrument with a low specificity value may misclassify a person who exerts maximal effort as exerting submaximal effort. Consequently, a person exerting sincere effort may be erroneously labeled as feigning disability. This error can lead to inappropriate diagnosis and treatment, reduced worker compensation settlement, withheld payments and even loss of job.[27, 65, 82, 83, 93, 94] For a sincerity of effort instrument, a low sensitivity value has been argued to be better than a low specificity value as "it is considered more ethical to miss subjects giving a deliberately submaximal effort rather than to misclassify as feigning a subject giving a genuine maximal effort" (p. 1828).[80] Unfairly misclassifying a sincere person as feigning can be very damaging to the individual and may promote clinically unfair decisions.[65] Thus, there is a great need to establish a method for identifying sincerity of effort that has high sensitivity and specificity values allowing it to avoid mistakes in classifying patients as sincere or feigning.

The force-time curve (F-T curve) has been shown to be very effective in detecting submaximal effort in uninjured individuals.[28] Based on physiological aspects of effort, the F-T curve has the potential to allow therapists to determine submaximal effort when exerted by injured individuals. The F-T curve also has the ability to assist in clinical decision-making concerning further treatment and/or referral. Moreover, the proposed project may further the understanding of motor unit recruitment in maximal and submaximal muscular effort of hand-injured patients, which has potential applications in rehabilitation, ergonomics, and biomechanics.

Previous Study

In a previous study, we analyzed the force-time curves (F-T curves) of maximal and submaximal grip strength trials exerted by healthy people for the slopes of both the force-generation phase and the force-decay phase. We simultaneously recorded the electromyographic (EMG) activity of the extrinsic flexor and extensor muscles of the digits.

Methods. Thirty healthy volunteers (15 men and 15 women) performed three maximal and three submaximal grip strength efforts with their dominant hand. We blinded the test administrator to the nature of the effort. For force measurements, we used a specialized dynamometer (Biopac Instruments) with a force transducer connected through a digital oscilloscope (Gould Instruments) to an analog-to-digital (A/D) converter (PowerLab, ADInstruments). The digital force signals were stored on a computer by a polygraph software system (Chart, ADInstruments). For EMG activity, we placed surface silver-silver chloride electrodes over the belly of the flexor digitorum superficialis muscle and the extensor digitorum communis muscle. The EMG activity was amplified and band-pass filtered in the range of 0.1-1.0 kHz (Grass Polygraph, Grass Instruments) and

led into the A/D converter (PowerLab, ADInstruments). The EMG data were digitally smoothed and rectified by the Chart software (ADInstruments).

Data analysis. For maximal and submaximal effort, we used the Chart software to calculate the slopes of the force-generation and the force-decay phases of the F-T curve as well as the amplitude of the EMG activity. The Chart calculates the slope from the least-squares line of best fit of the selected data points. The average rectified amplitude of the EMG activity was calculated for the duration of the F-T curve.[111]

Statistical analysis. Paired sample t-tests were used to analyze the difference between maximal and submaximal effort. Additionally, the sensitivity and specificity values of the slopes of the force-generation and force-decay phases were calculated. To find the optimal cutoff value for each of the two slopes, the receiver operating characteristic (ROC) curves were generated from the multiple combinations cutoff values.

Results. For the F-T curves, we found significant differences in slope between maximal and submaximal efforts for both the force-generation phase ($t=46.77$; $p<0.0001$) and the force-decay phase ($t=79.16$; $p<0.0001$). We also found significant differences between maximal and submaximal effort in time-to-peak force ($t=2.841$; $p\leq0.008$). For the EMG activity, we found significant differences in amplitude between maximal and submaximal efforts for both the flexor muscles ($t=4.52$; $p<0.0001$) and the extensor muscles ($t=3.82$; $p<0.001$). Table 1-1 presents the average and SD values of the F-T curve slopes and EMG amplitudes.

Conclusions. This study achieved excellent combinations of sensitivity and specificity values, especially when compared to the sensitivity and specificity of the

currently available clinical tests (Table 1-2). For the cutoff value of –0.075 during the force-decay phase, none of the male subjects who exerted a maximal effort were wrongly classified as exerting a submaximal effort. Of the male subjects exerting submaximal effort, only 7% were wrongly classified as giving a maximal effort (Figure 1-1).[28]

On examining the concurrent EMG and force recordings of the force-decay phase of maximal effort, starting at approximately 4.5 seconds after achieving peak force, we found the two recordings to decompose. While force continued to decline, EMG output actually increased, indicating that the muscles were maximally activated by the nervous system in an attempt to maintain the maximal contraction. In contrast, during submaximal effort, the EMG and force recordings exhibited similar trends indicating that the person was able to maintain the maximal contraction without additional activation of motor units (Figure 1-2).

Definition of Terms

This section defines the various terms used in this research project. When appropriate, the conceptual and operational definitions of terms specific to the study have been given.

1. Musculoskeletal system: Also called the locomotor system, the musculoskeletal system consists of the skeletal system (bones and joints) and the skeletal muscle system, and peripheral nerves that innervate the skeletal muscles. This system performs various functions including protection of internal organs, maintain posture, assist in movement, formation of blood cells, and storage of fats and minerals.[1, 112]
2. Musculoskeletal disorders:
    a. Conceptual definition: Musculoskeletal disorders include a diverse spectrum of diseases and syndromes with varied pathophysiology. However, they are linked anatomically and by their association with pain and impaired physical function. These conditions range from acute onset and short duration disorders to lifelong disorders. They commonly manifest as rheumatoid arthritis, osteoarthritis, osteoporosis, spinal

disorders, peripheral nerve injuries, major limb trauma, fibromyalgia, gout, and sprains and strains.[39, 42]

3. Musculoskeletal conditions:

    a. Conceptual definition: Musculoskeletal conditions have been defined differently in the literature. Some articles rely on physician provided diagnoses, some on self-report, some include injuries to the musculoskeletal system and some exclude injuries. The National Arthritis Data Task Force defines musculoskeletal conditions as those that include the International Classification of Diseases, Ninth Edition (ICD-9) codes 274 (gout) and 710.0 – 739.9 (diseases of musculoskeletal system and connective tissue).[34, 113]

4. Upper extremity musculoskeletal disorders and injuries (UEMDs):

    a. Operational Definition: It is a collection of various diseases, syndromes, and injuries that affect the musculoskeletal system (skeletal muscles, bones, joints, blood vessels, nerves and related connective tissue) of the upper extremity.

5. Disability exaggeration: Also called symptom magnification and malingering, disability exaggeration has been defined as "intentional production of false or grossly exaggerated physical or psychological symptoms, motivated by external incentives such as avoiding military duty, avoiding work, obtaining financial compensation, evading criminal prosecution, or obtaining drugs."[58] Moreover, disability exaggeration subsumes fraudulent persistence of symptoms. These persistent symptoms are observed when genuine symptoms cease but a patient asserts that the symptoms continue to exist.[114-117]

6. Effort: Effort is the perception of an individual regarding how much force he/she has exerted. Effort is a psychological construct and force variables can only provide an indirect measure of the construct.[31]

7. Maximal voluntary effort:

    a. Conceptual definition: Also called sincere effort, maximal effort indicates that a person consciously and voluntarily performs to the best of their ability during an evaluation.

    b. Operational definition: In relation to grip strength, maximal effort indicates that a person consciously and voluntarily performs a grip strength trial to the best of their ability.

8. Submaximal effort:

    a. Conceptual definition: It is a less than maximal effort.

b. Operational definition: In relation to grip strength, submaximal effort indicates that a person subconsciously or unintentionally performs a grip strength trial in which the force generated is less than that generated during a maximal voluntary effort.

9. Insincere effort:

    a. Conceptual definition: Also termed as low, submaximal, or less than honest effort[25, 28, 63-65, 93], insincere effort indicates that a person consciously performs at a level below the best of their ability during an evaluation.

    b. Operational definition: In relation to grip strength, insincere effort indicates that a person consciously or intentionally performs a grip strength trial in which the force generated is less than that generated during a maximal voluntary effort.

10. Sincerity of effort:

    a. Conceptual definition: It is a patient's conscious motivation to perform optimally during an evaluation.[82]

    b. Operational definition: In relation to grip strength testing, sincerity of effort indicates exertion of maximal voluntary strength/force during a grip strength trial.[118]

11. Surface electromyography (SEMG): It is a noninvasive method of measuring the electric potential field evoked by active muscle fibers through the intact skin [119]. The SEMG signal is measured as a time-varying signal.

12. Frequency content of SEMG: Any time-varying signal can be represented by successively adding the individual frequencies (f_n) present in the signal.[120, 121] The frequencies forming the EMG signal can be identified by performing a mathematical conversion called the Fourier Transformation.[121]

13. Power at frequency f_n: The Fourier Transformation of the EMG signal calculates two Fourier coefficients (b_n and c_n) for each frequency (f_n) in the EMG signal. The sum of the squares of these coefficients is termed as power at frequency f_n. The power indicates how much signal is composed of the frequency f_n.[121]

14. Power spectrum of EMG signal: A plot of power at each frequency f_n that composes the EMG signal is referred to as the power spectral density (PSD) plot or simply the power spectrum.[121]

15. Mean power frequency of EMG signal: It is the frequency of the EMG signal that represents the average power of a power spectrum.

16. Median power frequency of EMG signal: Sometimes know as the center frequency, it has been defined as “the frequency about which the power is distributed equally above and below. It is calculated as a median of a distribution” (p. 115).[105]

Table 1-1: F-T curve slope and EMG amplitude values from the pilot study

	Slope of the F-T curve		Rectified EMG Amplitude	
	Force-generation phase	Force-decay phase	Flexor muscle	Extensor muscle
Maximal Trials	2.61±1.40	-0.16±0.08	0.08±0.03	0.18±0.08
Submaximal Trials	0.98±0.44	-0.04±0.03	0.02±0.01	0.07±0.02

Table 1-2: Summary of sensitivity and specificity values of sincerity of effort tests

Measure	Value	Sensitivity	Specificity	Author
Slope of force-generation phase	Females =1.2	0.80	0.93	Shechtman et. al, 2007
	Males = 1.45	0.80	0.87	
Slope of force-decay phase	Females = -0.05	0.80	0.87	Shechtman et. al, 2007
	Males = -0.075	0.93	1.00	
Coefficient of Variation	11% CV cutoff	0.69	0.74	Shechtman, 2001
	15% CV cutoff	0.55	0.92	
Five-Rung	7.5 SD cutoff	0.7	0.83	Gutierrez & Shechtman, 2003
Rapid Exchange Grip	REG 45	0.65	0.66	Shechtman & Taylor, 2000

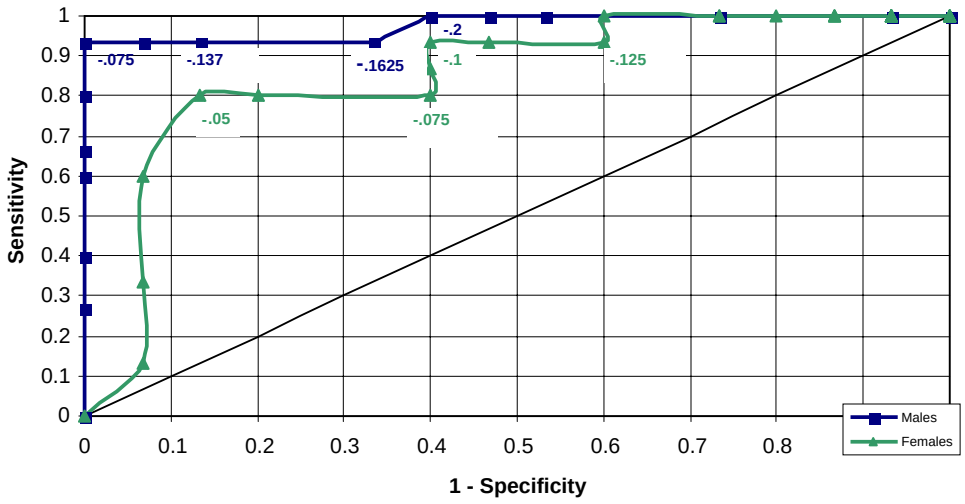


Figure 1-1: ROC curve for the slope of force-decay phase

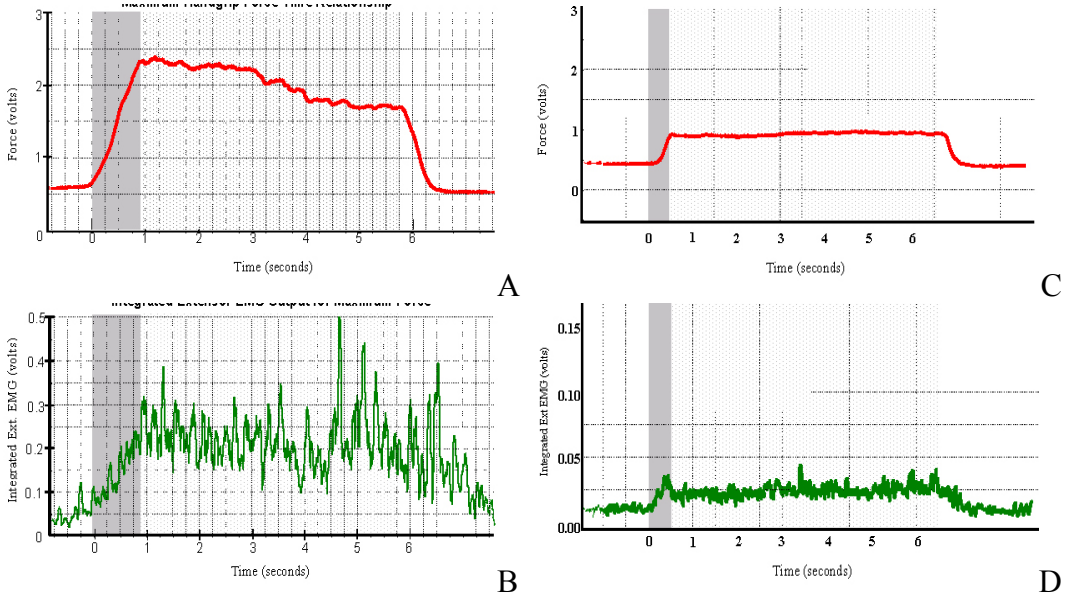


Figure 1-2: Typical maximal and submaximal grip efforts. A) F-T curve of a maximal effort. B) Rectified EMG signal of maximal grip effort. C) F-T curve of a submaximal effort. D) Rectified EMG signal of submaximal grip effort.

CHAPTER 2
LITERATURE REVIEW

Upper extremity musculoskeletal disorders and injuries (UEMDs) include a heterogeneous group of soft-tissue conditions that affect muscles, tendons, ligaments, joints, peripheral nerves and supporting blood vessels.[43, 122, 123] The reported prevalence rates of UEMDs range from 11-47%.[124-129] The frequent occurrence of UEMDs has challenged clinicians to develop new methods to improve the outcomes of rehabilitative care.

Cost, Magnitude and Description of Upper Extremity Disorders

Work-related musculoskeletal disorders (WMSDs) of the upper extremity impose an enormous burden on our society.[40, 130] WMSDs have also been described as cumulative trauma disorders as well as repetitive strain disorders. In 1989, cumulative trauma disorders of the upper extremity cost Americans over half-a-billion dollars in medical and indemnity expenses.[130] Since the 1980s, WMSDs of the upper extremity have grown rapidly. [131] Cumulative trauma disorders of the upper extremity increased from 1% in 1986 to 4% in 1993.[132] For the period 1993-94, 4.4% of worker compensation claimants had an upper extremity diagnosis.[133] In 1995, upper extremity WMSDs comprised a third of all WMSDs.[40] In 2003, among the 1.3 million injuries and illnesses occurring in the private industry, 33% were musculoskeletal disorders (MSDs) and 23% were upper extremity conditions. Also, over 20,000 people sustained carpal tunnel syndrome (CTS) and 7,000 people sustained tendinitis.[134] CTS also resulted in the highest lost work time (median = 32 days), which is higher than lost work time reported in 1997

(median = 25 days).[46, 134] Hence, the growing numbers of upper extremity WMSDs have increased the burden of care on the society.

Work-related activities involve low to high intensity repetitive tasks as well as awkward postures, which result in upper extremity musculoskeletal disorders and injuries (UEMDs).[135-140] WMSDs of the upper extremity have been broadly defined as "symptom complexes characterized by pain, paraesthesia, and/or weakness affecting the upper extremity or neck by the patient and/or their physicians to work" (p. 1279).[131, 141] WMSDs of the upper extremity frequently present as either tendinitis or entrapment neuropathy. Tendinitis involves inflammation of the muscle-tendon unit. When not allowed to heal, this inflammatory state evolves into a degenerative condition.[142] Entrapment neuropathies develop at specific points where nerves course around anatomical structures.[143, 144] Sites of entrapment distal to the elbow include the radial tunnel, supinator muscle[145-148], pronator teres muscle[149-151], cubital tunnel[152],and capral tunnel.[153-155] In the upper extremity, lateral epicondylitis is a common form of tendinitis and carpal tunnel syndrome is a common form of entrapment neuropathy.

Lateral epicondylitis or tennis elbow involves inflammatory and degenerative changes of the forearm extensor muscles.[43, 50, 156] Lateral epicondylitis has been associated with overuse of the elbow and is caused by force overload at the common extensor origin of the forearm muscles.[157-161] The muscle primarily affected is the extensor carpi radialis brevis.[3, 162-165] The chief clinical feature of lateral epicondylitis includes a gradually developing pain over the lateral aspect of the elbow that radiates distally into the forearm. The radiating pain increases with motor tasks that include

forearm pronation or supination, active wrist extension, passive wrist flexion against resistance and gripping.[156, 157]

Carpal tunnel syndrome (CTS), the most pervasive entrapment neuropathy[166-169], occurs when the structures within the carpal tunnel compress the median nerve.[153-155] The entrapment of the median nerve has been attributed to rheumatoid disease, pregnancy, diabetes, renal dialysis, space occupying lesions and the bony abnormalities of the wrist.[170] It has been postulated that edema due to impaired circulation ultimately causes CTS.[171] Symptoms of CTS include nocturnal pain, paraesthesia and hypaesthesia in the area of the hand innervated by the median nerve.[172] Later stages of CTS present with referred shoulder pain, burning pain, and wasting of thenar muscles.[173]

Use of Grip Strength to Assess Upper Extremity Musculoskeletal Disorders

Occupational and physical therapists frequently measure grip strength while assessing people with upper extremity musculoskeletal disorders and injuries (UEMDs). Grip strength scores have been used to determine the extent of injury[19], disease process[20], progress in rehabilitation[21] and functional integrity of an affected upper extremity.[174] The American Society of Hand Therapists (ASHT) recommends a standard method for measuring grip strength[175] as the strength output changes with factors such as positioning of the upper extremity. Change in position of the wrist[24, 176-178], forearm[179], elbow[180-184] and shoulder[184] have been shown to affect grip strength scores. Hence, grip strength measurements are less variable when using a standard testing protocol. However, the ASHT's method does not control for all sources of variability. For example, the protocol recommended by ASHT requires the tester to gently support the base of the dynamometer.[175] The dynamometer reading using this technique may become inaccurate if a patient exerts forces that are greater than the strength of the tester as it leads to

improper stabilization of the dynamometer.[185, 186] To identify outcomes of rehabilitative treatment, therapists compare grip strength scores of the injured extremity either with the uninjured extremity[21] or with the established grip strength norms.[187] These comparisons of grip strength are not accurate if a patient does not exert a maximal grip effort. Thus, a therapist needs to distinguish a maximal effort from a submaximal effort.

Differences between Maximal and Submaximal Effort

Based on the German literature of 1950s and 1960s, Kroemer and Marras[188] presented a neurophysiological model of maximal and submaximal effort.[27, 29, 64, 188, 189] According to Kroemer and Marras[188], an executive program regulates muscular contraction on the basis of the strength output profile. This program originates in the cerebral and cerebellar regions of the central nervous system (CNS).[188] Also, when a body part needs to generate greater effort, the CNS focuses greater mental attention on generating that effort as well as inhibiting body systems not involved in generating that effort.[190, 191] At the level of neuromuscular junction, two strategies are used to increase force output. Rate coding means 'frequency of motor neuron firing' whereas recruitment coding means 'sequence of motor unit activation.' A maximal effort results in maximal motor neuron firing and maximal recruitment of motor units. In contrast, a submaximal effort requires motor cortex to mix and precisely control submaximal frequency of motor neuron firing and recruitment of certain number and type of motor units.[188, 189, 192-194] Maximal and submaximal effort also differ in level of sensory feedback, which influences the order of motor unit recruitment.[188, 195] Sensory afferent fibers assist in calibration and modulation of magnitude of effort.[196, 197] This contribution of sensory afferent fibers distinguishes between maximal and submaximal effort. Maximal effort, which represents a lower order task, involves simple motor control (maximal motor unit

recruitment and firing) with minimal afferent feedback, which indicates full use of motor units.[188, 189, 192-194] In contrast, submaximal effort represents a higher order task, which requires a more complex motor control strategy. Maintenance of submaximal effort requires extensive and complex sensory afferent feedback.[188, 193, 194] Table 2-1 summarizes the differences between maximal and submaximal effort.

Grip Strength Tests for Detecting Submaximal Effort

Therapists use a variety of tests to detect submaximal effort, for example, the Waddell's non-organic signs, correlation between musculoskeletal evaluation and functional capacity evaluation, documentation of pain behavior, documentation of symptom magnification, and ratio of heart rate and pain intensity.[82] These methods may be divided into assessments that are commonly used and those not commonly used in the clinic.[64] The clinically-relevant methods can be administered easily and in a relatively short period time, and require minimal calculations and minimal equipment, e.g. grip strength based tests. In contrast, several tests are not commonly used in the clinic as they involve a lengthy administration time, complicated calculations, and expensive equipment, e.g. functional capacity evaluations and isokinetic tests. Other tests can cause pain and discomfort, e.g. tests involving supra-maximal stimulation of muscles. Among clinically relevant tests, the three grip strength based tests commonly used include the coefficient of variation, rapid exchange grip test and five rung grip test, which have been described next.

Coefficient of Variation (CV)

The CV is based on premise that submaximal exertion is more variable and less consistent than a maximal effort. The CV identifies submaximal effort when a calculated value is larger than a cut-off value.[64-66]

Physiological basis. Maximal effort can be easily replicated because it represents a lower order task. Maximal effort requires simple motor control based on maximal motor unit firing frequency and maximal motor unit recruitment. In contrast, submaximal effort is difficult to replicate because it represents a higher order task. Submaximal effort requires delicate proprioceptive feedback for grading muscle contraction, requires a precise combination of both rate coding and recruitment coding, and involves constant corrections of motor signals by sensory afferents.[29, 51, 64, 66, 188, 189, 192-194]

Administration protocols. The CV uses scores of at least 3 grip strength trials. The CV is calculated by dividing the standard deviation by the mean value of the grip strength trials. Next, the calculated value is compared to a predetermined cut-off value. In literature, this cut-off value ranges between 10% and 20%. A CV value that is greater than the cut-off value is labeled as submaximal and insincere. [64]

Advantages and limitations. The advantages of CV include:

1. The CV is simple to calculate.[64]
2. Some studies have shown that the CV differentiates between maximal and submaximal efforts.[64]
3. The CV is based on a standardized grip test.[64]

The limitations include:

1. The CV has not been shown to distinguish between maximal and submaximal efforts.[54, 198] This could be because variability in repeated measures of maximal effort has been reported to range from 10-24%.[64, 199, 200] Further, submaximal efforts in certain isometric tasks have been reported to be reproducible.[82] Furthermore, it has been suggested that psychological factors, such as fear of re-injury and pain, can increase variability between trials.[94]
2. The CV can only be used for comparing dispersion of data with different units. Since grip strength values are in same units, use of the CV as a sincerity of effort test becomes inappropriate.[92]

3. For the CV to be a valid measure of sincerity of effort, the average and standard deviation of repeated grip strength trials should increase proportionally (i.e. people with greater average grip strength should exhibit greater variability in grip strength trials).[64, 94] However, an inverse relationship has been described between grip strength and its variability.[201] Also, means and standard deviations of grip strength do not change proportionally.[66, 83]

4. The CV has been shown to have poor test-retest reliability.[66]

5. The sensitivity and specificity values of the CV do not allow it to effectively differentiate between maximal and submaximal effort.[65]

Rapid Exchange Grip Test (REG)

Physiological basis. Submaximal effort, which requires the motor cortex to mix and precisely control recruitment of motor units and their frequency of firing, requires a longer period of processing time than maximal effort. The rapid exchange of hands during the REG maneuver decreases the amount of time available for the cortex to compare between contractions. Hence, when an individual feigns weakness in one hand, the assessor expects that individual to exhibit greater REG scores than static grip (SG) score in the weaker hand.[26, 90, 193, 194, 202, 203]

Administration protocols. Lister developed the REG in 1983 to identify patients exerting submaximal effort.[91] The REG requires an individual to quickly grip a dynamometer with alternating hands. The REG test involves comparing REG scores to those of static grip (SG) test score. An SG test consists of slow, maximal grips and may be administered using either the five-rung (5R) test or the maximal static grip test (MSGT). In maximal effort, the clinician expects the REG scores to be less than SG scores resulting in a negative REG test score, which indicates sincere effort. In submaximal effort, the REG score is expected to be greater than the SG score resulting in a positive REG test score, which indicates insincere effort.[26] The testing protocols used by therapists vary with respect to hand switch rates (varying from 45 to 100 rpm), grip

repetitions (3 and 5 repetitions), type of SG score used for comparison (the 5R and the MSGT), and patient positioning while testing and handling of the dynamometer.[26, 27, 84]

Advantages and limitations. The advantages of REG include:

1. It is simple to administer that does not require any special equipment to administer.
2. It requires a short administration time.

The limitations of REG include:

1. Literature provides contradictory evidence for the REG as a test of sincerity of effort.26
2. Clinicians do not use a standard protocol while administering the REG test.26, 27, 84
3. Studies performed to validate the REG provide insufficient description of testing protocols. When described sufficiently, these protocols vary significantly.26
4. Speed of alternating grips plays an important role in the effectiveness of the REG test.26
5. Use of different handle settings of the Jamar dynamometer can influence grip test results.26, 27, 84
6. Clinicians do not determine sincerity of effort by just using the REG, but, by using it in conjunction with other tests indicating difficulty in interpreting the results of the REG.84
7. The sensitivity and specificity of the REG were not found to be sufficiently high.27, 204
8. The concept of 'positive REG' indicating a submaximal effort works only when comparing the peak REG scores with peak 5R scores.27, 204

Five Rung Grip (5R) Test

Physiological basis. The premise of the 5R test is based on the mechanical advantage of the muscles involved in gripping at the mid-range of hand position represented by rung 2 or 3 of the Jamar dynamometer. The mechanical advantage is based on length-tension relationship, leverage, and hand size. Increased lengthening (up to 110% of resting length) of the muscle prior to contraction produces greater muscle

forces during subsequent contraction. Lengthening the muscle beyond 110% will generate less tension due to reduced overlap of actin and myosin filaments. During maximal effort, the optimal resting muscle length produces the greatest contraction force. For most people the optimal length occurs at the second or third handle-position of the Jamar dynamometer, which also results in the best leverage. During submaximal effort, the person exerts a controlled, less than maximal muscular contraction. Hence, the person tends to exert approximately the same amount of force at all five rungs of the Jamar dynamometer.[85]

Administration protocols. The 5R test involves maximally gripping the Jamar dynamometer at the five available handle settings. On graphing the scores, a maximal effort produces a skewed bell shaped curve, whereas, a submaximal effort produces a flat line. Four different methods have been used to analyze the data from the 5R test: a) visual analysis of grip strength curves[85, 90], b) use of repeated measure analysis of variance with two within subject factors[31, 32, 86, 87, 89], c) normalization of grip strength scores[88, 205], and d) standard deviation of grip strength scores across all five trials.[22]

Advantages and limitations. The advantages of the 5R include:

1. It is easy to administer.
2. It requires a short administration time.

The limitations of 5R include:

1. The 5R test depends on the strength of the gripping hand. Hence, the test yields biased results when assessing sincerity of effort in people with upper extremity injuries93 and cannot distinguish between injured maximal effort and uninjured submaximal effort.206
2. Multiple studies on the effectiveness of the 5R test have provided conflicting evidence on its effectiveness as a sincerity of effort test.86, 87

3. Some studies have shown that subjects trained to feign can produce a curve that looks like a maximal effort curve.32, 86, 87

It is clear that the commonly used clinical tests are not reliable and valid for identifying submaximal effort. In contrast, tests based on the force-time curves[28] and EMG activity[31, 32, 89] can differentiate between maximal and submaximal effort (Table 2-2). The force-time curve has been used in various research studies to investigate both maximal[97-99] and submaximal[29, 55, 101] efforts. However, the force-time curve is not commonly used in the clinic because it requires specialized equipment.[28, 29, 55, 96, 101, 207-209]

Force-Time Curve

The force-time curve (F-T curve) graphically represents the force generated by a contracting muscle over a period of time during a single strength trial.[29] The vertical axis (Y-axis) represents change in force of muscular contraction and the horizontal axis (X-axis) represents time of muscular contraction. The typical F-T curve generated during a maximal voluntary isometric contraction (MVIC) consists of three phases: 1) the force-generation phase or the initiation phase that involves rapid or gradual development of force, followed by 2) the initiation peak that represents a relatively smooth peak curve, which may be followed by a secondary peak representing the maximum force value, and finally 3) the force-decay phase or the maintenance phase involving a steady rate of force development that may decrease gradually over time indicating onset of fatigue.[95, 96, 210-212]

The F-T curves of isometric[100, 213] as well as dynamic (concentric and eccentric) muscle contractions[214, 215] have been used to evaluate skeletal muscle functioning. The F-T curves have been used to identify differences in muscle function by age[100, 213, 216-218], gender[209, 213, 219, 220] and muscle fiber type.[100, 218, 221]

Reliability

Three studies have been performed identify test-retest reliability of various F-T curve characteristics of grip strength trials. In general, the F-T curve characteristics have been found to have moderate to high reliability coefficients.[95, 100, 207] Bemben et al.[100] identified the reliability of four different force-time curve (F-T curve) characteristics for interpreting age related changes in muscle function and force production. The study included 155 healthy men divided into 12 age groups ranging from 20 to 79 years. The characteristics included maximal force, total impulse, time to maximal force and maximal rate of force production for a 60 millisecond period. These characteristics were tested for five muscle groups: finger flexors, thumb abductors, forearm extensors, foot dorsiflexors and foot plantarflexors. Finger flexion force was recorded using a device similar to a handgrip dynamometer. For each muscle group, participants performed 3 maximal isometric contractions on 2 different days. Participants were instructed to exert maximal effort as hard and fast as possible and were told to relax when they felt that maximal force had been achieved. After each trial, participants rested for one minute. Day-to-day (test-retest) reliability was identified by comparing scores recorded on 2 different days using Pearson correlation coefficients. For finger flexors, correlation coefficients were found to be 0.98 for maximal force, 0.93 for maximal rate of force-production and 0.91 for total impulse. This study indicated that the four maximal force characteristics were consistently reached even by the oldest men, therefore allowing for accurate characterization of muscle function.[100]

Household et al.[95] identified the reliability as well as effect of fatigue on the variability of four different F-T curve characteristics including the maximum initiation force, absolute maximum force, maximum maintenance force, and slope of the

maintenance phase. Six healthy men with an average age of 36 years performed 3 maximal isometric grips on 3 different days using a modified Jamar dynamometer. The authors did not specify the handle position used in the study. The men were instructed to squeeze the dynamometer as rapidly as possible exerting maximal effort for a 7-s period. The grip trials were separated by a 30-s rest period, which did not eliminate the effects of fatigue. The test-retest reliability of the force characteristics across daily sessions was identified by calculating the coefficient of variation of the standard deviation for corresponding trials across the 3 sessions. The presence and degree of fatigue in a grip effort was determined by calculating slope of the maintenance phase using linear regression. The coefficient of variation of the force characteristics ranged from 0.11 to 0.9 with the smallest value for the maintenance force. Thus, the maximal maintenance force proved to be the most reliable parameter for quantifying maximal isometric contraction. The mean value of the maintenance phase slopes was calculated as – 13.5 N/s. There was a significant slope in 70% of the trials and when present it was negative. However, it was not more or less likely that there would be a decline in force during trials performed later on during a session. This indicated that intertrial and intratrial fatigue effects are somewhat independent.[95]

Demura et al.[207] compared the reliability of explosive and voluntary grip using 11 different F-T curve characteristics. The characteristics measured were divided into 5 categories of variables: time, average force, integrated area from the onset of exertion, maximal rate of force development, and mechanical power. Hundred healthy men with an average age of 17.8 $\pm$ 2.5 years performed two explosive as well as voluntary grips with their dominant hands using a digital dynamometer (ED-D100R). The men performed the

2 voluntary grips, rested for 5 minutes or longer, and finally performed 2 explosive grips. For the voluntary grip, the men were instructed to exert maximal grip after hearing the start signal. For the explosive grip, the men were instructed to exert maximal grip as fast and forcefully as possible after hearing the start signal. The cross-correlation coefficients indicated that between the two trials, the difference in explosive grip tended to be smaller than voluntary grip. The explosive grip had greater reliability coefficients for 9 of the 11 characteristics than voluntary grip. Also, the maximal grip strength scores had highest reliability coefficients between the two trials for explosive and voluntary grip.[207] While the F-T curves have primarily been employed in the athletics-related fields (e.g. exercise physiology and athletics), healthcare professionals have also investigated their use for the purposes of assessment and treatment in rehabilitation.

Athletics

In athletics, neuromuscular adaptations due to exercise have been associated with changes in F-T curves. The F-T curves have been commonly used to assess muscular strength[97-100], endurance[216, 222, 223], and performance.[214, 224] Strength, endurance and performance related differences in F-T curves have been attributed to several physiological factors including muscle fiber type composition[100, 216, 218, 221, 225], muscle cross-sectional area[226], stiffness of muscle-tendon complex[227], and neural drive to the muscle.[215, 228-231]

Strength training, including heavy-resistance and speed training, has been found to change F-T curve characteristics, such as peak force and rate of force development (RFD).[98, 99, 215, 229, 232] Strength training causes a muscle to undergo rapidly occurring neural adaptations as well as gradually occurring hypertrophic adaptations. A stronger

neural drive has been associated with increases the RFD, whereas muscle hypertrophy primarily increases peak force.[98, 99, 215, 228, 229, 232]

In relation to grip strength, F-T curve characteristics based on the force-generation phase[100, 207-209] and the force-decay phase[96] have been used to investigate maximal isometric contractions. Bemben et al.[100] indicated that F-T curve characteristics, including rate of force development (force generation), can reliably identify age related changes in explosive grip strength. Explosive strength has been defined as "the rate of rise of contractile force at the onset of contraction, i.e. the rate of force development (RFD) exerted within the early phase of rising muscle force."[229] Bemben et al.[100] also indicated that F-T curves allow for successful implementation of strength training programs among older men, who may be concerned with fear of injury. Demura et al.[207-209] studied explosive grip using multiple F-T curve characteristics, including the RFD (force generation). Demura et al.[207-209] found the F-T curve characteristics to be larger in stronger subjects[208], and different between males and females.[209] Moreover, the force-generation phase of explosive grip was found to be more reliable than slow maximal grip.[207] Although, F-T curve characteristics of explosive strength tests have been found more reliable than slow strength tests, it may be safer to use slow strength tests in people with injuries as the explosive tests may cause re-injury.

Healthcare

Among people with injuries, the F-T curve characteristics of slow grip strength trials seem to be most appropriate for identifying muscle function. When compared to explosive grip strength test, the slow maximal grip strength test seems to be safer. Explosive grip requires the gripping to be performed as fast and forcefully as possible. In contrast, the slow grip allows a person with an injury to determine their own motor unit

recruitment strategy.[28, 207] Two studies have been performed to identify the effect of injury on the F-T curves of grip strength.[211, 212]

Helliwell et al.[212] measured grip strength in people with rheumatoid arthritis (RA) using a torsion dynamometer. Study participants consisted of 33 females and 13 males with a mean age of 57 years. The participants gripped the dynamometer 3 times with a rest period lasting a few seconds between trials. The F-T curves generated from each grip lasted 4.4-s and generated 6 characteristics: maximum grip strength, time to maximum value, fatigue rate, amount of fatigue, release rate, and power factor. The study identified adequate reproducibility of the 6 characteristics, with moderate reproducibility of time to maximum value and fatigue rate. Helliwell et al.[212] also reported 2 phases of the F-T curve: an initial steep rise in grip strength, and a subsequent slower decline after achieving peak strength.[212] Similar phases of the F-T curve have been reported in people without injuries.[95, 96] Therefore, it appears that the shape of an F-T curve remains the same in presence and absence of injury.

Hakkinen et al.[211] studied changes in shape of knee extensor F-T curves as a result of strength training and detraining. The study participants included 20 healthy people and 43 people with recent-onset rheumatoid arthritis (RA). Participants with RA were randomly divided into an experimental and a control group. The experimental group participated in a progressive strength training program for 6 months. In contrast, the control group maintained their habitual physical activities. With the knee positioned at 100°, the participants exerted maximal effort as rapidly as possible and maintained it for approximately 5-s. The David 200 dynamometer was used to record the maximal voluntary isometric F-T curves at 0, 6 and 42 months. The F-T curves at 6 months

indicated the training effect and at 42 months indicated the detraining effect. The study found that participants with RA took longer than healthy participants to produce the same level of force at 0, 6 and 42 months. At 6 months, the shape of the F-T curve did not change significantly in the experimental group, most likely because the participants did not perform explosive-type training.[211]

Maximal Effort

Physiological basis. The F-T curves generated on exerting maximal effort differ from curves of submaximal effort, which can be described on the basis of work by Kroemer and Marras.[188] During submaximal contractions, continuous feedback signals control muscle output by modifying muscle fiber firing rate and muscle fiber recruitment. During maximal contractions, central nervous system sends out the commands to recruit all available fibers at their highest firing rates. Hence, submaximal effort involves a slower buildup of force than in maximal effort.[29, 101, 188] Further, motor units fire asynchronously during submaximal efforts and fire synchronously during maximal or near maximal efforts.[233]

Previous studies. The F-T curves generated from isokinetic[234] as well as isometric[29, 55, 101] muscle contractions have been used to identify submaximal effort. Fishbain et al.[234] developed an isokinetic test using the shoulder press and pull-down movement. The study included 34 healthy participants (18 males and 16 females) who performed the isokinetic movement on the Ariel machine. The participants exerted 6 best effort strokes, followed by a 1 minute rest period, and then repeating the 6 strokes giving a faking effort. Mathematical analysis of the F-T curves generated 80 different characteristics. Further, discriminant analysis was performed to identify the three best characteristics for males and females. For males, the characteristics were found to be duty

cycle down, work weight/down, peak value down, and the characteristics for females were average power up, 40% repetition down, and duty cycle up. The resulting discriminant functions were used to identify predictive validity of the test. In a hold out group of six males, the test classified 75% of the efforts correctly with a sensitivity value of 0.83 and a specificity value of 0.67. This is an important study as it identified the predictive validity of the F-T curve characteristics. Sincerity of effort tests have been rarely tested for their predictive validity, which needs to be identified because "the predictive models or cutoff scores obtained from validation studies should always be cross-validated on a second sample to determine if the test criteria can be generalized across samples" (p. 107).[92] However, Fishbain et al.[234] used statistical performance instead of physiological interpretation to select F-T curve characteristics. The authors do not describe why these F-T curve characteristics can distinguish between maximal and submaximal effort. Hence, these characteristics should be used with caution.

Three studies have used F-T curve characteristics generated from isometric grip contractions to identify submaximal effort.[29, 55, 101] In 1983, Gilbert and Knowlton[29] distinguished maximal and submaximal effort using the F-T curves. The study included 36 participants randomly assigned to either a sincere or faker group. The sincere group performed maximal voluntary grip contraction (MVGC) and faker group performed 75% MVGC using a specially designed grip dynamometer. The resulting F-T curves were analyzed for the following characteristics: rate of force application (SLP), peak force (PK), ratio of average force to peak force (DEV), and ratio of peak force to body weight (WTRATIO). The sum of z-scores of all the variables for each subject correctly identified effort in 87.5% of the females (N = 16) and 80% of the males (N = 20). Discriminant

analysis, performed by gender, revealed DEV to be the only significant predictor of effort for females, and DEV, SLP and WTRATIO to be significant predictors for males. This study suggested that F-T curves can be used to distinguish between maximal and submaximal effort.[29] This study, however, did not identify the ability of F-T curves to distinguish between maximal and submaximal effort exerted by the same participant.

Around 1990, Smith et al.[55, 101] assessed the differences between maximal and submaximal effort using F-T curve characteristics of the plateau phase: ratio of average and peak force, coefficient of variation, peak-average difference, and peak-average root difference. A predictive equation combined these characteristics in order to identify submaximal effort. The equation revealed the peak-average root difference to be the most important characteristic.[55, 101] However, this characteristic does not seem to be valid. The peak-average root difference deals with such small variability that it requires multiplication of 10^8 and is subject to a significant round-off error. Currently, these characteristics are not used to detect submaximal effort in either the clinic or in research studies.[28]

In a recent study, we found that the slopes of the force-generation phase and the force-decay phase two phases of the F-T curve successfully differentiated between maximal and submaximal grip effort in healthy subjects. The Receiver operating characteristic (ROC) curves identified the best combinations of sensitivity and specificity values for the slopes. We found excellent sensitivity and specificity values for the slopes, with sensitivity values ranging from 0.8 to 0.93 and the specificity values ranging from 0.93 to 1.0. Also, the lowest overall error rates ranged between 7% and 33%.[28] These error rates are excellent when compared to the error rates of the five-rung test, rapid

exchange grip test and the coefficient of variation, which range from 47% to 69%.[27, 65, 93] The grip efforts in the pilot study were recorded using the Biopac dynamometer, which has been identified to be reliable and valid for measuring grip force.

Biopac Dynamometer

The Biopac TSD121C hand dynamometer has a force sensor, whose reliability and validity have been established by using precision weights[235] and human participants.[236] Reliability with precision weights was established using repeated measures, both within a single testing session and over several occasions. After being spanned with a mass of 89.36 kg, masses weighing 79.2, 49.41, 29.67 and 9.59 kg were suspended from the dynamometer to measure the output. Each testing session comprised of 8 loading procedures, moving alternately down and up the measurement scale. This protocol was repeated on 3 separate occasions over 3 weeks. The mean coefficient of variation (CV) and their 95% confidence intervals (CI) assessed the reproducibility of the mass measurements. The mass measurements were found to be highly reproducible during a single testing period and over separate testing occasions (mean CV ranged from 0.4 to 0.8 and their CI ranged from 0.3 to 1.2). Therefore, the Biopac dynamometer has been found to be reliable in measuring weights in the range of 0-90 kg under laboratory conditions.[235]

Validity was established for both single and multiple sessions by performing repeated measures at one time and over several occasions. After being spanned with a mass of 9.59 kg, masses weighing 9.59, 29.67, 49.41 and 79.2 kg and were suspended from the dynamometer to measure the output. Each testing session comprised of 3 loading procedures, moving alternately up and down the measurement scale. The entire procedure was replicated with span masses of 29.67, 49.41 and 79.2 kg. The entire protocol was performed at 3 occasions over 3 weeks.[235] Bland and Altman's 95% limits

of agreement (LOA) were used to compare the actual mass to mass measured by the dynamometer. The LOA revealed that the span mass of 0-29.67 kg provided the most accurate agreement between measured and actual values.[235]

Surface Electromyographic Activity

Electromyography can be defined as the study of electrical activity of a muscle.[237] To produce muscular contraction, muscle fibers receive an impulse from a motor neuron. The motor neuron is activated by electrical impulses that originate in the brain and travel via the spinal cord to the motor neurons. On reaching the motor neurons, the electrical impulses are propagated to the motor endplate resulting in ionic changes that generate the muscle fiber action potential[237], which is recorded as electromyographic (EMG) activity. The following section describes the origin and propagation of EMG signal.

Origin and Propagation

The impulses that stimulate muscles originate in the motor cortex of the CNS. The motor cortex, lying in front of the central sulcus in the brain, has contralateral control over movements. Specific body parts move on the right side of the body on stimulating different regions of the left motor cortex. This representation of the whole body in the motor cortex has been referred to as the motor homunculus. Hence, impulses that activate forearm muscles originate in the region that represents the forearm in the motor homunculus. Specifically, most of these impulses originate in the pyramidal cells of layer V of cortex. The pyramidal tract then transmits these impulses down the spinal cord.[237, 238]

The pyramidal tract (PT) is one of the five major tracts that descend from the brain to the spinal cord. The PT originates in motor cortex and Betz cells (large pyramidal cells). From the motor cortex, this tract travels through the internal capsule and the

middle of cerebral peduncles. At the level of the medulla, it forms into discrete bundles called the pyramids and hence named the pyramidal tract.[238] In the spinal cord, the pyramidal tract divides into two separate tracts. At the lower level of the medulla, 90% of the pyramidal tract crosses over to the opposite side forming the lateral corticospinal tract. The remaining tract, which does not cross over, forms the anterior corticospinal tract.[238-240]

The lateral and anterior corticospinal tracts ultimately end on motor neurons in the ventral horn of the spinal cord. Afferents from interneurons and receptors as well as fibers from other descending tracts also end on these motor neurons. The motor neurons represent the ultimate path through which all nervous excitation related to a motor act must pass and thus have been called the 'final common path.' These motor neurons also have an orderly and systematic arrangement. For example, medial neurons innervate the trunk muscles and the most lateral neurons innervate the most distal parts of the limbs.[239]

The motor neuron action potential arrives at the neuromuscular junction and releases acetylcholine (ACH). The release of ACH depolarizes the postsynaptic membrane. By a passive process, this depolarization spreads in both directions of the neuromuscular junction. This spread occurs in both directions along the length of the muscle fiber. The deeper portions of the muscle fiber also require electrical stimulation, which occurs via the transverse tubular system. Transmission of the depolarization stimulus through the transverse tubules releases calcium in the sarcoplasmic reticulum. Ultimately, this calcium release assists in the breakdown of ATP that provides energy for muscle contraction. When transverse tubules and sarcoplasmic reticulum get depolarized, it results in a depolarization wave along the direction of muscle fibers. These

depolarization waves, and subsequent repolarization waves, are observed by recording electrodes as EMG activity.[237, 241]

A muscle uses two different strategies to increase the muscular force output – recruitment coding and rate coding. Recruitment coding means 'sequence of motor unit activation.' Muscles produce higher forces by following the size principle. That is, smaller motor units are recruited first, and successively larger motor units are recruited as the force requirement increases.[189, 192, 194, 237] Rate coding means 'frequency of motor neuron firing' which represents how frequently the motor units are activated by the nervous system. As the firing rate of the motor unit increases, it produces an increasing amount of muscular force.[189, 192, 193, 237]

Signal Properties

The electromyographic (EMG) signal is a time-varying signal that conveys information about muscle activity. Any time-varying signal has four properties: amplitude (a), offset (a_0), phase angle (θ), and frequency (f). The amplitude (a) represents the magnitude of the signal. The dimension for measuring amplitude depends on the type of signal.[121] For example, amplitude of an electrical signal may be measured in volts (V), a unit of electrical potential or electromotive force. The offset (a_0) represents average value of the signal.[121] The dimensions of the offset depend on the type of signal. For example, the offset for an alternating current (AC) is zero volts. The phase angle (θ) is the amount of time the signal is shifted in time.[121] The phase angle may be measured in degrees (°) or radians (r). The frequency (f) represents how rapidly the signal oscillates and is usually measured in cycles per second (s) or hertz (Hz). One hertz (Hz) equals one cycle per second.[121]

Amplitude and frequency. The EMG signal properties frequently analyzed and interpreted include its amplitude and frequency.[237] The amplitude can be computed in several different ways, including average rectified amplitude and root mean square amplitude. The normal EMG signal is an alternating current and mean of such a signal is zero. Therefore, to compute the averaged amplitude the signal must be rectified, which involves converting the negative voltage to positive values. The average of all voltage values results in the average rectified EMG amplitude.[237] In contrast, the root mean square EMG amplitude does not require rectification of the EMG signal as it integrates the squares of EMG voltages recorded for a period of time. The square-root of the integrated EMG voltage results in the root mean square EMG amplitude.[237]

The frequency of EMG signal is commonly computed using 2 different methods: identifying turning points and zero crossings as well as by identifying mean or median spectral frequency. “Turning points” is calculated by counting the number spike peaks per unit time. Each peak represents an instance when the signal changes its direction. Therefore, counting the number of peaks indicates the frequency the signal. Similarly, the number of times the EMG signal crosses zero volts in a unit time indicates the frequency of the signal. Counts of turning points and zero crossings provide an estimate of EMG signal frequency.[237] In contrast, the frequency distribution of EMG signal can be identified using spectral analysis. The EMG signal is a time-varying signal that can be mathematically represented by successively adding its individual frequencies (f_n).[120, 121] The mathematical conversion used to identify the individual EMG frequencies is termed the Fourier Transformation.[121] For each frequency (f_n) in the signal, the Fourier transformation calculates a power, which indicates the amount of signal composed of that

frequency (f_n). The plot of frequency along the X-axis versus the power of the frequency along the Y-axis results in a graph that is commonly termed as the power spectrum or the frequency spectrum.[121] The mean or median frequency of the power spectrum has been commonly used to represent the frequency of the EMG signal. The mean frequency is a frequency that represents the average power of the power spectrum. In contrast, the median frequency represents the frequency that divides the power spectrum into two regions with equal power, i.e. the parts of the spectrum above and below the median frequency have equal distributions of power.[105] Also, when compared to mean frequency, median frequency is less susceptible to noise in the signal.[242]

Increasing Force

Literature provides several explanations for EMG changes with increasing muscle force. Force-related changes in amplitude and frequency have been associated with changes in motor unit recruitment as well as motor unit firing rates.[237] Several studies have identified a high correlation between perceived effort and amplitude of surface EMG.[2, 243, 244] The amplitude of EMG signal represents magnitude of muscle activity, which predominantly increases due to increase in the number of active motor units as well as the motor unit firing rate. The firing rate of motor units represents the frequency of activation of motor units by the nervous system.[237] Suzuki et al.[245] found that as the force being generated by a muscle increased, the motor unit voltage increased to the same degree as mean absolute surface EMG amplitude. This increase implies that motor unit size and firing rate explain the increase in mean absolute surface EMG amplitude with increasing force generation.[245]

The frequency of EMG signal also changes with increase in recruitment and firing rate of motor units. Increase in active motor units results in an increase in the number of

spikes and turns in the surface EMG signal. Similarly, the frequencies of EMG signal change with motor unit firing rate.[237] According to Hermens et al.[246], the EMG power spectrum usually has a pronounced peak in the region of 10-25 Hz. Other authors have also observed this peak.[247, 248] This low frequency peak, according to some models,[249, 250] represents the mean firing frequency of the active motor units. During an increase in force, this low frequency peak may change: its standard deviation increases as well as it shifts to the right. If an increase of force does not show any shift in the peak, it is reasonable to assume that the increase of force is mainly caused by an increase in the number of active motor units.[246]

Gander et al.[248] reported that the frequency spectrum shifts to higher frequencies with an increase in muscle force. Hagberg and Ericson[251] found an increase in mean power frequency when force increases from 0 to 40%. They attributed this change to low level of tissue filtering. That is, as contraction level increases, larger motor units closer to the surface are recruited; the electric signal from these fibers suffers less high frequency attenuation through the overlying tissue; and thus the power spectrum shifts to higher frequencies.[248, 251] Although recruitment/tissue filtering is in part responsible for the increase in mean power frequency, firing rate also increases with contraction level.[248, 252] Also, the average firing rate of active motor units is apparently manifested as a low frequency peak in the power spectrum. The frequency of this peak has been observed to increase with muscle force even at low contraction levels.[247, 248, 253] Therefore, a combination of both recruitment and rate coding is a responsible for the increase in mean frequency.[248]

Fatigue

It is well documented that a sustained forceful contraction often causes muscular fatigue, which shifts the EMG power spectrum to a lower frequency.[254-260] As early as 1912, a fatiguing contraction was found to result in a decrease in the Piper rhythm[256, 261], which is the tendency of motor unit potentials in steadily contracting human muscles to group in the range of 40-60 Hz.[262] Cobb and Forbes[261] observed an increase in the amplitude of the EMG signal along with a decrease in the Piper rhythm. Kogi and Hakamada[254] found that the increase in EMG amplitude was due to an increase in the lower frequency region of the power spectrum. Furthermore, fatigue was found to result in an increase in the lower frequency spectrum[255] as well as a decrease in the higher frequency spectrum[255, 263, 264], which clearly indicated a shift in the power spectrum towards the lower frequencies.[260]

A fatigued muscle has a reduced ability to produce tension when excited. In an effort to compensate for the decrease in force of contraction, recruitment of motor units takes place.[105, 193, 265, 266] An increase in number of active motor units progressively increases the electrical activity.[265] The power spectral shift to lower frequencies as a result of fatigue has been explained using three physiological mechanisms: 1) motor unit de-recruitment[193, 265-267] and motor unit synchronization[193, 255], 2) conduction velocity[256, 259, 268, 269], and 3) shape of muscle action potential.[269] 1) The shift to lower frequencies as explained by motor unit de-recruitment occurs as a muscle fatigues. The replacement of some of the fast twitch motor units with lower frequency fatigue-resistant units decreases the higher frequency spectrum.[255, 260] Motor unit synchronization has also been proposed as a mechanism for the spectral shift. An increase in lower frequency content has been suggested to result from increased synchronization of motor units.[255, 260] 2) Lindstrom et

al.[256] identified a reduction in conduction velocity along with a downward spectral shift during a fatiguing contraction. The velocity and spectral changes were attributed to a strong contraction that occluded blood flow through the muscle. The subsequent lack of oxygen resulted in anaerobic metabolism, and therefore, accumulation of lactic acid, which, in turn reduced the intracellular pH. A decrease in pH slows down the conduction velocity causing the action potential to become more "sluggish" and yielding a reduced higher frequency content of the power spectrum.[256] 4) Kranz et al.[269] examined the median frequency of EMG spectrum as well as compound action potential (CAP) of 45-s maximal contractions of thenar muscles. As the contraction progressed, they found that spectrum shifted to the lower frequency region and the CAP shape widened indicating that the two phenomena are related. They suggested that a muscle contraction imposes a metabolic load on the muscle, which alters its electrical properties. Altered electrical properties slow the muscle action potential conduction velocity that causes the action potential to widen as well as shift of power spectrum to a lower frequency region.[269]

Injury

Generally, the EMG patterns vary according to the disease and according to the technique used to record EMG signal.[270] Several studies have identified EMG changes as a result of cumulative trauma disorders and central neurological disorders. Bauer and Murray[271] measured surface EMG output of forearm flexors, forearm extensors and triceps brachii muscle to detect lateral epicondylitis. People with lateral epicondylitis, during simulated play, had earlier, longer and greater activation of forearm extensors when compared to individuals not suffering from the condition.

Needle EMG findings in carpal tunnel syndrome (CTS) can be useful in detecting denervation/reinnervation of pronator quadratus (PQ), flexor pollicis longus (FPL) and

two lateral heads of flexor digitorum profundus (FDP). Presence of spontaneous activity in form of fasciculations or positive waves indicates denervation. In contrast, polyphasic motor unit potential (MUP) and increased amplitude and/or duration of MUP indicates reinnervation of these muscles.[272] Ogura et al.[106] used power spectral analysis to assess the compound muscle action potential (CMAP) in CTS. The study included 50 healthy people and 24 people with CTS. The CMAP was obtained from the abductor pollicis brevis muscle with supramaximal stimulation (rectangular waves, duration: 0.2 ms) of the median nerve. Using the Hanning window function and fast Fourier transformation (FFT) a power spectrum of the CMAP was obtained, which was used to calculate the mean and peak spectral frequencies. On an average, people with CTS had smaller mean and peak frequencies than healthy people. In people with CTS, a negative correlation was found between distal latency of CMAP and mean frequency. The decrease in mean frequency was associated with temporal dispersion of the CMAP at the entrapped site. In people with muscle atrophy, the reduced frequency was associated with reduction in number type II muscle fibers, which are associated with a high frequency component of the spectrum.[106]

In stroke, on observing activity of biceps brachii and brachioradialis after sustained exercise, median frequency of surface EMG output decreased on the non-paretic side and not on the paretic side. This suggested that a bout of sustained activity significantly alters ability of central nervous system to activate muscles in the paretic arm, but, not on the non-paretic arm.[273]

Sanjak et al.[210] evaluated muscle fatigue during 30 seconds of maximal voluntary isometric contraction (MVIC) by simultaneously measuring force as well as surface

EMG output. Elbow flexor and ankle dorsiflexor muscles were evaluated in 13 people with amyotrophic lateral sclerosis (ALS) and 13 normal controls (NC) for fatigue by comparing the first 5-s to the last 5-s of the contraction. Mechanical fatigue, represented by decline in force output, was expressed as the force fatigue index (FFI). Myoelectric fatigue, represented by compression in the EMG power spectrum, was identified by calculating the median frequency shift (MFS). People with ALS, when compared to NC, had a greater value of FFI and a smaller value of MFS. The dissociation between FFI and MFS was explained by selective atrophy of type II (fast glycolytic, fast oxidative) muscle fibers and/or higher prevalence of type I (slow-twitch oxidative) muscle fibers. A shift in the power spectrum to lower frequencies during fatigue has been suggested to primarily occur because of a decrease in muscle fiber action potential conduction velocity (MFCV), which is greater in type II fibers than type I fibers. Therefore, type I fibers have inherently lower frequency content than type II fibers, which are de-recruited with fatigue. Presence of fewer type II fibers would indicate a lower MFS.[210]

Maximal Effort

In 1987, Janda et al.[30] used of electromyographic (EMG) recordings to characterize normal grip patterns. Four healthy people, representing different hand sizes, performed maximal grips at the 5 handle positions of the Jamar dynamometer. The EMG signal was recorded from the forearm flexor area and dorsum of hand. Neither did the authors indicate the location of recording electrodes nor did they indicate specific muscles used for recording EMG signal. Janda et al.[30] found that the forearm flexor muscles were active at all the handle positions whereas the intrinsic hand muscles were only active while gripping the narrower handle positions. It was also suggested that the force

recordings obtained from repeated maximal voluntary grip effort would be more reproducible than recordings from submaximal grip efforts.[30]

In 1990's, Niebuhr and coauthors[31, 32, 89] used EMG signal to distinguish between maximal and submaximal grip effort. The EMG signal was recorded from flexor carpi radialis (FCR) and palmaris longus (PL) muscles as they have been reported to represent total active flexor musculature during handgrip maneuvers.[30-32] The EMG activity of a submaximal grip effort was found to have smaller amplitude than that of a maximal voluntary effort.[31, 32, 89] Niebuhr et al.[31, 32, 89], however, reported conflicting findings regarding the mean power frequency (MPF). The MPF of a submaximal grip effort was reported to either be greater than maximal voluntary effort[31] or not to be different than that of maximal voluntary effort.[32, 89] A primary advantage of using EMG signal for identifying submaximal effort is that the EMG output is highly consistent over measurement sessions.[89] However, EMG signal of submaximal effort showed equal amount of variability when compared to maximal effort. Hence, variability of EMG cannot be associated with level of effort.[89] In conclusion, forearm muscle EMG properties have the potential of being a valuable adjunct for clinicians involved in identifying submaximal grip effort.[32]

It is not clear how muscle activity is impacted by pain. There is mostly agreement regarding effect of pain on voluntary effort. Studies have demonstrated that pain is associated with decreased voluntary electromyographic (EMG) activity[11, 12], shorter endurance time[13], decreased motor unit discharge rates[14, 15] and decreased γ-motor neuron activity.[16] However, there is a disagreement regarding involuntary motor activity. Pain has been found to be associated with unaltered activity of α-motor neurons[274] and γ-motor

neurons.[275] Yet other studies show that pain is related to increased involuntary (reflexive) muscle activity including transient increases in resting EMG levels[276] and increased activity of γ-motor neurons resulting in muscle spasm.[274, 276-280]

Pain

Over the past century, the understanding of the behavioral, psychological and physiological aspects of pain has been transformed. One significant transformation has been a paradigm shift in the understanding of neural mechanisms underlying a pain experience – from a linear mechanism to a nonlinear mechanism[70, 281] In other words, earlier paradigms explained pain experience as an end product of linear sensory transmission of noxious stimuli.[282, 283] Instead, current paradigms explain pain experience as a dynamic process that involves continuous interaction among ascending and descending pathways of the nervous system.[283, 284] This dynamic process begins with an injury or a disease that produces pain signals. Pain signals, after originating in the periphery, enter the central nervous system (CNS). The CNS is an active system influenced by culture, stress, anxiety and depression among other factors. The CNS selects, abstracts, and synthesizes pain signals with other sensory signals. Therefore, pain is a complex experience influenced by attitudes and responses of people including past experiences, meaning of a situation, attention and other psychological variables.[69, 70] The complex nature of a pain experience has been succinctly captured in the definition of pain by the International Association for the Study of Pain (IASP). The IASP defines pain as "an unpleasant and emotional experience associated with actual or potential tissue damage, or described in terms of such damage."[285, 286] This definition, among other components, describes pain as an unpleasant and unwanted experience. Nevertheless, pain serves an important function in humans: protection.[287]

Pain protects humans by warning of occurrence of biologically harmful processes.[287] For example, people protect themselves from burns, bruises and wounds primarily due to reflex activity but also because of associated emotional arousal. Reflexes, regulated at the level of spinal cord, protect by removing a body part away from danger.[288] Quite often, associated emotional arousal, experienced as distress or fear, may also motivate a person to move away from a painful stimulus.[289] Fear of pain can also prevent a person from moving, which in turn promotes healing of the injury resulting in that pain.[290] Additionally, from the perspective of evolutionary biology, pain may elicit an empathic, comforting, and health promoting behavior in people observing a person in pain. Observers react in a parental nature by taking care, assisting and consoling a person in pain. Such pain reactions result from mammalian phylogeny, i.e. to serve in the well-being of their young.[291] Hence, pain acts as a warning system that activates protective mechanisms in people experiencing pain and parental mechanisms in people around them. These mechanisms promote safety and recovery. In contrast, pain can interfere with daily functioning of a person.[292] Pain may interfere with daily functioning when it prevents people from performing their social roles, vocational roles, and impacts their psychological well-being.[290] To appreciate this duality of pain, i.e. protective and interfering nature of pain, one must understand the CNS mechanisms of pain transmission and regulation.

Transmission of Pain Sensation

Four specific parts of the nervous system transmit pain signals from the periphery to the higher centers of the CNS: 1) the nociceptors, 2) the dorsal horn neurons, 3) the ascending tracts, and 4) the supraspinal projections. Nociceptors, one type of somatosensory receptors, are the first order neurons of pain pathways. These receptors

generate pain signals in response to harmful stimuli. Different types of nociceptors have been identified that respond to mechanical, heat and chemical stimuli or any combination of these stimuli. Cell bodies of the nociceptors reside in the dorsal root ganglia (DRG). Nerve fibers leaving the DRG bifurcate and send one branch to the periphery and the other branch to the dorsal horn (DH). The peripheral fibers conduct pain signals from the skin, muscles, fascia, vessels, and joint capsules to the DRG.[293, 294] Peripheral fibers transmitting pain and other somatosensations, and therefore called the sensory peripheral fibers, have been classified into three types based on their diameter, myelination and conduction velocity: the A-fibers (with four subtypes – α, β, γ and δ), B-fibers and C-fibers. The C-fibers and A-δ fibers conduct pain signals, but, at different velocities.[294] A-δ fibers conduct fast pain (a sensation immediately after an injury that indicates location of injury) and C-fibers conduct slow pain (follows sharp pain and can be characterized as a dull, throbbing ache with poor localization).[293, 294] Fibers entering the DH synapse with the second order neurons.[294]

Two types of second order neurons perceive pain: nociceptive specific (NS) neurons and wide dynamic range (WDR) neurons. The NS and WDR neurons conduct pain signals to the brain via various ascending tracts in the spinal cord. Primarily, the NS respond to noxious stimuli while the WDR respond to both innocuous and noxious stimuli.[292, 294] Table 2-3 summarizes other differences between these neurons.

Axons of the second order neurons (the NS and WDR neurons) form the ascending tracts, through which pain signals travel in the spinal cord. Different ascending tracts conduct fast and slow pain signals. Fast pain travels via the neospinothalamic tracts. The fast pain transmitting A-δ fibers predominantly terminate on the nociceptive specific

(NS) neurons in laminae I and II of the DH. The axons of the NS neurons cross the midline of spinal cord in the anterior white commissure. The crossed NS axons ascend to the thalamus as the neospinothalamic tract. In contrast, slow pain travels via multiple parallel ascending pathways. The slow pain transmitting C-fibers terminate on interneurons in laminae I, II, and/or V of the DH. The interneurons synapse with wide dynamic range (WDR) neurons in laminae V to VIII of the DH. The WDR axons ascend to the midbrain as spinomesencephalic tract, reticular formation as spinoreticular tract, and thalamus as paleospinothalamic tract. Slow pain signals primarily ascend via the paleospinothalamic tract. The other two tracts serve functions of arousal, motivation, reflexive function, and activation of descending fibers.[293]

Supraspinal projections can also be divided on the basis of which fibers conduct slow pain and which fibers conduct fast pain. The NS axons, that conduct fast pain, mostly end in the ventral posterolateral (VPL) nucleus of the thalamus. Third order neurons arise from the VPL nucleus and project to the primary somatosensory cortex (SI) and the secondary somatosensory cortex (SII). These projections allow for interpreting sensory features of pain, which includes location, intensity and quality of pain.[293-295] In contrast, the tracts conducting slow pain (the spinomesencephalic, spinoreticular, and paleospinothalamic tracts) terminate in different areas of the brain. The spinomesencephalic tracts conduct pain signals to the superior colliculus and periaqueductal gray and finally to the hypothalamus and raphe nuclei. These areas assist in turning the eyes and head towards the noxious stimulus. The spinoreticular tracts terminate in the reticular formation in the brainstem. The paleospinothalamic tracts project to the midline and intralaminar nuclei of the thalamus. These nuclei further

project to basal ganglia, prefrontal cortex, anterior cingulate cortex, and primary motor cortex. Together, activity in the spinoreticular and paleospinothalamic tracts results in arousal, withdrawal, and, autonomic and affective responses to pain.[292, 293]

Brain activity studies have implicated several supraspinal centers to be involved in processing and modulating pain signals. These supraspinal centers can be divided into subcortical and cortical areas. The subcortical areas most notably activated by pain signals include thalamus, basal ganglia, and cerebellum. In contrast, commonly reported cortical areas include somatosensory cortices (SI and SII), anterior cingulate cortex and insular cortices, prefrontal cortex, and motor and pre-motor cortex. These areas serve different purposes when a person experiences pain. Specifically, the somatosensory cortices have been implicated in interpreting sensory features of pain. The anterior cingulate cortex and insular cortices, both components of the limbic system, have been implicated in affective processing of pain. Moreover, prefrontal cortical areas, as well as parietal association areas, are also sometimes activated in response to noxious stimuli and may be related to cognitive variables, such as memory and stimulus evaluation. Motor and pre-motor cortical areas, also activated on occasion by pain stimuli, have been suggested to be related to pain epiphenomena, such as suppression of movement or actual pain evoked movements.[295] Hence, a noxious stimulus originating in the periphery travels through multiple transmission systems to reach various parts of the CNS. The CNS does not receive a noxious stimulus passively. Rather, it processes this stimulus using various regulatory mechanisms.

Regulation of Pain Sensation by the Nervous System

Passive transmission of noxious stimuli cannot explain how people experience pain. Rather, their pain experience can be explained by an active process. This active

process includes several regulatory mechanisms that participate in attenuating or accentuating the perception of a noxious stimulus.[294] An accentuated pain experience can be associated with factors such as edema, fear, anxiety, and release of endogenous chemicals that sensitize nerve endings.[296] Two spinal cord level mechanisms explain an accentuated pain experience: 1) wind-up, and 2) central sensitization.

1) In 1965, Mendell and Wall coined the term "wind-up" to describe a gradual increase in discharge frequency of the WDR neurons on repeatedly stimulating the C fibers at a low frequency.[294, 297] Furthermore, a low frequency noxious stimulus (> 3 Hz) results in progressively greater pain. Physiologically, this temporal summation of pain can be explained to be similar to wind-up. Temporal summation of pain is exaggerated in neuropathic pains and can only be evoked by activation of C fibers.

2) Central sensitization includes a complex sequence of chemical events that result in an increased responsiveness of the nociceptive dorsal horn neurons, which results in enhanced conduction of pain signals to the brain. For example, following cutaneous injury, an area of undamaged skin adjacent to the damaged tissue can be stimulated to evoke pain by either an innocuous stimulus (secondary allodynia) or more pain by a previously painful stimulus (secondary hyperalgesia). The nociceptors supplying area of secondary allodynia and hyperalgesia are not sensitized. However, central sensitization occurs due to input from nociceptors that supply an area of damage. Input from these nociceptors leads to a transient central sensitization.[298] Hardy et al.[299] provide a physiological explanation of this phenomenon. According to their model, active nociceptors produce pain signal, which in turn primarily activates the spinothalamic tracts (STT). These nociceptors also activate neural circuits in the spinal cord dorsal horn that

also sensitize other STT cells that receive input from mechanoreceptors and nociceptors that supply an adjacent, but uninjured, region. Therefore, enhanced response of these STT cells to innocuous and noxious stimuli applied to uninjured skin results in secondary allodynia and hyperalgesia.[298, 299]

In contrast, two classic examples describe how regulatory mechanisms can attenuate pain. First, after injuring a hand, a person may shake it vigorously to reduce pain sensation. Second, an athlete, although injured during a game, may not feel injury related pain until end of game. Regulatory mechanisms that attenuate pain act at four levels of the CNS: 1) the dorsal horn (DH; includes second order neurons of ascending pain pathways), 2) the descending fibers (from periaqueductal gray, raphe nuclei, and locus ceruleus), 3) hormonal system (cells located in the hypothalamus, pituitary gland, and adrenal medulla), and 4) cerebral cortex (prefrontal cortex, insular cortex, and amygdala). The most understood mechanisms that attenuate pain occur in the substantia gelatinosa of the DH, and, through descending fibers originating from the periaqueductal gray, raphe nuclei, and locus ceruleus.

1) Mechanisms that attenuate pain at the dorsal horn (DH) have their basis in the gate control theory.[283] According to the gate control theory, first order pain neurons (nociceptors) and second order pain neurons (WDR neurons) receive inhibitory signals from non-nociceptive A-β afferents. The A-β afferents are fast, myelinated, large diameter sensory peripheral nerves that arise from muscle spindles, golgi tendon organs, joint receptors or cutaneous tactile receptors. Increased activity of these fibers inhibits the WDR neurons in the DH, which are predominantly stimulated by the C fibers.[292, 294]

Inhibition of the WDR neurons reduces pain signals reaching the brain, which reduces level of pain perceived, and, therefore attenuates pain experience.

2) Descending fibers also attenuate pain experience.[294] The axons of the raphe nuclei, which receive information on noxious stimuli from periaqueductal gray, descend in the spinal cord via the dorsolateral funiculus. Their axons form the descending fibers that attenuate pain. These fibers attenuate pain experience by strongly inhibiting the second order pain neurons in the laminae I, II or/and V of the DH. This inhibition of the second order pain neurons reduces conduction of pain signals that travel from the periphery to the higher centers in the brain.[292]

3) The action of β-endorphin (BE), which is formed by activity of the hypothalamo-pituitary-adrenocortical (HPA) axis, attenuates pain resulting from injury in situations such as accidents, disasters, or athletic contests. In such situations, an injured person may have a delayed onset of pain, i.e. pain begins at the end of an emergency or a contest. A delayed pain results partly because of BE that acts as a potent analgesic with its effect lasting a few hours.[285, 296] The release of BE from the HPA axis, in presence of noxious stimulus, can be explained by a group of neuronal projections.[285] These projections include pathways ascending from the second order pain neurons in the DH of the spinal cord to the medial and lateral hypothalamus and several telencephalic regions, and pathways from the medullary reticular formation via the ventral noradrenergic bundle (VNB) to the periventricular gray of hypothalamus. The periventricular gray, which acts as the coordinating center of the HPA axis, responds to noxious stimuli (received from ascending pathways originating in the DH) by initiating a complex series of events regulated by feedback mechanisms. In response to noxious stimuli, the periventricular

gray synthesizes and releases corticotropin-releasing hormone (CRH) into the portal circulation. This CRH stimulates the anterior pituitary gland to secrete several pro-opiomelanocortin derived neuropeptides into systemic circulation.[285] These neuropeptides include adrenocorticotrophic hormone (ACTH) and BE.[285, 300] BE binds with opiate receptors in the brain and the DH to result in analgesia.[285, 296, 300] The amount of BE formed is regulated by ACTH, which stimulates the adrenal cortex to release corticosteroids such as hydrocortisone and corticosterone. These corticosteroids provide feedback to the regulatory processes by inhibiting the anterior pituitary, which represses the formation of pro-opiomelanocortin, thereby attenuating further secretion of BE and ACTH.[285]

4) The cortical role in attenuating pain can be described in context of stimulation-produced analgesia (SPA). SPA involves a highly specific suppression of behavioral responses to noxious stimuli produced by electrical stimulation of specific brain sites. Experimental SPA was first elicited by electrical stimulation of the periaqueductal gray in rodents. Upon this electrical stimulation, rodents remained alert and active. However, their responses to noxious stimuli (orientation, vocalization and escape) were absent. Similarly, a SPA-like response has been elicited in humans. Subsequent research has indicated that periaqueductal gray plays an important part in this analgesia. The periaqueductal gray receives afferents from brainstem, diencephalon, medial prefrontal cortex, limbic system insular cortex, and amygdala (that receives massive input from hippocampus and neocortex). The periaqueductal gray also projects efferents rostrally to the medial thalamus and orbital frontal cortex[301] and the rostral ventromedial medulla (RVM). The periaqueductal gray integrates inputs from various afferents with ascending

nociceptive inputs, and, in turn controls spinal nociceptive neurons through relays in the RVM. The RVM, which consists of the raphe nuclei and surrounding reticular nuclei, projects fibers to the DH to exert bidirectional control over nociceptive transmission. Bidirectional control by RVM involves both inhibitory and excitatory interneurons.[294, 300] The RVM has 'off cells' and 'on cells.' The increased activity of 'off cells' has an inhibitory effect, which attenuates pain by reducing activity of second order pain afferent neurons in the DH. However, the increased activity of 'on cells' has an excitatory effect, which accentuates pain by increasing activity of second order pain afferent neurons in the DH.[294, 296]

Pain transmission and regulatory mechanisms have been explained using different pain theories. Among these theories, the Gate Control Theory[283] has been well accepted as an explanation of these mechanisms. According to this theory, the substantia gelatinosa in the dorsal horn (laminae II and III) of the spinal cord acts as a gate for pain signals. This gate determines whether or not pain signals reach the brain. Ability of pain signals to pass the gate appears to depend on two characteristics of somatosensory signals: 1) the strength of signals that reach the gate, and 2) signals that first reach the gate.[302]

1) Ability of pain signals to reach the brain depends on their strength at the gate. This strength is governed by intensity of a stimulus. A noxious stimulus acts on the skin to generate action potentials in nociceptors. These action potentials travel via the A-δ and C fibers to reach the gate. Varying intensity of stimulus results in different events occurring at the gate. A gentle, but sudden, pressure stimulus to the skin generates action potentials in larger number of A-δ fibers as compared to C-fibers. Disproportionately

larger number of active A-δ fibers stimulates transporter cells in the dorsal horn that facilitate conduction of pain signals to the brain. Active A-δ fibers also stimulate the gate thereby shortening the activity of the transporter cells. As the intensity of stimulus on the skin increases and gradually becomes noxious, it increases recruitment of A-δ fibers and C fibers and also increases firing frequency of active fibers. The C fibers activate the transporter cells and inhibit the gate. As a result, positive and negative effects of A-δ fibers and C fibers counteract each other, and therefore T cells gradually conduct more pain signals to the brain.[283, 302]

2) Pain signals compete with non-pain signals at the gate. An injury in a body part generates pain signals that travel to the gate via the A-δ fibers or the C fibers. Whereas, acts performed in an effort to reduce pain, such as massaging, vigorously moving, or exerting deep pressure on the injured part, result in non-pain signals. Non-pain signals travel via the A-β fibers – large, myelinated nerve fibers, with a low threshold for stimulation. The A-β fibers conduct non-pain signals at a much faster rate than either A-δ or C fibers conduct pain signals. Due to this faster speed, non-pain signals occupy the gate and do not allow conduction of pain signals to the brain. When pain reducing actions stop, non-pain signals do not occupy the gate allowing for pain signals to be conducted to the brain.[283, 302]

Acute versus Chronic Pain

Pain has been commonly classified on the basis of its duration for which one experiences it. Based on the duration, and extent of associated tissue damage, pain can be classified into acute and chronic pain.[294, 303, 304]

1) Acute pain has been defined as “pain associated with tissue damage, inflammation, or a disease process that is of relatively brief duration (i.e. hours, days, or

even weeks), regardless of its intensity."[304] Usually, a serious local injury, such as a surgical incision, activates nociceptors, their central connections and autonomic nervous system in that region, which provokes acute pain.[303] Acute pain persists until healing takes place[290] or stops long before healing has been completed.[303] Healing can occur without medical intervention as an injury with acute pain does not overwhelm the body's reparative mechanisms. Such healing usually takes a few days to a few weeks, and therefore acute pain lasts for the same duration.[303] Additionally, acute pain has been associated with anxiety. The clinical observation that greater the anxiety the greater the perception of an injury as painful appears warranted. However, a clear empirical basis for this simple proposition does not exist. Different studies indicate that anxiety enhances, relieves or has no impact on pain.[290] Acute pain has also been observed after trauma and some diseases. Pain in these conditions, except for malignant diseases, that persists for months or years is not considered acute pain.[303]

2) Chronic pain has been defined as "pain that persists for extended periods of time (i.e. months or years), that accompanies a disease process (e.g. rheumatoid arthritis), or that is associated with an injury that has not resolved within an expected period of time (e.g. myofascial pain syndromes, complex regional pain syndrome, and chronic pelvic pain)."[304] Chronic pain indicates that the pain has lost its biological role of triggering recuperative behavior.[305] Chronic pain, although triggered by injury or disease, however, has other factors associated with it that prolong its presence. These factors include continued tissue damage, loss of a body part, extensive trauma, or damage to the nervous system as a result of injury.[303] Due to these factors, the pain persists either beyond the expected course of disease, or beyond the time expected for an injury to heal, or it recurs

at various times for months or years.[305] In such situations, the injury may exceed the body's capability to heal. Additionally, intensity of chronic pain may be out of proportion of original injury or damage, and syndromes, such as complex regional pain syndrome, may occur spontaneously without any signs of injury.[303] Chronic pain impairs an individual's social, vocational and psychological well being. Among psychological factors, chronic pain has been frequently associated with depression, which may vary from minor to severe. Depression also appears to intensify chronic pain. While some patients display depression, others maintain a dispassionate attitude. Patients with a dispassionate attitude appear to have either strong personal or social resources or the pain disorder provides a focus in life that enables them to ignore stressful life challenges, thereby controlling depression.[290] Clinically, acute and chronic pain can be distinguished on the basis of dimensions of pain. In terms of these dimensions, described next, people experiencing acute pain provide a clear and specific picture of their experience.[296]

Dimensions of Pain

Until the 1960's, researchers considered pain as purely a sensory experience with no specific dimensions.[284] Distinct dimensions of pain, having surfaced only recently, were triggered by the gate control theory. The gate control theory allowed various psychological factors, earlier dismissed as 'reactions to pain,' to be considered as an integral part of pain processing.[306] Currently, at least four dimensions or categories of pain experience can be assessed: 1) pain intensity, 2) pain affect, 3) pain quality, and 4) pain location.[289]

1) Pain intensity may be defined as how much a person hurts. It provides a quantitative estimate of the severity or magnitude of the perceived pain.[289] Pain assessment tools use descriptors to describe the intensity of a painful experience varying

from ‘no pain’ to ‘worst imaginable pain.’[307] Physiologically, pain intensity is encoded by the number of peripheral fibers that are activated by the painful stimulus and their discharge frequency.[294] The wide dynamic range (WDR) neurons assist in identifying intensity of various noxious stimuli. These neurons receive input from both nociceptive and non-nociceptive afferents. Non-nociceptive stimuli, such as touch, cause the WDR neurons to discharge at lower levels and nociceptive stimuli cause them to discharge more vigorously.[292] By increasing discharge frequency in presence of noxious stimulus, the WDR neurons assist in identifying the intensity of a noxious stimulus. The rapidly conducting spinal systems also allow for identifying pain intensity. Intensity of pain signals is interpreted in the primary somatosensory cortex (SI), which reach there via the A-δ fibers and the neospinothalamic tracts.[293, 294]

2) Pain affect has been defined as “emotional arousal and disruption engendered by the pain experience.”[289] Pain affect has been identified as an intrinsic, but conceptually and empirically distinct component of pain.[70, 285, 308-310] As people can have mixed feelings with respect to events, people in pain can have multiple emotions associated with their painful experience.[289] Pain assessment tools used to describe the affective component of pain, use words such as distracting, depressing, dreadful, or unbearable.[289] Physiologically, this affective component of pain can be described by activity of the WDR neurons[292], which is then projected by the divergent pathways to parts of the brain for emotional arousal.[293] It has been proposed that while nociceptive transmission excites the spinothalamic pathways to generate sensory processes, the spinoreticular pathways are used to generate affective processes. The affective dimension of pain is then produced by activation of noradrenergic limbic structures. Also, the hormonal system, including the

HPA axis, mediates a stress response related to pain and forms a mechanism for expressing its emotional dimension.[285]

3) Pain location may be defined as part of body where a person experiences pain. This location may be same or different from where tissue injury takes place. Pain assessment tools use line diagrams of whole body or specific parts of the body to describe the pain location. People in pain identify location of their pain by marking these diagrams.[289] Physiologically, the nociceptive specific (NS) second order neurons, present in the DH, allow for good localization of pain because of their small receptive fields and being somatotopically organized in the lamina I.[292] The NS neurons receive information on pain signals via the fast conducting A-δ fibers and further project these signals via the spinothalamic pathways to the primary somatosensory cortex (SI). Perception of pain in the SI identifies exact location of pain in the body.[293]

4) Pain quality has been usually included as an aspect of the sensory-discriminative component of pain. Melzack and Casey first described this component in 1968.[311] The sensory-discriminative component of pain can be defined as including information that maps the sensory nature of the stimulus (thermal, mechanical, or chemical) as well as bodily location, intensity and temporal aspects of the experience.[290] Specifically, pain quality describes sensory nature of stimulus and sensitivity to pain.[289, 312] Examples of words that are used in pain assessments to describe pain quality include sharp, dull, hot, cold, deep, superficial, sensitive and itchy.[312] Physiologically, rapidly conducting spinal systems, i.e. the neospinothalamic tracts, influence pain quality through the nociceptive specific (NS) neurons.[70] The A-δ fibers conduct pain sensation via the NS neurons,

whose axons form the neospinothalamic tracts, to the primary somatosensory cortex (SI). The SI interprets the quality of pain sensation.[293, 294]

Assessment of Pain

The multidimensional nature of pain needs to be assessed accurately for improving clinical and research outcomes. These outcomes include 1) identifying underlying cause of pain, 2) determining most effective treatment of pain and evaluating new methods to control pain, and 3) evaluating degree of disability or impairment of function related to pain.[313]

1) Assessment of pain, especially identifying descriptors of its sensory qualities, can assist in diagnosis of pain etiology. For example, a burning quality of pain may indicate peripheral injury[313], and cramping quality of pelvic pain may indicate menstrual pain.[314] Furthermore, people tend to use a constellation of descriptors to explain their pain experience. These constellations can assist clinicians to discriminate various types of pain.[313, 315]

2) Accurate assessment of pain also determines the most effective treatment for pain. For example, it has been suggested that osteoarthritis (OA) pain can be managed by blocking newly found analgesic targets. Primary afferent neurons in affected joints express excessive amounts of abnormally functioning sodium (Na) channels. These Na channels may play an integral role in OA pain. Therefore, analgesics that target these Na channels may provide relief from OA pain.[316] Pain needs to be accurately assessed to identify the efficacy of new pharmacological treatments that target these Na channels as compared to existing treatments.

3) Pain assessment forms an important component of impairment and disability evaluation.[313] Pain commonly occurs in adults with conditions that result in physical

disability, such as spinal cord injury, cerebral palsy, multiple sclerosis and post polio syndrome.[317] In such situations, pain contributes to impairments and exacerbates limitations.[318, 319] Therefore, pain assessment needs to be a component of impairment or disability evaluation. Many rehabilitation related situations require that the pain related outcomes be assessed in a short duration of time.[320]

Until the 1960's, researchers considered pain as a purely sensory experience with no specific dimensions.[284] At present, four different dimensions of pain experience have been identified, which include pain intensity, pain affect, pain quality, and pain location.[289] For this study, we will focus on pain intensity. Pain intensity provides a quantitative estimate of the severity or magnitude of the perceived pain.[289] In the nervous system, pain intensity is encoded by the number and discharge frequency of peripheral fibers that are activated by a painful stimulus.[294] The wide dynamic range (WDR) neurons, which receive input from both nociceptive and non-nociceptive afferents, assist in identifying intensity of various noxious stimuli. Nociceptive stimuli cause the WDR neurons to discharge more vigorously than non-nociceptive stimuli.[292] The rapidly conducting spinal systems, which include the A-δ fibers and the neospinothalamic tracts, also allow for identifying pain intensity. Ultimately, pain intensity is interpreted in the primary somatosensory cortex (SI) of the brain.[293, 294]

A variety of assessments have been developed to evaluate pain intensity.[304] These assessments can be classified into three general categories: verbal rating scale (VRS), visual analog scale (VAS), and numerical rating scale (NRS).[289] These assessments tend to have statistically similar psychometric properties but have their own strengths and weaknesses[289, 309, 321], which have been summarized in Table 2-4.

The VAS has been used extensively to assess pain intensity[322], and is possibly the most widely used pain measure.[323] The VAS is non-intrusive, is easy to administer and score, is suitable for repeated use, and has simple instructions.[322, 324] The VAS has also been found to be the most sensitive measure of pain when compared to various other methods.[325, 326]

The VAS that assesses pain intensity usually consists of an unbroken line, 10 centimeter (cm) long, placed horizontally on a piece of paper, with anchor points on each end.[322] One anchor of this line represents "no pain" and the other anchor represents "maximum perceived pain intensity."[289] People rate their perceived pain intensity by placing a mark through the line.[322] The distance from the "no pain" anchor to this mark results in the overall pain intensity score.[289, 322] Commonly, this distance is measured in millimeters, and therefore, the score ranges from 0 to 100.[322] Since its initial development almost 70 years ago[323], many different versions of the VAS have been used to assess pain intensity.[289] For example, the words describing the anchors have been varied[327], the length of the line has been varied[328], the line has been placed vertically on a piece of paper[329], and mechanical[289] and electronic versions[330] have been developed.

Perceived Magnitude of Grip Force

The Psychophysical Law by Stevens[331] states that a power function represents the relationship between magnitude of a sensation and its judgment by an individual. This power function is expressed as 'the magnitude estimations of a sensation increase as a power of the actual intensity of that sensation.'[331] The exponent of the power function varies by sensation, sensory modality and condition of stimulus presentation.[332] The Steven's Law has been shown to govern the sense of force, i.e. the magnitude of apparent force increases as a power of the force exerted.[333-336] For handgrip force, the power

function exponent varies between 1.6 and 2.0.[335, 336] Also, a power function with an exponent of 0.6 describes the association between apparent grip force and duration of a sustained grip. That is, on maintaining a handgrip at a constant force, a power function represents an increase in apparent force with duration of the handgrip.[335] Similarly, participants maintain a constant handgrip effort by reducing the grip force over time. The relationship between the decay in grip force and duration of grip is represented by a double exponential function.[337] Two self-report scales have been used to identify the level of perceived intensity of force, which include the Rating of Perceived Exertion (RPE) Scale[338] and the Category Ratio (CR-10) Scale.[339] We will use the CR-10 Scale as it has been shown to be effective in assessing perceived exertion of grip strength.[340] Further, the CR-10 Scale has been used to describe the relationship between perceived effort and associated EMG changes during a sustained isometric grip.[243] Furthermore, the CR-10 Scale has attributes of a ratio scale.[339, 341] This ratio scale will allow study participants to report the perceived level of force applied during submaximal grip efforts as a percentage of their maximal grip efforts.

Summary

The present cost of managing musculoskeletal disorders (MSDs) stands at an estimated $20 billion per year.[40] By 2020, an estimated 59.4 million Americans (18.4%) will suffer from MSDs[35], which would further increase the financial burden. MSDs commonly affect the upper extremities, whose rehabiltative outcomes are commonly assessed using grip strength. Grip strength is a valid method of assessing rehabilitative outcomes only when a person exerts maximal effort. A person may exert submaximal effort either intentionally (e.g. financial gain) or unintentionally (e.g. injury-related pain). Various grip strength based tests have been used to distinguish between maximal and

submaximal effort. However, these methods have been shown to have poor reliability and validity. In contrast, a recent pilot study indicated that the force-time curve (F-T curve) characteristics and electromyographic (EMG) properties can accurately identify maximal effort. The pilot study was performed using healthy participants. Therefore, the current study will assess the ability of F-T curve characteristics and EMG properties to identify maximal voluntary effort of isometric grip in people with upper extremity disorders and injuries.

Table 2-1: Differences between maximal and submaximal effort

Characteristic	Maximal Effort	Submaximal Effort
Order of task	Lower order task	Higher order task
Somatosensory system		
Afferent activity	Indicates full utilization of motor recruitment and firing	Assists in calibration and modulation of effort
Cerebral cortex		
Metabolic uptake ratio	Decreases in the first minutes of recovery	No significant change
Mental effort	Large	Small
Inhibition of uninvolved systems	Increased inhibition	Less inhibition than in maximal effort
Motor system		
Motor unit recruitment	Maximal	Increases with level of effort
Motor unit firing	Synchronous	Asynchronous
Variability in effort	Less variability	Maximum variability at 60% of MVC
Onset of Fatigue		
Force production	Declines	Maintained
Motor unit recruitment	Cannot be further increased	Increases
Motor unit firing	Shifts from high to low value	Stays constant
EMG frequency	Decreases	Maintained
Brain activity (fMRI)	Increases with decreased muscle activity	Not reported

Table 2-2: Sensitivity and specificity values of different sincerity of effort tests

Measure	Value	Sensitivity	Specificity	Author
CV	11% CV cutoff	0.69	0.74	Shechtman, 2001
	15% CV cutoff	0.55	0.92	
Five-Rung	7.5 SD cutoff	0.7	0.83	Gutierrez & Shechtman, 2003
Rapid Exchange Grip	REG 45	0.65	0.66	Shechtman & Taylor, 2000
Slope of force-generation phase	Females =1.2	0.80	0.93	Shechtman, et al, 2007
	Males = 1.45	0.80	0.87	
Slope of force-decay phase	Females = -0.05	0.80	0.87	Shechtman, et al, 2007
	Males = -0.075	0.93	1.00	

Table 2-3: Differences between second order pain neurons

Difference	Nociceptive Specific (NS) Neurons	Wide Dynamic Range (WDR) Neurons
Activating fibers	A-δ and C fibers [342]	A-β, A-δ and C fibers [292]
Activating stimuli	Nociceptive (fast and slow pain) [342]	Innocuous (cutaneous touch and pressure) and Nociceptive (fast and slow pain) [343]
Location	Mostly in Lamina I of spinal cord [344, 345]	Mostly in Lamina V and VII of spinal cord [343]
Lamina I	Somatotopically organized [342]	Not somatotopically organized [342]
Pain receptive field	Restricted to relatively small areas [292]	Vary with stimulus strength; much larger than those of NS neurons [342]
Discharge strength	Vigorous increase in discharge as a result of noxious stimuli (e.g. pinching and strong compression) [292]	Discharge at lower levels in response to innocuous stimuli; discharge more vigorously in response to noxious stimuli [343]
Contribution to Spinothalamic Tract	Make up 20–25% of tract [342]	Make up about 75% of tract [342]
Function	Involved in sensory-discriminative aspects of pain (localization of pain [292]; nature of pain stimulus [292, 344])	Involved in affective-motivational aspects of pain (intensity; differences in noxious stimuli intensities; initiation of complex behavioral responses to pain) [292]
Pain theory supported	Specificity theory: presence of specific neurons activated only by noxious stimuli [345, 346]	Pattern theory: presence of second order neurons that discharge differently to noxious and innocuous stimuli [292]

Table 2-4: Strengths and weaknesses of pain intensity assessments

Strength	Weakness
Verbal Rating Scale (VRS)	
Simple, complete and a usable pain assessment[347]	Some adjectives may be ambiguous[323]
Adjectives may convey more subtle meanings of pain[348]	Familiarity with adjectives required[289]
Easy to administer[289]	Equal intervals may not exist between adjectives[289]
Easy to score[289]	Cross modality matching reduces patient compliance[289]
Usually easy to comprehend[289]	Longer lists have long response times[289]
Good compliance rates[289]	Included adjectives may not describe level of pain experience[289]
Have internal consistency and temporal stability[349]	Adjectives pose literacy challenges[289]
Cross-modality related ratio scores are valid, reliable and objective measures[289, 308, 350]	Pain affect and intensity assessments are not always distinct[289]
Responsive to change in pain state[289]	Single adjective may not describe pain experience[323, 347]
Ability to discriminate between different types of pain[351, 352]	Use of adjectives varies with ethnic groups and gender[353]
Visual Analog Scale (VAS)	
Simple and easy to construct[324]	Scoring is more time-consuming and involves more steps than other measures[289]
Easily grasped[322]	The respondent needs to have minimum level of motor abilities to use the scale[289]
Require little motivation to complete and quickly filled out[322]	Cognitive difficulties make it harder to use[289]
Suitable for use by untrained staff[324]	May have increased measurement error due to freedom in reporting[356]
Linear scale[354, 355]	
Ratio qualities[289, 324]	
Valid measures of pain state[289]	
More responsive than other measures[289]	
Suitable for repeated use[322]	
Numerical Rating Scale (NRS)	
Valid & correlates with other pain intensity measures[289]	Scores cannot be necessarily treated as ratio data[357]
Sensitive to treatments that impact pain intensity[289]	
Easy to administer and score[289]	
Can be administered over the phone[289]	

CHAPTER 3
METHODS

Participants

Forty participants (20 males and 20 females) who currently had upper extremity musculoskeletal disorders and injuries (UEMDs) were recruited for this study. The sample size was calculated based on the data from a preliminary study involving healthy participants (Appendix A).

We used convenience sampling to recruit the study participants (the recruitment process is described in the "procedure" section on page 84). Specific inclusion and exclusion criteria were used to select the participants. The inclusion criteria were as follows: Participants were 1) aged between 18 and 65 years, 2) treated for unilateral UEMDs involving the elbow or distally in the last 1 year. The exclusion criteria were: People who 1) had bilateral UEMDs, 2) had UEMDs proximal to the elbow, 3) were unable to safely perform 4 maximal and 8 submaximal grip trials with their affected extremity, 4) verbally report their pain intensity to be greater than 7 on a scale of 0 to 10, 5) were currently ill and/or taking medication which would compromise their grip strength, 6) had impaired cognition.

Materials and Equipment

This section discusses the equipment we used for recording the force-time curve (F-T curve) and EMG activity, as well as for reporting participant demographics, perceived exertion, and current and imagined level of pain. The instruments used to record the F-T curve characteristics and EMG properties of the isometric grips included:

1) signal sensors: a transducer for recording grip force and surface electrodes for recording the muscles EMG activity, 2) signal conditioner for amplifying, filtering and processing the EMG activity signal, 3) an analog-to-digital (A/D) converter for transforming a continuous electrical signal into a discrete electrical signal, and 4) a computer with polygraph software for processing the discrete signal and for generating the F-T curve and EMG activity. A diagram of the equipment setup has been presented in Figure 3-1.

The paper-and-pencil tests included: 1) demographic questionnaire, 2) visual analog scale (VAS) for measuring current pain intensity and for assigning imagined pain, and 3) VAS for rating perceived grip effort. The specific equipment is discussed next.

Instruments for Generating the F-T Curve

Hand dynamometer. The force characteristics of the grip efforts were captured using a force transducer in the form of an electronic Jamar dynamometer (Thought Technology Ltd; Figure 3-2). A transducer is an electrical device that converts one form of energy to another.[358] The transducer in the modified Jamar dynamometer converts grip pressure (measured in Kilograms; kg) into an electrical signal (measured in Volts; V). The modified Jamar dynamometer has an operating range of 0-90.72 kg (0-200 lbs.) and converts 1kg of external force into an electrical potential difference of 23.11 mV. This conversion factor was calculated by suspending known weights (10, 20, and 25kg) from the dynamometer prior to beginning data collection on 3 consecutive days. The observed voltage readings were used to calculate 3 linear equations, Equation 3-1 for day 1, Equation 3-2 for day 2, and Equation 3-3 for day 3. In the 3 equations, x represents the weight of a load in kilograms and y represents the voltage output observed as a result of

suspending a load. Using these equations, we calculated a conversion factor for each day, which when averaged resulted in a value of 23.11 mV.

$$y = 20.356x + 551.16 \quad (3\text{-}1)$$
$$y = 20.631x + 547.63 \quad (3\text{-}2)$$
$$y = 20.669x + 545.08 \quad (3\text{-}3)$$

The calibration of the dynamometer was checked once a week by measuring the electrical output on suspending known weights (10, 20, and 25kg). A linear relationship between the suspended loads and electrical activity indicated a calibrated transducer because the electrical output should increase proportionally to the load of the suspended weights. We examined the linear relationship between the suspended loads and the electrical activity by performing regression analysis and calculating the coefficient of determination (r^2) for each week. For the duration of the study, the average r^2 value was calculated as 0.999. To identify differences in weekly calibration, we correlated the voltage outputs using Pearson product-moment correlation coefficient (Pearson r) as well as the Intraclass correlation coefficient (ICC 3, 1). We found perfect correlations between the weekly voltage (Pearson r = 1.0, Appendix B). We also found perfect test-retest reliability between the first and last weekly voltage outputs (ICC 3,1 = 1.0). Large coefficients of determination as well as perfect correlation coefficients indicate that the dynamometer maintained its calibration. The electrical signal from the Jamar dynamometer was amplified and fed into the FlexComp analog-to-digital converter for analog display of the signal.

Instruments for Recording the EMG Signal

Surface EMG electrodes. The electromyographic (EMG) signal of two groups of gripping muscles was captured using the MyoScan active sensor (Model # SA9401M, Thought Technology Ltd., Montreal, QC; Figure 3-3) and the Triode electrode featuring a

bi-metal design, where silver-silver chloride (Ag-AgCl) contacts the skin and conducts the captured signal via nickel-plated brass dome to the MyoScan sensor. The forearm has 2 muscle groups that play an important role in gripping.[359] The recording electrodes were placed over the belly of the flexor digitorum superficialis muscle (forearm flexor area) and over the belly of the extensor digitorum communis muscle (forearm extensor area).[360] Alcohol swabs were used to cleanse the skin before applying the electrodes. The signal from the recording electrodes was transmitted to the signal conditioner.

Signal conditioner. The EMG output was amplified and filtered using the MyoScan active sensor and the FlexComp Infiniti encoder (Model # SA7550, Thought Technology Ltd., Montreal, QC; Figure 3-4). An amplifier takes a small analog signal and increases its magnitude.[358] The MyoScan sensor detects EMG signal in the range of $\pm$ 1600μV and uses a gain value of 500 to amplify it. The amplified signal was band-pass filtered at 20-500 Hz (high-passed to 20Hz by the MyoScan sensor and low-passed to 500Hz by the FlexComp Infiniti), which eliminated the frequencies that mostly represent noise.[237] The filtered and amplified EMG signal and the force signal were led into the analog-to-digital (A/D) converter.

Analog-to-digital (A/D) converter. The A/D converter (FlexComp Infiniti encoder) transformed the analog data (F-T curve and EMG signal) into digital form, which was stored and used for data processing. The FlexComp A/D converter sampled a continuous/analog voltage signal and converted it into discrete voltage values. The discrete voltage values were further translated into numerical values with a scale called 'A/D units' and stored in the computer for data analysis purposes.[358]

For the present study, we used a channel bandwidth of 20-500Hz at a sampling rate of 2048 samples/second. It has been recommended that for proper analog-to-digital conversion, the amplified EMG output of a maximal voluntary isometric contraction (MVIC) be less than half the range of voltage accepted by the A/D converter.[241] Also, the Nyquist theorem states that the data should be sampled at least at twice the rate of the highest frequency that is present in the signal.[237] The amplified EMG signal from the MyoScan sensor has an active range of $\pm$ 0.8V, which is half the voltage range of the FlexComp A/D converter ($\pm$ 1.7V centered around a 2.8V offset).[361] This range was appropriate for digital conversion of our amplified analog signal. Also, the FlexComp A/D converter samples data at 2kHz, which met the requirement of the Nyquist theorem as the highest frequency in our signal was 500Hz.[361]

Computer with polygraph software. The BioGraph Infiniti software (Version 3.1, Thought Technology; Figure 3-5) was used to generate the F-T curve characteristics and EMG properties. For the F-T curves, we employed the BioGraph Infiniti's linear transformer to convert force values from volts to kilograms. The slopes of the F-T curve were calculated by exporting force values, sampled at a rate of 2048 samples/second, into Microsoft Excel (Version 2003) and employing its function of the least-square line of best fit. For the amplified and band-passed EMG signal, we rejected the 60Hz hum (power-line noise) by employing BioGraph Inifiniti's notch filter. The notch filtered signal was used to calculate the amplitude and median power frequency. The amplitude of the EMG signal was calculated as average rectified amplitude for the duration of the grip. The frequency spectrum was generated by applying a Fourier transformation algorithm. To achieve a resolution of 1 Hz, a 2048-point Fast Fourier Transformation

(FFT) with the Hanning window function was applied to the EMG signal. The resulting power spectrum was used to calculate the median power frequency, which was smoothed using an averaging factor of 40. The median frequency was computed for two separate 1-second intervals, the first interval beginning at peak force (called the median frequency of the first second, or MF first second) and the second interval forming the last second of the force decay phase (called the median frequency of the last second, or MF last second). We also computed the ratio of last to first second values of MF, or the MF-ratio.

Paper-and-Pencil Tests

1) Demographic Questionnaire. A demographic questionnaire was used to collect participant information on demographic variables such as age and gender. The questionnaire also included questions on UEMD-related variables such as diagnosis and site of condition (Appendix C).

2) Visual Analog Scale (VAS) for pain intensity. For the present study, a VAS was used to assess current pain intensity. The VAS consists of a 10 cm line anchored by 2 extremes of pain, i.e., 'no pain' (numerical score of 0) and 'pain as bad as it could be' (numerical score of 10; Figure 3-6). Participants were instructed to mark the VAS at a point that identified their current pain level. The VAS was administered at the beginning of the testing session and before each gripping effort in both hands to ensure that pain returned to pre-injury level. Also, based on the initial VAS, an imagined level of pain intensity was verbally assigned as 2-3 cm above the initial perceived pain level.

3) Visual Analog Scale (VAS) for perceived grip effort. The perceived exertion of grip effort was rated using a VAS (Figure 3-7). It consisted of a 10 cm line anchored by 2 extremes of effort, i.e., 'no grip force' (numerical score of 0) and 'strongest grip force' (numerical score of 10). We used the effort scale to examine how imagined pain

can affect the level of effort. The effort scale was used to compute perceived submaximal effort as a percentage of perceived maximal effort. In the present study, the effort scale was given immediately after each grip trial for the participant to report his or her perceived grip effort.

Study Design

The present study employed a repeated measures design. Each participant served as their own control for two variables – levels of grip efforts (maximal vs. submaximal) and levels of injury (injured vs. uninjured hand). The participants were divided into two groups on the basis of gender (male vs. female).

Rationale for the Study Design. Stringent controls have been applied to the research design. The stringent controls would identify any significant differences between maximal and submaximal effort as well as to identify their association with pain. The steps taken to make the study design conservative and stringent include:

- Appropriate sample size was calculated based on previous data and was sufficient to indicate if the force-time curve (F-T curve) characteristics and EMG properties truly differentiate between maximal and submaximal grip efforts.
- A repeated measures design provides the ability to control for potential influence of individual differences. We can safely assume that important participant characteristics, such as age, gender and disability related to the upper extremity condition remained constant through the course of the experiment.[92]
- One disadvantage of a repeated measures design is the potential for carryover effects when a participant is exposed to multiple-treatment conditions. Carryover/residual effects, such as fatigue due to grip strength trials, can be reduced by allotting sufficient time between successive treatment conditions to allow for complete dissipation of previous effects.[92] To dissipate carryover effects, study participants were provided with a rest break lasting a minute after each grip trial[96, 362], and were also provided with a 10 minute break between the two sessions.[362-364]
- This design also controls for order effects by randomizing the sequence of maximal and submaximal effort and which extremity was used to begin the grip efforts.[365]

Procedure

Participant Recruitment Phase

Participants with upper extremity conditions were recruited from various hand therapy clinics and rehabilitation clinics in the cities of Gainesville, and St. Augustine, Florida. Health care professionals, including physical therapists and occupational therapists, were provided with inclusion/exclusion criteria and a standard script for recruiting participants. The criteria and directions were provided to the healthcare professionals as part of a letter (Appendix D). The script is as follows:

> "A study is being conducted to identify how pain affects grip strength among people with upper extremity musculoskeletal conditions. Your condition makes you eligible to participate in this study. This study involves gripping a hand dynamometer 12 times with each hand and rating your pain and perceived grip effort. If you agree to participate, you will attend one session lasting approximately 45 minutes and will be paid $20.00 for participating in the study. Please let me know if you are interested in participating and I can provide you with information to contact the research group."

These health care professionals communicated the information on the study to their patients who they judged to be able to safely perform 4 maximal and 8 submaximal efforts with their injured extremity. Interested participants were asked to call or email the investigators indicating their interest in participating in the study and to setup an appointment for collecting data.

Data Collection Phase

1) Instrument calibration. The Jamar dynamometer and the FlexComp Infiniti were calibrated prior to the testing session. The calibration of the dynamometer was checked by measuring the electrical output on suspending known weights (10, 20, and 25kg). The setup used to check the calibration of the dynamometer has been presented in Figure 3-8. The FlexComp Infiniti includes a built-in voltage reference that possesses

good temperature stability. This reference voltage was used to self-calibrate the unit. The self-calibration process sets the gain and offset of each channel of the unit to a value within their preset specifications.[361]

2) Participant preparation. All participants first read and signed the informed consent form approved by the Institutional Review Board at the University of Florida. The participants then filled out a demographic questionnaire (Appendix C). While completing the questionnaire, the participants were also provided with instructions on how to complete the pain-intensity VAS. Next, the participants were prepared for EMG data collection from forearm flexor and extensor muscles by cleaning the forearm skin using alcohol swabs. The forearm flexor compartment was represented by the flexor digitorum superficialis (FDS) muscle and the extensor compartment by the extensor digitorum communis (EDC) muscle. The location of the recording electrode on the FDS muscle was identified as follows[360]:

1. Place the participant's forearm in supination.
2. Ask the participant to close and open their fist 3-5 times.
3. Look and feel for the muscle belly while the participant performs the movement.
4. Place the electrode on the muscle's belly, approximately 1-2 inches below the cubital fossa.

The location of the recording electrode on the EDC muscle was identified as follows[360]:

1. Place the forearm of the participant in pronation, and ask the participant to close and open their fist.
2. Feel for the bulge of the muscle in the upper forearm.
3. To confirm the muscle's location, ask the participant to flex and extend the metacarpophalangeal joint of the long/middle finger while the rest of the fingers are in flexion.

4. Place the electrode on the bulge, approximately 3 inches below the lateral epicondyle.

3) Protocol. Each participant participated in a total of 2 sessions of gripping. In each session, a participant exerted 2 maximal and 4 submaximal grip efforts with each hand. Hence, a participant exerted a total of 12 grips with each hand. Each grip lasted 6 seconds. After each grip effort, the participant rested for a period of 1 minute. Between the 2 sessions, the participant received a rest break lasting 10 minutes. For all grips, the participant was seated in an adjustable chair without arm rests. The participant assumed the testing position recommended by the American Society of Hand Therapists.[175] The participant's feet were fully resting on the floor and the hips were as far back in the chair as possible, with the hips and knees positioned at approximately 90°. The shoulder of the tested extremity was adducted and neutrally rotated, the elbow flexed to 90°, and the forearm and wrist held in a neutral position.

After each grip effort, the participant rested for a period of 1 minute. At the beginning of the rest period, the test administrator asked the participant to complete the effort VAS for perceived exertion of grip strength. At the end of the rest period, the participant completed the pain intensity VAS for pain resulting from the grip. If the reported level of pain was more than 1-point higher than the range of pain usually experienced then the participant continued to rest until the level of pain returned to within 1-point of the initial level of pain. This time was recorded exactly on the checklist used by the test administrator (Figure F-1). Before the first session, the participant also performed a practice grip with each hand to get used to the dynamometer and to check if the force and EMG signal were being recorded properly. The participant also practiced marking the pain and effort VAS.

A data collection form was used to record the perceived grip force and pain intensity. The form recorded effort and pain associated with the practice trial as well as with maximal and submaximal grip effort trials. The form was compiled prior to beginning of the data collection phase of the study and followed the same order that was assigned to a participant. An example of a data collection form has been provided in Appendix G. Table 3-1 presents an example of the study protocol.

To control for order effects, the sequence of maximal vs. submaximal effort and injured vs. uninjured extremity was randomly assigned. The random assignment was performed prior to the beginning of the study and was implemented by an assistant. An assistant used the randomization sheet (Appendix E) to assign the order (sequence) of gripping. Each participant was assigned 1 of 4 possible gripping sequences based on starting with one of the hands (injured vs. uninjured) and one of the levels of effort (maximal vs. submaximal) (Appendix E). To reduce measurement bias, the test administrator was blinded to the level of effort. An assistant implemented the randomization by providing participants with standard instructions (see next section).

4) Instructions. When maximal effort was assigned, the instructions were be as follows:

> "In this session, I want you to give maximal effort with your injured/uninjured hand for all 2 grip trials. Follow the directions of the test administrator to exert full effort. Do you have any questions? This task will test your grip strength. When I say go, give your maximum effort in a smooth manner. Be careful not to jerk the tool while gripping. You will exert a maximal effort for 6 seconds. You will be given a rest period after each grip. Before each trial I will ask you 'Are you ready?' and then the computer will tell you 'Are you ready? Go!' The computer will tell you to stop after 6 seconds. If you experience any unusual pain or discomfort at any point during testing, stop immediately. Do you have any questions?"

The submaximal effort instructions for the injured extremity assigned on the basis of imagined pain level were as follows:

> "In this session, I want you to imagine that the level of pain that you are experiencing is affecting your grip. I want you to imagine that your pain is 2 points higher on the VAS and is at a level of (__ number) out of 10. Imagine that this higher intensity pain causes your grip to be weaker. I want you to perform the grip trials in such a way that you convince me that you are more affected by pain than you really are, in other words, to exert less than a maximal effort. When I say go, give your submaximal effort in a smooth manner. Be careful not to jerk the tool while gripping. You will exert a submaximal effort for 6 seconds. You will be given a rest period after each grip. Before each trial I will ask you 'Are you ready?' and then the computer will tell you 'Are you ready? Go!' The computer will tell you to stop after 6 seconds. If you experience any unusual pain or discomfort at any point during testing, stop immediately. Do you have any questions?"

The submaximal effort instructions for the uninjured extremity assigned on the basis of imagined pain level were as follows:

> "In this session, I want you to imagine that the level of pain that you are experiencing is affecting your grip. I want you to pretend that you are experiencing pain that equals the intensity of pain you experienced in your injured extremity at the beginning of the session and is at a level of (__ number) out of 10. Imagine that this pain causes your grip to be weaker. The test administrator will ask you to exert your maximal effort. I want you to perform the grip trials in such a way that you convince the administrator that you are more affected by pain than you really are, in other words, to exert less than a maximal effort when gripping. Try to be consistent in repeating the force of your grip. The test administrator will ask you, throughout the testing session, to give maximal effort, but you need to ignore his instructions. Do you have any questions? When I say go, give your submaximal effort in a smooth manner. Be careful not to jerk the tool while gripping. You will exert a submaximal effort for 6 seconds. You will be given a rest period after each grip. Before each trial I will ask you 'Are you ready?' and then tell you to 'Go!' I will tell you to stop after 6 seconds. If you experience any unusual pain or discomfort at any point during testing, stop immediately. Do you have any questions?"

The submaximal effort instructions for the injured as well as uninjured extremity assigned on the basis of 50% of maximal effort were as follows:

> "In this session, I want you to perform the grip trials in such a way that you exert 50% of your maximal effort. When I say go, give your submaximal effort in a smooth manner. Be careful not to jerk the tool while gripping. You will exert a submaximal effort for 6 seconds. You will be given a rest period after each grip. Before each trial I will ask you 'Are you ready?' and then tell you to 'Go!' I will tell you to stop after 6 seconds. If you experience any unusual pain or discomfort at any point during testing, stop immediately. Do you have any questions?"

The test administrator, who was blinded to the level of effort, instructed the participant to exert maximal grip strength effort regardless of whether the assigned effort was maximal or submaximal. The grip effort instructions given before each session were as follows:

> "This task will test your grip strength. When I say go, give your maximum effort in a smooth manner. Be careful not to jerk the tool while gripping. You will exert a maximal effort for 6 seconds. You will be given a rest period after each grip. Before each trial I will ask you 'Are you ready?' and then tell you to 'Go!' I will tell you to stop after 6 seconds. If you experience any unusual pain or discomfort at any point during testing, stop immediately. Do you have any questions?"

Before each grip trial, the grip effort instructions to the participant were as follows:

> "During the next grip, give your maximum/submaximal effort. Are you ready? Go! (After 6 seconds) Stop!"

A practice trial was given before gripping begins. The instructions for the practice trial are as follows:

> "This is a practice trial so you can get used to gripping the dynamometer and practice marking the pain and effort scales. Please do not exert maximal effort during this practice trial so that you don't fatigue. This is just a practice trial. Do you have any questions? Are you ready? Go! (After 6 seconds) Stop!"

Before the practice trial, the participant practiced marking the pain VAS and after the practice trial, the participant was instructed on how to complete the effort VAS on the "Practice Trial" sheet of the Data Collection Form (Appendix F) as follows:

> "Refer to the Effort Scale on the practice trial page of the data collection form. You will use the Effort Scale for recording the amount of effort you think you exerted during that grip. On this scale, 0 means no grip force and 10 means strongest grip force. Mark a vertical line at a point that indicates the level of effort you just exerted. Do you have any questions?"

Instructions for completing the effort VAS immediately after each grip trial were as follows:

> "Now please complete the effort scale. Mark a vertical line at a point that indicates the level of effort you just exerted."

The participant was also instructed on how to complete the VAS for pain intensity. While completing the demographic questionnaire, the instructions for answering questions 14 and 15 were as follows:

> "You will use the pain scale for recording the pain that you are currently experiencing in your injured upper extremity. On this scale, 0 means no pain and 10 means pain as bad as it could be. Mark a vertical line between 0 and 10 at a point that indicates your pain level. Do you have any questions?"

Instructions for completing the pain VAS before each grip trial (at the end of the 1 minute rest period) were as follows:

> "Now please complete the pain scale. Mark a vertical line at a point that indicates your pain level."

Statistical Analysis

The statistical analysis varied according to the specific aims of the study. For specific aims 1 and 2, we used repeated measures analysis of variance (ANOVA) for identifying differences between maximal and submaximal effort. All tests were considered significant at the $p \leq 0.05$. Due to exploratory nature of the study, we did not adjust the p-value for inflation in Type I error resulting from performing multiple comparisons. For specific aim 3, we used Intraclass correlation coefficients (ICC) to examine test-retest reliability and sensitivity and specificity analysis to assess validity and effectiveness of identifying maximal vs. submaximal efforts. All tests were performed using SPSS 15.0.[366]

Specific Aims 1 and 2. We used the General Linear Model (GLM) Repeated Measures Analysis of Variance (ANOVA) to compare between maximal and submaximal efforts. The ANOVA consisted of three within-subject variables, effort (maximal vs. submaximal), injury (injured vs. uninjured hand), and session (first vs. second), and one between-subject variable, gender (male vs. female). Repeated Measures ANOVA

analyzes a group of related dependent variables that represent different measurements of the same attribute.[366] The dependent variables for Aim 1 were the peak force, time-to-peak force, slope of the force-generation phase and slope of the force-decay phase of the F-T curve. The dependent variables for Aim 2 were the flexor and extensor EMG amplitude and median frequency ratio between first and last second of a 6-second grip.

Specific Aim 3. We examined the validity of the F-T curve characteristics and EMG properties in differentiating between maximal and submaximal efforts. However, a valid test first needs to be reliable.[92] The test-retest reliability of F-T curve characteristics and EMG properties was examined using the Intraclass Correlation Coefficient (ICC 3, 1). The ICC 3, 1 has become the preferred index for testing rater reliability as it reflects both correlation (correspondence) and agreement. Correlation indicates how scores vary together, whereas, agreement identifies any significant differences between scores.[92] In the designation "ICC 3, 1", 3 represents model 3 and 1 represents a single rater. The ICC 3,1 has been suggested to be appropriate for testing intrarater reliability with multiple scores from the same rater.[92, 367] ICC *r* values range from 0.00 to 1.00. According to Portney and Watkins[92], "reliability coefficients of measurements used for decision making or diagnosis of individuals need to be higher, perhaps at least 0.9 to ensure valid interpretations of findings" (p. 65). Portney and Watkins[92] further suggest that an index greater than 0.9 is a guideline and not an absolute standard.[92] For the present study, the ICC 3, 1 was used to compare the mean scores of the two trials of the first and second sessions. We expected coefficients of $r \geq 0.9$ to indicate that an F-T curve characteristic or EMG property had good reliability.

The validity indicators in the present study include: 1) significant differences in aims 1 and 2, 2) calculating sensitivity and specificity values, and 3) generating ROC curves to identify optimal cutoff value as well as effectiveness of the test. Significant differences were examined in aims 1 and 2. Sensitivity and specificity was calculated for different cutoff values. A cutoff value can be any value in the range of measures of an F-T curve characteristic or EMG property. For each cutoff value, sensitivity and specificity can be calculated by finding the number of true and false positives and negatives.[27, 64, 65, 109] For example, for the slopes of the force-decay phase, let a cutoff value be denoted by X. Steeper slopes have been associated with maximal effort.[28] Therefore, any slope value greater than X is considered positive (indicating submaximal effort). A true-positive exists when submaximal effort has really occurred. We calculated sensitivity by dividing the number of true-positives by the total number of times submaximal effort was exerted. Likewise, any slope value less than X is considered negative (indicating maximal effort). A true-negative exists when submaximal effort has really occurred. We calculated specificity by dividing the number of true-negatives by the total number of times maximal effort was exerted (Table 3-2). We also calculated the overall error rate by using the formula (1-sensitivity) + (1-specificity). The false-positive rates will be calculated by subtracting the specificity values from 1.0 (1-specificity).[92]

Sensitivity and specificity values change with the cutoff value, as an inverse relationship exists between the two, i.e., as sensitivity increases the specificity decreases and vice versa.[27, 64, 65] One way to evaluate how different cutoff values affect sensitivity and specificity is by plotting the receiver operating characteristic (ROC) curve.[110] The ROC curve is a plot of true-positive rates (sensitivity) against false-positive rates (1-

specificity). It can be used to identify the optimal combination of sensitivity and specificity values.[110] The area under the ROC curve, or the area under the curve (AUC), is an index of separation of signal and noise distributions. A higher value of AUC indicates a more effective test.[110] The AUC was calculated by plotting the ROC curve on a graph paper, counting the number of squares below the curve and dividing it by the total number of squares. Sensitivity and specificity analyses were performed using the first session values of the injured hands only.

Post-hoc analysis. We wanted to examine if pain significantly affected grip and if there were significant differences in pain between males and females and the four different orders of testing. Repeated measures ANOVA was conducted with the within subjects variable as pain (baseline pain vs. pain after last maximal grip) and the between subjects variables were gender (male vs. female) and order (1 vs. 2 vs. 3 vs. 4).

Table 3-1: Schematic representation of the study protocol

Order	Event	Time
	Grip 1	6 sec
	Rest 1	
	Complete Effort VAS	1 min
Sub-pain injured	Complete Pain VAS	
	Grip 2	6 sec
	Rest 2	
	Complete Effort VAS	1 min
	Complete Pain VAS	
	Grip 1	6 sec
	Rest 1	
	Complete Effort VAS	1 min
Sub-pain uninjured	Complete Pain VAS	
	Grip 2	6 sec
	Rest 2	
	Complete Effort VAS	1 min
	Complete Pain VAS	
	Grip 1	6 sec
	Rest 1	
	Complete Effort VAS	1 min
Sub-percent injured	Complete Pain VAS	
	Grip 2	6 sec
	Rest 2	
	Complete Effort VAS	1 min
	Complete Pain VAS	
	Grip 1	6 sec
	Rest 1	
	Complete Effort VAS	1 min
Sub-percent uninjured	Complete Pain VAS	
	Grip 2	6 sec
	Rest 2	
	Complete Effort VAS	1 min
	Complete Pain VAS	
	Grip 1	6 sec
	Rest 1	
	Complete Effort VAS	1 min
Maximal injured	Complete Pain VAS	
	Grip 2	6 sec
	Rest 2	
	Complete Effort VAS	1 min
	Complete Pain VAS	
	Grip 1	6 sec
	Rest 1	
	Complete Effort VAS	2 min
Maximal uninjured	Complete Pain VAS	
	Grip 2	6 sec
	Rest 2	
	Complete Effort VAS	1 min
	Complete Pain VAS	
	Rest	10 min
	Repeat	

Table 3-2: Calculating sensitivity and specificity for the slope cut-off value of X during the force-decay phase

		EFFORT		
		+ (Submaximal Effort)	- (Maximal Effort)	**Total**
SLOPE TEST	+ (Slope≥X)	***a*** True-positives	***b*** False-positives	***a + b***
	- (Slope<X)	***c*** False-negatives	***d*** True-negatives	***c + d***
	Total	***a + c***	***b + d***	**N**

Sensitivity = a/(a + c) = True-positives/Total Submaximal Effort
Specificity = d/(b + d) = True-negatives/Total Maximal Effort

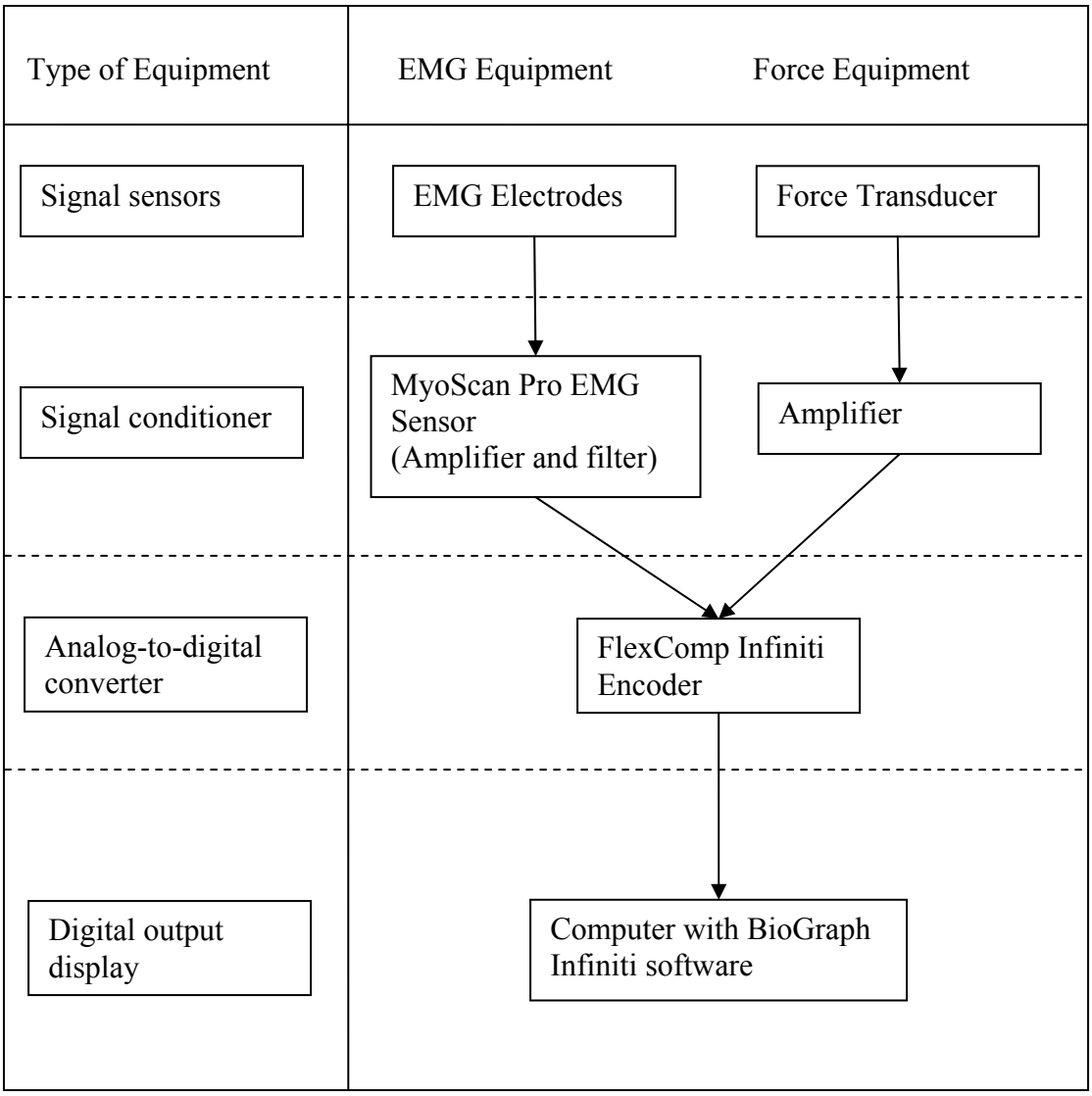


Figure 3-1: Biomechanical instruments for recoding force and electromyographic signals

Figure 3-2: Electronic Jamar dynamometer

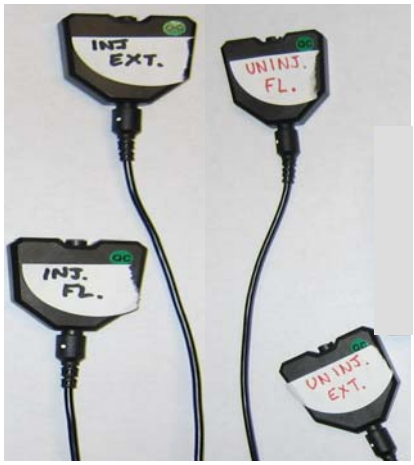


Figure 3-3: MyoScan active sensors

Figure 3-4: FlexComp Infiniti encoder

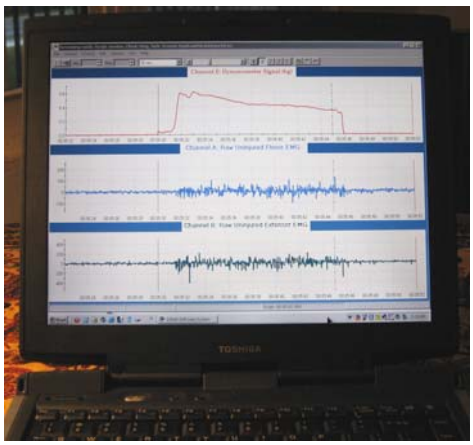


Figure 3-5: BioGraph Infiniti polygraph software

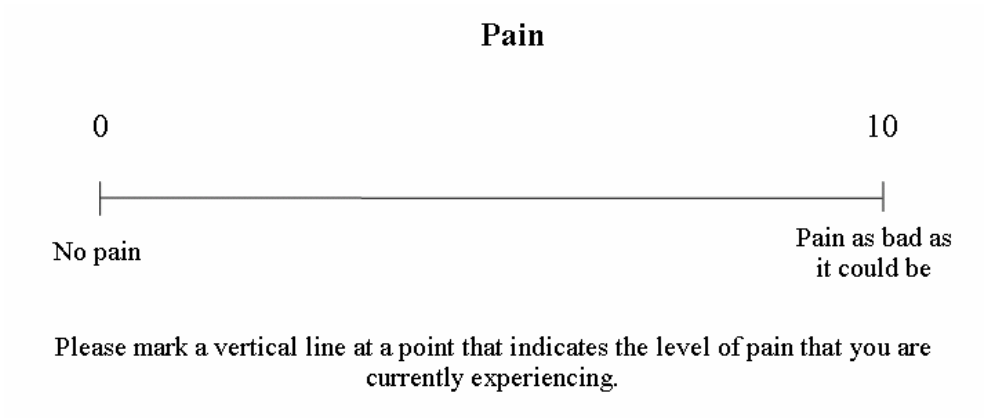


Figure 3-6: Pain Intensity Visual Analog Scale

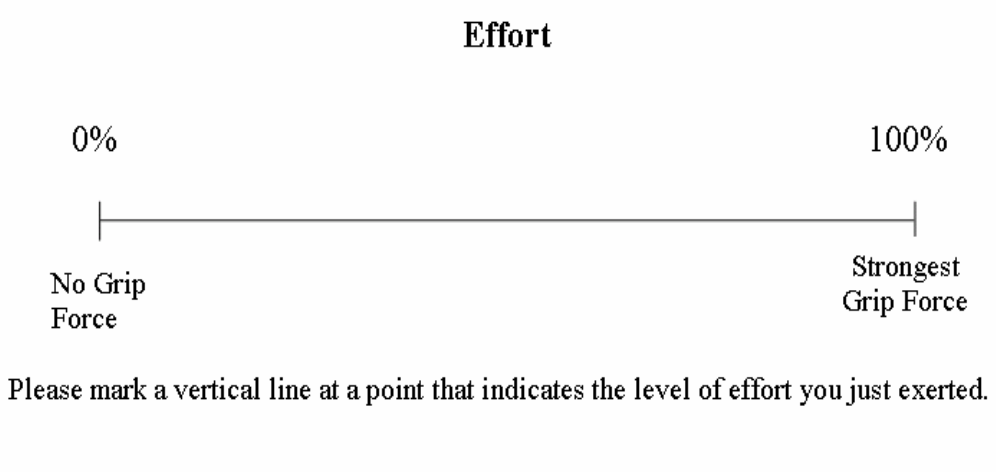


Figure 3-7: Perceived Effort Visual Analog Scale

Figure 3-8: Setup used to check the dynamometer calibration

CHAPTER 4
RESULTS

Subjects

Forty subjects (20 males and 20 females) participated in the study. Average age was 37 $\pm$ 12 years. At the time of the study, over half (N=23) of the subjects were employed, with the most being employed by educational institutions (N=7). All subjects had unilateral upper extremity musculoskeletal conditions, with two-thirds (N=26) experiencing injury to their dominant side (Table 4-1). The most common location of the injury was to the hands (N=16). Almost all men (N=19) experienced traumatic injuries. In contrast, equal number of women experienced traumatic injuries (N=9) and cumulative trauma disorders (N=10). Injury-related baseline pain as measured by the VAS ranged from 0-6 cm with an average and SD of 1.6 $\pm$ 1.8 cm. Three-eights of the subjects (N=15) experienced reduced ability to independently perform activities of daily living due to their injury (Table 4-2).

Specific Aim 1

For the specific aim 1, differences were examined for 4 force-time curve (F-T curve) characteristics including peak force, time-to-peak force, slope of force-generation phase and slope of force-decay phase using Repeated Measures ANOVA. The within-subjects variables were 1) effort (maximal vs. submaximal), 2) session (1 vs. 2), and 3) injury (injured vs. uninjured), while the between-subjects variable was gender (male vs. female). When significant differences existed between the two sessions, we computed separate ANOVAs for the first and second sessions. When there were no significant

differences between sessions, we considered only the values of the first session. All differences were deemed significant at the 0.05 alpha levels. Average values of the four F-T curve characteristics for males and females are presented in Tables 4-3 and 4-4.

Peak Force

Peak force indicates strength of an isometric contraction. We found a significant interaction between session and injury [F (1, 38) = 5.05, $p \leq 0.03$] (Table 4-5). When compared to the first session, peak force during second session increased for injured hands but decreased for uninjured hands (Figure 4-1). For both sessions, there were significant main effects for injury, effort, and gender. Peak force was significantly greater for uninjured vs. injured hand, maximal vs. submaximal effort, and males vs. females (Table 4-6, Table 4-7, Figure 4-2). When analyzed separately, both sessions showed significant interaction effects between gender and effort as well as between injury and effort. The difference in peak force between maximal and submaximal efforts was greater for males than for females and for the uninjured hands vs. the injured hands (Figure 4-3).

Time-to-peak Force

Time-to-peak force indicates the time required to reach the highest force exerted during an isometric contraction. Time-to-peak force values were not significantly different between the first and second session [F (1, 38) = 1.93, $p \leq 0.1$] (Table 4-8). For the first session time values, the main effect was not significant for gender [F (1, 38) = 0.32, $p \leq 0.57$] and injury [F (1, 38) = 0.24, $p \leq 0.62$] but was significant for effort [F (1, 38) = 33.64, $p \leq 0.0001$] (Table 4-9, Figure 4-4). Time-to-peak force for maximal effort was greater than submaximal effort by 0.53 seconds.

Slope of the Force-generation Phase

The slope of force-generation phase indicates the rate of force development during the initial phase of an isometric contraction. A significant interaction effect existed between injury and effort [F (1, 38) = 5.77, $p \leq 0.02$] (Table 4-10). When compared to submaximal effort, the slopes of maximal effort were steeper for uninjured than for the injured hands (Figure 4-5). The main effect for session was not significant [F (1, 38) = 0.37, $p \leq 0.54$] (Table 4-10). For the first session slopes, significant main effects existed for injury [F (1, 38) = 10.0, $p \leq 0.003$], effort [F (1, 38) = 55.77, $p \leq 0.0001$], and gender [F (1, 38) = 8.37, $p \leq 0.006$] (Table 4-11, Figure 4-6). In other words, the slopes of force-generation phase were steeper for the uninjured hand than the injured hand (by 0.24 V/s), for the maximal effort than the submaximal effort (by 0.61 V/s), and for males than females (by 0.46 V/s).

Slope of the Force-decay Phase

The slope of the force-decay phase indicates the extent of fatigue during an isometric contraction. A significant interaction effect existed between injury and effort [F (1, 38) = 4.03, $p \leq 0.052$] (Table 4-12). In other words, the decrease in slope between maximal effort and submaximal effort was greater for the uninjured hand compared to the injured hand (Figure 4-7). A significant interaction effect also existed between session and gender [F (1, 38) = 9.47, $p \leq 0.005$] (Table 4-12). That is, the steepness of the slopes during the second session (as compared to the first session) increased for males but decreased for females (Figure 4-8).

For both sessions, significant main effects existed for injury and effort. A significant main effect for gender existed for the second session and not for the first session (Tables 4-13 and 4-14). That is, the slopes of force-decay phase were

significantly steeper for the uninjured than the injured hand, the maximal vs. submaximal effort, and males vs. females (Figure 4-9).

Specific Aim 2

For the specific aim 2, differences were examined for 2 electromyographic (EMG) properties, namely amplitude and median frequency ratio (MF-ratio) using Repeated Measures ANOVA. The within-subjects variables were 1) effort (maximal vs. submaximal), 2) session (1 vs. 2), and 3) injury (injured vs. uninjured), while the between-subjects variable was gender (male vs. female). When significant differences existed between the two sessions, we performed separate ANOVAs for the first and second session. When there were no significant differences between sessions, we considered only the values of the first session. All differences were deemed significant at the 0.05 alpha levels. Average values of the EMG properties for males and females are presented in Tables 4-15, 4-16 and 4-17.

Flexor EMG Amplitude

The amplitude of the EMG signal represents the magnitude of the muscle activity. There were no significant differences in flexor EMG amplitude between the first and second session [F (1, 38) = 0.02, $p \leq 0.87$] (Table 4-18). For the first session, significant main effects existed for injury [F (1, 38) = 6.29, $p \leq 0.01$] and effort [F (1, 38) = 91.35, $p \leq 0.0001$] but not for gender [F (1, 38) = 0.18, $p \leq 0.6$] (Table 4-19). In other words, flexor EMG amplitude was significantly greater for the uninjured vs. injured hands, and for maximal vs. submaximal efforts (Figure 4-11). The first session revealed a significant interaction effect between injury and effort [F (1, 38) = 7.81, $p \leq 0.01$] (Table 4-19). That is, flexor EMG amplitude was similar for the injured and uninjured hands during submaximal effort but greater for uninjured hand during maximal effort (Figure 4-10).

Extensor EMG Amplitude

A significant interaction effect existed between effort and session [F (1, 38) = 5.89, $p \leq 0.02$] (Table 4-20). That is, the decrease in extensor EMG amplitude between the first and second session was greater for maximal than for submaximal efforts (Figure 4-12). For both sessions, significant main effects existed for effort but not for gender and injury (Tables 4-21 and 4-22). In other words, extensor EMG amplitude was significantly greater for maximal vs. submaximal efforts (Figure 4-13).

Flexor Median Frequency Ratio

The median frequency ratio (MF-ratio) represents the extent of fatigue or motor unit de-recruitment during an isometric contraction. The flexor MF-ratio was not significantly different between the first and second session (Table 4-23). For the MF-ratios in the first session, significant main effects existed for effort [F (1, 38) = 30.27, $p \leq 0.0001$] but not for gender [F (1, 38) = 0.43, $p \leq 0.52$] or injury [F (1, 38) = 0.02, $p \leq 0.9$] (Table 4-24). In other words, MF-ratio was significantly smaller for maximal vs. submaximal efforts (Figure 4-14). Also, a significant interaction effect existed between injury, effort, and gender (Tables 4-23 and 4-24). The decrease in MF-ratio between submaximal and maximal efforts was greater for uninjured vs. injured hands in males but not in females (uninjured and injured hands showed the same decrease in MF-ratio) (Figure 4-15).

Extensor Median Frequency Ratio

A significant main effect existed for session [F (1, 38) = 4.61, $p \leq 0.04$] (Table 4-25). Therefore, we performed separate ANOVAs for each session. For both sessions, main effects were significant for effort but not significant for gender and injury (Tables 4-26 and 4-27). That is, MF-ratio was significantly smaller for maximal vs. submaximal

efforts (Figure 4-16). During the first session, a significant interaction effect existed between injury and effort (Table 4-26). In other words, the decrease in MF-ratio between submaximal and maximal efforts was greater for uninjured hand when compared to the injured hand (Figure 4-17).

Specific Aim 3

To examine the validity of the various force and EMG measures we first examined the test-retest reliability and then the effectiveness of the most highly significant variables. The test-retest reliability of the F-T curve characteristics and EMG properties was analyzed using the Intraclass Correlation Coefficient (ICC 3, 1). Generally, coefficients below 0.50 represent poor reliability, coefficients between 0.50 and 0.75 represent moderate reliability, and values above 0.75 represent good reliability. Moreover, to ensure valid interpretations, reliability should exceed 0.90.[109] The validity of the F-T curve characteristics and EMG properties was examined by calculating sensitivity and specificity values for the four measures that showed the most significant differences between maximal and submaximal efforts. In addition, ROC curves were generated to identify the optimal cutoff values of these measures. The sensitivity and specificity analyses were performed using injured hands only.

Test-Retest Reliability

When examining the test-retest reliability, we will discuss only the values of maximal effort because it has been documented that submaximal effort is less consistent.[188] The test-retest reliability of F-T curve characteristics ranged from $r = 0.3$ to $r = 0.96$ (Table 4-28). The test-retest reliability of EMG properties ranged from $r = 0.7$ to $r = 0.96$ (Table 4-29).

Validity

The measures that showed in the greatest significance between maximal and submaximal efforts were time-to-peak force, slope of force-generation phase, flexor MF-ratio, and extensor MF-ratio (Table 4-30). Sensitivity and specificity values as well as overall error rates for multiple cutoff values were calculated and are shown for slopes of force-generation phase (Table 4-31), slopes of force-decay phase (Table 4-32), flexor MF-ratio (Table 4-33), and extensor MF-ratio (Table 4-34). We did not calculate the sensitivity and specificity values for time-to-peak force because it had poor test-retest reliability rendering it as an invalid measure. Using the sensitivity and specificity values for various cutoff values, we created ROC curves. When significant differences in gender existed, we generated separate ROC curves for males and females. We did not create ROC curves for the slope of force-decay phase because it had poor sensitivity and specificity values. The optimal cutoff values for slope of force-generation phase, flexor MF-ratio, and extensor MF-ratio are presented in Table 4-35.

Slope of force-generation phase

The ROC curve revealed that for the force-generation phase, the slope cutoff value of 1.5 V/s for men yielded the most optimal combination of sensitivity (0.85) and specificity (0.55) and the lowest overall error rate (0.6). For women, the slope cutoff value of 0.5 V/s yielded the most optimal combination of sensitivity (0.6) and specificity (0.85) and the lowest overall error rate (0.55) (Table 4-31). The proportional area under the ROC curve was greater for women (76%) than for men (72%) (Figure 4-18).

Slope of force-decay phase

The slope cutoff value of –0.04V/s yielded the most optimal combination of sensitivity (0.85) and specificity (0.27) and the lowest overall error rate (0.87) (Table 4-32).

Median frequency ratio

The ROC curve for flexor MF-ratio revealed that the ratio cutoff value of 102% yielded the most optimal combination of sensitivity (0.53) and specificity (0.78) and the lowest overall error rate (0.70) (Table 4-33, Figure 4-19). The proportional area under the ROC curve for flexor frequency ratio was. For the ratio of extensor median frequency, the ratio cutoff value of 100% yielded the most optimal combination of sensitivity (0.63) and specificity (0.7) producing the lowest overall error rate (0.68) (Table 4-34). The proportional area under the ROC curve was the same for the frequency ratio for forearm flexors (66.25%) as well as extensors (71%) (Figure 4-19).

Post-Hoc Analysis

There were no significant differences between baseline pain and pain after last maximal effort grip [F (1, 38) = 0.33, $p \leq 0.56$]. There were no significant differences in pain between males and females [F (1, 38) = 0.008, $p \leq 0.92$] and between the four orders of testing [F (1, 38) = 1.37, $p \leq 0.26$].

Summary

1. Session differences were identified by peak force, slope of force-decay phase, extensor amplitude, and extensor MF-ratio.
2. Differences between injured and uninjured hands were identified by peak force, slopes of force-generation phase and force-decay phase, flexor EMG amplitude, flexor MF-ratio, and extensor MF-ratio.
3. Differences between maximal and submaximal efforts were identified by all F-T curve characteristics and EMG properties.
4. Gender differences were identified by peak force, slope of the force-generation phase, slope of force-decay phase, and flexor MF-ratio.

5. The test-retest reliability of force variables ranged from $r = 0.3$ to $r = 0.96$ and EMG variables ranged from $r = 0.7$ to $r = 0.96$.
6. Based on the area under the ROC curve, the slope of the force-generation phase was the most effective in distinguishing between maximal and submaximal efforts. Yet, 15% of the men who exerted submaximal effort were misclassified as exerting a maximal effort and 45% of the men who exerted maximal effort were misclassified as exerting a submaximal effort. Further, 40% of women who exerted submaximal effort were misclassified as exerting a maximal effort and 15% of women who exerted maximal effort were misclassified as exerting maximal effort.

Table 4-1: Demographic characteristics of the study sample

	Men (N=20)		Women (N=20)		All (N=40)	
	Mean or Number	SD or %	Mean or Number	SD or %	Mean or Number	SD or %
Age (years)	37	11.8	39	12.73	37.7	12.14
Height (inches)	71	2.81	66	3.6	63	4.04
Weight (lbs.)	208	36	172	46	190	44
Race						
European	13	65	17	85	30	75
African	4	20	1	5	5	12.5
Hispanic	2	10	2	10	4	10
Asian	1	5	--	--	1	2.5
Occupation Classification						
Business and Financial	--	--	2	10	2	5
Education	7	35	3	15	10	25
Healthcare	3	15	4	20	7	17.5
Food and Service	--	--	3	15	3	7.5
Sales	1	5	1	5	2	5
Office and Administrative	1	5	4	20	5	12.5
Construction	1	5	--	--	1	2.5
Installation, and Maintenance	1	5	--	--	1	2.5
Production	2	10	--	--	2	5
Transportation	2	10	--	--	2	5
Sports Occupations	--	--	2	10	2	5
Retired/Not working	2	10	1	5	3	7.5
Current work status						
Full-time	4	20	11	55	15	37.5
Part-time	3	15	5	25	8	20
Not working	9	45	4	20	13	32.5
Dominant extremity						
Left	4	20	3	15	7	17.5
Right	16	80	17	85	33	82.5
Injured extremity						
Left	10	50	7	35	17	42.5
Right	10	50	13	65	23	57.5

Table 4-2: Injury related characteristics of the study sample

	Men (N=20)		Women (N=20)		All (N=40)	
	Ave/Num	SD/%	Ave/Num	SD/%	Ave/Num	SD/%
Location of injury						
Hand	10	50	6	30	16	40
Wrist	4	20	7	35	11	27.5
Forearm	1	5	5	25	6	15
Elbow	5	25	2	10	7	17.5
Duration of injury (months)	8	15	16.15	29	19.7	41
Etiology						
Cause of injury						
Traumatic	19	95	9	45	28	70
Motor vehicle accident	3	15	5	25	8	20
Sports injury	6	30	--	--	6	15
Violence-related injury	2	10	--	--	2	5
Falls	3	15	3	15	6	15
Occupational injury	1	5	--	--	1	2.5
Other	4	20	1	5	5	12.5
Cumulative Trauma	1	5	10	50	11	27.5
Sports injury	1	5	3	15	4	10
Occupational injury	--		6	30	6	15
House maintenance	--	--	1	5	1	2.5
Do not know	--	--	1	5	1	2.5
Signs/Symptoms						
Pain intensity in past week (cm.)	3.15	2.1	3.46	2.2	3.3	2.1
Current pain intensity (cm.)	1.57	1.87	1.61	1.94	1.5	1.8
Injury limits ADL	6	30	9	45	15	37.5
Management						
Currently taking pain medications	5	25	6	30	11	27.5
Undergone surgical intervention	12	60	10	50	22	55
Benefited from surgery	12	60	9	45	21	52.5
Length of rehabilitative care						
Duration (weeks)	6.05	7.01	30.82	4.62	11.1	21.6
Times per week (median)	2	--	2	--	2	--
Success of rehabilitative care	18	90	16	80	34	85
Somewhat successful	2	10	3	15	5	12.5
Successful	10	50	7	35	17	42.5
Very successful	6	30	6	30	12	30

Table 4-3: First session averages of the F-T curve characteristics

	Males (N=20)				Females (N=20)			
	Injured Hand		Uninjured Hand		Injured Hand		Uninjured Hand	
	Average	SD	Average	SD	Average	SD	Average	SD
Peak Force (kg)								
Maximal effort	29.90	15.44	39.67	10.50	20.14	10.22	26.87	8.86
Sub-pain effort	16.03	10.86	21.01	9.92	10.88	7.15	13.31	7.50
Sub-percent effort	15.60	8.92	20.22	9.20	10.43	6.39	14.49	7.66
Time-to-peak force (s)								
Maximal effort	1.75	1.08	1.44	0.58	1.35	0.63	1.29	0.55
Sub-pain effort	0.96	0.41	1.07	0.44	1.12	0.42	1.10	0.45
Sub-percent effort	0.93	0.34	0.94	0.36	0.86	0.33	0.99	0.34
Slope of force-generation phase (V/s)								
Maximal effort	1.690	1.343	1.973	1.061	0.936	0.589	1.354	0.710
Sub-pain effort	0.883	0.762	0.930	0.602	0.412	0.271	0.626	0.407
Sub-percent effort	0.863	0.648	1.221	0.848	0.522	0.357	0.631	0.367
Slope of force-decay phase (V/s)								
Maximal effort	-0.030	0.064	-0.043	0.043	-0.024	0.019	-0.046	0.023
Sub-pain effort	-0.016	0.037	-0.030	0.042	-0.015	0.015	-0.029	0.029
Sub-percent effort	-0.022	0.028	-0.032	0.036	-0.020	0.014	-0.027	0.028

Table 4-4: Second session averages of the F-T curve characteristics

	Males (N=20)				Females (N=20)			
	Injured Hand		Uninjured Hand		Injured Hand		Uninjured Hand	
	Average	SD	Average	SD	Average	SD	Average	SD
Peak Force (kg)								
Maximal effort	29.68	15.21	38.40	10.75	20.35	9.96	25.59	8.44
Sub-pain effort	16.76	9.43	21.00	9.27	11.26	6.31	13.82	7.98
Sub-percent effort	16.95	8.90	20.28	7.26	10.75	6.04	13.10	6.13
Time to peak force (s)								
Maximal effort	1.57	1.08	1.36	0.54	1.27	0.70	1.38	0.70
Sub-pain effort	0.92	0.30	1.06	0.44	1.04	0.36	0.90	0.28
Sub-percent effort	0.85	0.35	0.93	0.30	0.95	0.38	0.82	0.25
Slope of force-generation phase (V/s)								
Maximal effort	1.622	1.292	1.996	1.530	0.949	0.692	1.455	0.925
Sub-pain effort	0.832	0.589	1.074	0.872	0.474	0.301	0.663	0.417
Sub-percent effort	1.021	0.865	1.150	0.738	0.526	0.465	0.652	0.344
Slope of force-decay phase (V/s)								
Maximal effort	-0.035	0.049	-0.051	0.045	-0.023	0.014	-0.040	0.023
Sub-pain effort	-0.030	0.034	-0.040	0.039	-0.016	0.017	-0.022	0.022
Sub-percent effort	-0.034	0.031	-0.037	0.028	-0.015	0.012	-0.022	0.019

Table 4-5: Four-Way ANOVA on the values of peak force

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	7446.76	1	7446.76	9.82	0.003*
Within-Subjects					
Injured	2906.15	1	2906.15	41.77	0.0001*
Effort	14894.06	1	14894.06	183.69	0.0001*
Session	0.32	1	0.32	0.02	0.883
Injured x Gender	125.51	1	125.51	1.80	0.187
Effort x Gender	425.23	1	425.23	5.24	0.028*
Session x Gender	2.92	1	2.92	0.20	0.656
Injured x Effort	340.31	1	340.31	15.49	0.0001*
Injured x Session	31.45	1	31.45	5.05	0.031*
Effort x Session	13.47	1	13.47	1.32	0.257
Injured x Effort x Gender	11.31	1	11.31	0.51	0.477
Injured x Session x Gender	0.00	1	0.00	0.00	0.997
Effort x Session x Gender	1.10	1	1.10	0.11	0.745
Injured x Effort x Session	0.01	1	0.01	0.00	0.970
Injured x Effort x Session x Gender	4.97	1	4.97	0.70	0.409

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Session = Session 1 vs. Session 2

Table 4-6: Three-Way ANOVA on first session values of the peak force

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	3577.37	1	3577.37	9.01	0.005*
Within-Subjects					
Injured	1771.10	1	1771.10	39.82	0.0001*
Effort	7901.72	1	7901.72	156.37	0.0001*
Injured x Gender	62.65	1	62.65	1.41	0.243
Effort x Gender	234.76	1	234.76	4.65	0.038*
Injured x Effort	168.33	1	168.33	9.57	0.004*
Injured x Effort x Gender	0.64	1	0.64	0.04	0.849

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-7: Three-Way ANOVA on second session values of the peak force

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	3872.31	1	3872.31	10.31	0.003*
Within-Subjects					
Injured	1166.49	1	1166.49	37.24	0.0001*
Effort	7005.81	1	7005.81	171.99	0.0001*
Injured x Gender	62.86	1	62.86	2.01	0.165
Effort x Gender	191.56	1	191.56	4.70	0.036*
Injured x Effort	172.00	1	172.00	14.95	0.0001*
Injured x Effort x Gender	15.64	1	15.64	1.36	0.251

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-8: Four-Way ANOVA on the values of time-to-peak force

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	0.42	1	0.42	0.33	0.570
Within-Subjects					
Injured	0.07	1	0.07	0.37	0.545
Effort	21.50	1	21.50	58.14	0.0001*
Session	0.45	1	0.45	1.93	0.173
Injured x Gender	0.01	1	0.01	0.04	0.845
Effort x Gender	0.77	1	0.77	2.09	0.157
Session x Gender	0.00	1	0.00	0.01	0.904
Injured x Effort	0.38	1	0.38	1.72	0.197
Injured x Session	0.00	1	0.00	0.00	0.993
Effort x Session	0.01	1	0.01	0.04	0.842
Injured x Effort x Gender	0.53	1	0.53	2.37	0.132
Injured x Session x Gender	0.11	1	0.11	0.97	0.331
Effort x Session x Gender	0.09	1	0.09	0.32	0.577
Injured x Effort x Session	0.27	1	0.27	1.64	0.207
Injured x Effort x Session x Gender	0.20	1	0.20	1.20	0.281

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Session = Session 1 vs. Session 2

Table 4-9: Three-Way ANOVA on the first session values of time-to-peak force

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	0.25	1.00	0.25	0.32	0.572
Within-Subjects					
Injured	0.03	1.00	0.03	0.24	0.629
Effort	11.25	1.00	11.25	33.64	0.0001*
Injured x Gender	0.09	1.00	0.09	0.63	0.434
Effort x Gender	0.69	1.00	0.69	2.08	0.158
Injured x Effort	0.65	1.00	0.65	2.95	0.094
Injured x Effort x Gender	0.04	1.00	0.04	0.18	0.672

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-10: Four-Way ANOVA on the slopes of the force-generation phase

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	30.56	1	30.56	6.99	0.012*
Within-Subjects					
Injured	7.49	1	7.49	18.61	0.0001*
Effort	36.28	1	36.28	52.06	0.0001*
Session	0.12	1	0.12	0.37	0.548
Injured x Gender	0.01	1	0.01	0.03	0.854
Effort x Gender	0.55	1	0.55	0.78	0.382
Session x Gender	0.01	1	0.01	0.03	0.869
Injured x Effort	0.92	1	0.92	5.77	0.021*
Injured x Session	0.02	1	0.02	0.07	0.786
Effort x Session	0.00	1	0.00	0.01	0.916
Injured x Effort x Gender	0.34	1	0.34	2.10	0.155
Injured x Session x Gender	0.00	1	0.00	0.00	0.965
Effort x Session x Gender	0.06	1	0.06	0.30	0.588
Injured x Effort x Session	0.19	1	0.19	1.26	0.268
Injured x Effort x Session x Gender	0.08	1	0.08	0.52	0.476

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Session = Session 1 vs. Session 2

Table 4-11: Three-Way ANOVA on the first session slopes of the force-generation phase

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	15.80	1	15.80	8.37	0.006*
Within-Subjects					
Injured	3.40	1	3.40	10.00	0.003*
Effort	18.43	1	18.43	55.77	0.0001*
Injured x Gender	0.00	1	0.00	0.01	0.907
Effort x Gender	0.48	1	0.48	1.46	0.234
Injured x Effort	0.14	1	0.14	0.88	0.355
Injured x Effort x Gender	0.37	1	0.37	2.36	0.133

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-12: Four-Way ANOVA on the slopes of the force-decay phase

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	0.00855	1	0.00855	1.25	0.271
Within-Subjects					
Injured	0.01665	1	0.01665	32.56	0.0001*
Effort	0.00860	1	0.00860	8.38	0.006*
Session	0.00082	1	0.00082	1.60	0.213
Injured x Gender	0.00004	1	0.00004	0.07	0.788
Effort x Gender	0.00031	1	0.00031	0.30	0.587
Session x Gender	0.00484	1	0.00484	9.47	0.004*
Injured x Effort	0.00225	1	0.00225	4.03	0.052
Injured x Session	0.00035	1	0.00035	0.72	0.401
Effort x Session	0.00000	1	0.00000	0.00	0.957
Injured x Effort x Gender	0.00011	1	0.00011	0.20	0.655
Injured x Session x Gender	0.00003	1	0.00003	0.07	0.795
Effort x Session x Gender	0.00007	1	0.00007	0.17	0.685
Injured x Effort x Session	0.00002	1	0.00002	0.05	0.821
Injured x Effort x Session x Gender	0.00019	1	0.00019	0.45	0.507

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Session = Session 1 vs. Session 2

Table 4-13: Three-Way ANOVA on the first session slopes of the force-decay phase

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	0.00026	1	0.00026	0.06239	0.804
Within-Subjects					
Injured	0.01091	1	0.01091	15.96264	0.0001*
Effort	0.00440	1	0.00440	5.62535	0.023*
Injured x Gender	0.00007	1	0.00007	0.10293	0.750
Effort x Gender	0.00004	1	0.00004	0.05665	0.813
Injured x Effort	0.00091	1	0.00091	1.93942	0.172
Injured x Effort x Gender	0.00030	1	0.00030	0.62882	0.433

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-14: Three-Way ANOVA on the second session slopes of the force-decay phase

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	0.013126	1	0.013126	4.1709	0.048*
Within-Subjects					
Injured	0.006091	1	0.006091	19.5771	0.0001*
Effort	0.004200	1	0.004200	6.5429	0.015*
Injured x Gender	0.000000	1	0.000000	0.0002	0.989
Effort x Gender	0.000330	1	0.000330	0.5142	0.478
Injured x Effort	0.001356	1	0.001356	2.6824	0.110
Injured x Effort x Gender	0.000005	1	0.000005	0.0093	0.924

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-15: Average values for EMG amplitude

	Males (N=20)				Females (N=20)			
	Injured Hand		Uninjured Hand		Injured Hand		Uninjured Hand	
	Average	SD	Average	SD	Average	SD	Average	SD
First Session								
Flexor EMG amplitude (μV)								
Maximal effort	59.57	35.38	69.43	34.52	47.61	24.51	62.56	34.76
Sub-pain effort	24.37	15.16	24.26	9.99	23.58	11.50	28.52	18.49
Sub-percent effort	23.08	8.92	22.52	8.83	22.10	12.93	26.00	17.15
Extensor EMG amplitude (μV)								
Maximal effort	126.94	85.38	150.12	106.90	101.51	82.76	101.93	44.58
Sub-pain effort	68.68	54.14	64.38	52.29	45.36	33.20	49.86	22.12
Sub-percent effort	56.86	33.80	62.08	39.04	41.78	30.68	42.60	21.33
Second Session								
Flexor EMG amplitude (μV)								
Maximal effort	58.26	33.96	65.93	34.95	49.73	30.77	61.36	30.37
Sub-pain effort	25.00	10.63	23.47	10.25	24.21	13.25	29.55	23.82
Sub-percent effort	24.30	12.94	21.68	7.58	22.02	10.11	26.58	19.64
Extensor EMG amplitude (μV)								
Maximal effort	120.66	83.20	139.24	82.24	97.63	83.02	100.61	47.44
Sub-pain effort	62.78	48.38	64.86	46.32	48.13	37.53	45.47	23.72
Sub-percent effort	60.87	34.35	62.08	31.59	44.66	35.58	42.15	21.52

Table 4-16: Average values of EMG median frequency for the first session

	Males (N=20)				Females (N=20)			
	Injured Hand		Uninjured Hand		Injured Hand		Uninjured Hand	
	Average	SD	Average	SD	Average	SD	Average	SD
First second								
Flexor Median Frequency (Hz)								
Maximal effort	110.46	15.60	120.62	10.49	116.52	10.45	116.77	12.35
Sub-pain effort	110.13	17.80	115.54	11.90	115.21	13.57	116.28	11.96
Sub-percent effort	109.18	13.26	117.25	10.64	116.10	15.61	114.96	12.12
Extensor Median Frequency (Hz)								
Maximal effort	132.74	14.24	141.75	14.39	136.86	14.20	138.52	11.38
Sub-pain effort	130.59	12.43	137.58	13.12	137.96	12.97	137.18	11.85
Sub-percent effort	134.84	13.22	139.86	16.34	136.16	15.71	137.72	10.19
Last second								
Flexor Median Frequency (Hz)								
Maximal effort	107.56	16.03	111.33	13.98	113.64	9.83	115.30	12.16
Sub-pain effort	112.54	16.82	119.19	13.36	119.36	14.92	119.37	11.31
Sub-percent effort	111.81	17.48	122.98	12.53	117.95	12.60	118.68	10.81
Extensor Median Frequency (Hz)								
Maximal effort	132.79	18.87	137.42	16.24	131.45	15.56	133.37	14.95
Sub-pain effort	135.11	16.51	142.84	15.63	138.25	13.88	139.82	12.72
Sub-percent effort	135.63	15.33	145.44	18.38	138.43	15.41	141.19	12.41
Flexor Median Frequency Ratio (% initial MF)								
Maximal effort	97.75	2.05	92.22	7.06	97.84	7.93	98.95	7.20
Sub-pain effort	103.10	2.67	103.36	7.64	104.11	12.40	102.95	6.75
Sub-percent effort	102.25	1.75	105.02	7.08	102.27	9.08	103.66	7.78
Extensor Median Frequency Ratio (% initial MF)								
Maximal effort	100.43	3.31	96.95	5.77	96.02	5.09	96.18	5.87
Sub-pain effort	103.61	2.23	103.79	5.14	100.40	7.34	101.99	4.81
Sub-percent effort	100.59	1.31	103.96	4.71	101.88	5.83	102.55	5.60

Table 4-17: Average values of EMG median frequency for second session values

	Males (N=20)				Females (N=20)			
	Injured Hand		Uninjured Hand		Injured Hand		Uninjured Hand	
	Average	SD	Average	SD	Average	SD	Average	SD
First second								
Flexor Median Power Frequency (Hz)								
Maximal effort	111.56	14.68	121.27	11.39	116.04	10.44	117.35	10.76
Sub-pain effort	109.01	15.15	118.20	13.11	117.03	14.43	113.73	9.66
Sub-percent effort	109.51	21.29	119.15	10.72	115.40	14.95	115.31	12.65
Extensor Median Power Frequency (Hz)								
Maximal effort	136.65	17.27	143.57	14.54	138.26	14.59	138.47	10.66
Sub-pain effort	135.06	16.34	143.12	13.25	138.58	13.44	138.47	10.16
Sub-percent effort	136.51	17.36	144.70	14.62	138.99	13.84	137.68	10.41
Last second								
Flexor Median Power Frequency (Hz)								
Maximal effort	108.21	17.79	112.32	13.70	113.52	9.01	115.40	10.82
Sub-pain effort	112.09	17.78	119.65	12.88	117.36	12.83	118.86	11.44
Sub-percent effort	110.02	25.28	121.76	13.29	118.88	10.82	119.55	11.43
Extensor Median Power Frequency (Hz)								
Maximal effort	134.07	17.80	139.25	16.15	133.16	16.59	133.82	12.95
Sub-pain effort	135.73	18.06	144.78	16.87	140.15	15.85	137.87	15.66
Sub-percent effort	138.22	18.72	145.03	14.57	141.66	14.72	141.17	12.13
Flexor Median Frequency Ratio (% initial MF)								
Maximal effort	96.88	7.31	92.75	8.59	98.21	7.96	98.55	6.85
Sub-pain effort	103.05	10.14	101.43	6.01	100.77	8.96	104.80	8.92
Sub-percent effort	99.54	10.69	102.46	9.69	103.84	9.79	104.16	8.05
Extensor Median Frequency Ratio (% initial MF)								
Maximal effort	98.72	13.26	97.13	7.20	96.27	5.41	96.68	6.35
Sub-pain effort	100.72	9.51	101.11	6.82	101.06	4.68	99.44	6.81
Sub-percent effort	101.34	6.76	100.33	5.14	101.93	3.70	102.55	4.47

Table 4-18: Four-Way ANOVA on flexor EMG amplitude

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	271.25	1	271.25	0.09	0.772
Within-Subjects					
Injured	2805.68	1	2805.68	4.72	0.036*
Effort	102376.24	1	102376.24	102.07	0.000*
Session	1.87	1	1.87	0.02	0.877
Injured x Gender	885.46	1	885.46	1.49	0.230
Effort x Gender	1716.29	1	1716.29	1.71	0.199
Session x Gender	48.88	1	48.88	0.63	0.432
Injured x Effort	1885.15	1	1885.15	7.16	0.011*
Injured x Session	52.08	1	52.08	2.52	0.121
Effort x Session	28.51	1	28.51	0.56	0.457
Injured x Effort x Gender	8.49	1	8.49	0.03	0.858
Injured x Session x Gender	9.67	1	9.67	0.47	0.498
Effort x Session x Gender	39.26	1	39.26	0.78	0.384
Injured x Effort x Session	21.13	1	21.13	0.48	0.492
Injured x Effort x Session x Gender	18.79	1	18.79	0.43	0.517

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Session = Session 1 vs. Session 2

Table 4-19: Three-Way ANOVA on first session values of the flexor EMG amplitude

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	275.21	1	275.21	0.18	0.674
Within-Subjects					
Injured	1811.12	1	1811.12	6.29	0.017*
Effort	52910.89	1	52910.89	91.35	0.000*
Injured x Gender	355.01	1	355.01	1.23	0.274
Effort x Gender	1137.34	1	1137.34	1.96	0.169
Injured x Effort	1152.70	1	1152.70	7.81	0.008*
Injured x Effort x Gender	1.01	1	1.01	0.01	0.935

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-20: Four-Way ANOVA on extensor EMG amplitude

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	64338.83	1	64338.83	2.92	0.096
Within-Subjects					
Injured	2045.07	1	2045.07	0.45	0.507
Effort	345249.89	1	345249.89	61.35	0.0001*
Session	439.71	1	439.71	1.00	0.323
Injured x Gender	1501.12	1	1501.12	0.33	0.569
Effort x Gender	5212.78	1	5212.78	0.93	0.342
Session x Gender	167.83	1	167.83	0.38	0.540
Injured x Effort	2042.04	1	2042.04	3.13	0.085
Injured x Session	86.64	1	86.64	0.51	0.480
Effort x Session	1037.29	1	1037.29	5.89	0.020*
Injured x Effort x Gender	1144.00	1	1144.00	1.75	0.193
Injured x Session x Gender	27.07	1	27.07	0.16	0.693
Effort x Session x Gender	229.29	1	229.29	1.30	0.261
Injured x Effort x Session	35.09	1	35.09	0.19	0.662
Injured x Effort x Session x Gender	52.27	1	52.27	0.29	0.594

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured Hand

Session = Session 1 vs. Session 2

Table 4-21: Three-Way ANOVA the on first session extensor EMG amplitude

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	35539.32	1	35539.32	2.99	0.092
Within-Subjects					
Injured	1486.78	1	1486.78	0.61	0.439
Effort	192067.72	1	192067.72	55.76	0.0001*
Injured x Gender	562.52	1	562.52	0.23	0.633
Effort x Gender	3814.31	1	3814.31	1.11	0.299
Injured x Effort	770.88	1	770.88	1.99	0.167
Injured x Effort x Gender	842.68	1	842.68	2.17	0.149

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured Hand

Table 4-22: Three-Way ANOVA on the second session extensor EMG amplitude

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	28967.34	1	28967.34	2.74	0.106
Within-Subjects					
Injured	644.93	1	644.93	0.28	0.599
Effort	154219.45	1	154219.45	65.37	0.0001*
Injured x Gender	965.67	1	965.67	0.42	0.520
Effort x Gender	1627.76	1	1627.76	0.69	0.411
Injured x Effort	1306.25	1	1306.25	2.93	0.095
Injured x Effort x Gender	353.59	1	353.59	0.79	0.379

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured Hand

Table 4-23: Four-Way ANOVA on the flexor EMG median frequency ratio

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	343.13	1	343.13	1.26	0.269
Within-Subjects					
Injured	0.41	1	0.41	0.00	0.967
Effort	3133.33	1	3133.33	36.68	0.0001*
Session	41.25	1	41.25	1.14	0.292
Injured x Gender	107.52	1	107.52	0.44	0.510
Effort x Gender	108.02	1	108.02	1.26	0.268
Session x Gender	55.06	1	55.06	1.52	0.225
Injured x Effort	304.34	1	304.34	7.08	0.011*
Injured x Session	7.63	1	7.63	0.22	0.642
Effort x Session	10.04	1	10.04	0.41	0.525
Injured x Effort x Gender	284.58	1	284.58	6.62	0.014*
Injured x Session x Gender	11.37	1	11.37	0.33	0.570
Effort x Session x Gender	62.19	1	62.19	2.56	0.118
Injured x Effort x Session	2.95	1	2.95	0.11	0.745
Injured x Effort x Session x Gender	1.18	1	1.18	0.04	0.837

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Session = Session 1 vs. Session 2

Table 4-24: Three-Way ANOVA on the first session values of flexor EMG median frequency ratio

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	61.64	1	61.64	0.43	0.52
Within-Subjects					
Injured	2.25	1	2.25	0.02	0.901
Effort	1749.05	1	1749.05	30.27	0.0001*
Injured x Gender	24.48	1	24.48	0.17	0.682
Effort x Gender	167.07	1	167.07	2.89	0.097
Injured x Effort	183.60	1	183.60	8.04	0.007*
Injured x Effort x Gender	161.23	1	161.23	7.06	0.011*

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured hand

Table 4-25: Four-Way ANOVA on the extensor EMG median frequency ratio

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	114.58	1	114.58	0.47	0.499
Within-Subjects					
Injured	0.08	1	0.08	0.00	0.981
Effort	1687.78	1	1687.78	26.77	0.0001*
Session	102.07	1	102.07	4.61	0.038*
Injured x Gender	13.25	1	13.25	0.09	0.760
Effort x Gender	145.26	1	145.26	2.30	0.137
Session x Gender	65.39	1	65.39	2.95	0.094
Injured x Effort	82.87	1	82.87	2.32	0.136
Injured x Session	23.51	1	23.51	1.31	0.259
Effort x Session	5.24	1	5.24	0.44	0.513
Injured x Effort x Gender	56.60	1	56.60	1.59	0.216
Injured x Session x Gender	0.47	1	0.47	0.03	0.873
Effort x Session x Gender	0.51	1	0.51	0.04	0.838
Injured x Effort x Session	54.02	1	54.02	5.40	0.026*
Injured x Effort x Session x Gender	44.56	1	44.56	4.46	0.041*

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured Hand

Session = Session 1 vs. Session 2

Table 4-26: Three-Way ANOVA on the first session values of extensor EMG median frequency ratio

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	176.55	1	176.55	1.33	0.256
Within-Subjects					
Injured	10.41	1	10.41	0.14	0.710
Effort	940.59	1	940.59	21.16	0.0001*
Injured x Gender	9.34	1	9.34	0.13	0.725
Effort x Gender	64.31	1	64.31	1.45	0.236
Injured x Effort	135.36	1	135.36	5.07	0.030*
Injured x Effort x Gender	100.80	1	100.80	3.78	0.059

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured Hand

Table 4-27: Three-Way ANOVA on the second session values of extensor EMG median frequency ratio

Source	Sum of Squares	DF	Mean Square	F	p-value
Between-Subjects					
Gender	3.43	1	3.43	0.03	0.875
Within-Subjects					
Injured	13.18	1	13.18	0.16	0.693
Effort	752.43	1	752.43	24.58	0.0001*
Injured x Gender	4.37	1	4.37	0.05	0.820
Effort x Gender	81.46	1	81.46	2.66	0.111
Injured x Effort	1.54	1	1.54	0.08	0.778
Injured x Effort x Gender	0.36	1	0.36	0.02	0.891

* Indicates significant differences at the $p \leq 0.05$ alpha level

Gender = Male vs. Female

Effort = Maximal vs. Submaximal according to imagined pain vs. Fifty percent of maximal effort

Injured = Injured hand vs. Uninjured Hand

Table 4-28: Intraclass Correlation Coefficients for F-T curve characteristics

	Injured hand	Uninjured hand
	r-value	r-value
Peak Force		
Maximal effort	0.957	0.950
Sub-pain effort	0.904	0.919
Sub-percent effort	0.859	0.873
Time-to-peak force		
Maximal effort	0.306	0.368
Sub-pain effort	0.539	0.257
Sub-percent effort	0.414	0.586
Slope of force-generation phase		
Maximal effort	0.822	0.598
Sub-pain effort	0.783	0.788
Sub-percent effort	0.711	0.706
Slope of force-decay phase		
Maximal effort	0.579	0.592
Sub-pain effort	0.677	0.713
Sub-percent effort	0.610	0.604

Table 4-29: Intraclass Correlation Coefficients for EMG properties

	Injured hand	Uninjured hand
	r-value	r-value
Flexor EMG amplitude		
Maximal effort	0.926	0.933
Sub-pain effort	0.824	0.874
Sub-percent effort	0.792	0.938
Extensor EMG amplitude		
Maximal effort	0.967	0.930
Sub-pain effort	0.822	0.915
Sub-percent effort	0.917	0.914
Flexor MF-ratio		
Maximal effort	0.702	0.740
Sub-pain effort	0.618	0.715
Sub-percent effort	0.298	0.777
Extensor MF-ratio		
Maximal effort	0.893	0.710
Sub-pain effort	0.518	0.481
Sub-percent effort	0.496	0.535

Table 4-30: Summary of main effects of effort for force and EMG measures

	Both Sessions		First Session		Second Session	
	F-value	p-value	F-value	p-value	F-value	p-value
F-T Curve						
Peak force	183.68	0.0001	156.37	0.0001	171.99	0.0001
Time-to-peak force	58.14	0.0001	33.64	0.0001	--	--
Slope of force-generation phase	52.06	0.0001	55.77	0.0001	--	--
Slope of force-decay phase	8.38	0.006	5.62	0.023	6.54	0.015
EMG						
Flexor amplitude	102.07	0.0001	91.35	0.0001	--	--
Extensor amplitude	61.35	0.0001	55.76	0.0001	65.37	0.0001
Flexor MF-ratio	36.68	0.0001	30.27	0.0001	--	--
Extensor MF-ratio	26.77	0.0001	21.16	0.0001	24.58	0.0001

Table 4-31: Sensitivity and specificity of specific slope cutoff values for force-generation phase

Slope	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
Males																	
Sensitivity	0.00	0.00	0.20	0.30	0.35	0.45	0.45	0.50	0.55	0.55	0.60	0.60	0.60	0.65	0.70	**0.85**	0.85
Specificity	1.00	1.00	0.95	0.85	0.80	0.80	0.75	0.75	0.70	0.60	0.55	0.55	0.55	0.55	0.55	**0.55**	0.50
Overall error rate	1.00	1.00	0.85	0.85	0.85	0.75	0.80	0.75	0.75	0.85	0.85	0.85	0.85	0.80	0.75	**0.60**	0.65
Females																	
Sensitivity	0.00	0.05	0.10	0.35	**0.50**	0.60	0.70	0.75	0.75	0.85	0.90	0.95	0.95	0.95	0.95	1.00	1.00
Specificity	1.00	1.00	1.00	0.95	**0.85**	0.85	0.60	0.60	0.55	0.45	0.35	0.25	0.20	0.15	0.15	0.15	0.15
Overall error rate	1.00	0.95	0.90	0.70	**0.65**	0.55	0.70	0.65	0.70	0.70	0.75	0.80	0.85	0.90	0.90	0.85	0.85

Table 4-31: Continued

Slope	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3
Males																	
Sensitivity	0.90	0.90	0.95	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Specificity	0.50	0.50	0.40	0.25	0.25	0.25	0.25	0.20	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Overall error rate	0.60	0.60	0.65	0.80	0.75	0.75	0.75	0.80	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Females																	
Sensitivity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Specificity	0.15	0.15	0.10	0.10	0.10	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overall error rate	0.85	0.85	0.90	0.90	0.90	0.95	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 4-31: Continued

Slope	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7
Males														
Sensitivity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Specificity	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.10	0.10	0.05	0.05	0.05	0.05	0.00
Overall error rate	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.90	0.90	0.95	0.95	0.95	0.95	1.00
Females														
Sensitivity	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Specificity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overall error rate	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 4-32: Sensitivity and specificity values of specific slope cutoff values for force-decay phase

Slope	-0.2	-0.18	-0.16	-0.14	-0.12	-0.1	-0.08	-0.06	-0.04	-0.02	0.07
Sensitivity	1	1	1	1	1	1	0.975	0.95	**0.85**	0.575	0
Specificity	0	0.025	0.025	0.025	0.075	0.075	0.075	0.125	**0.275**	0.425	1
Overall error rate	1	0.975	0.975	0.975	0.925	0.925	0.95	0.925	**0.875**	1	1

Table 4-33: Sensitivity and specificity of specific flexor MF-ratio cutoff values

Frequency Ratio (%)	75	80	85	90	92	95	96	97	98	99	100
Sensitivity	1.00	0.98	0.95	0.95	0.93	0.88	0.83	0.78	0.73	0.63	0.58
Specificity	0.00	0.03	0.08	0.20	0.28	0.35	0.38	0.45	0.48	0.50	0.58
Overall error rate	1.00	1.00	0.98	0.85	0.80	0.78	0.80	0.78	0.80	0.88	0.85

Table 4-33: Continued

Frequency Ratio (%)	102	103	105	107	108	110	115	120	125	130
Sensitivity	**0.53**	0.48	0.35	0.25	0.20	0.15	0.05	0.03	0.03	0.00
Specificity	**0.78**	0.80	0.85	0.88	0.90	0.93	0.98	0.98	1.00	1.00
Overall error rate	**0.70**	0.73	0.80	0.88	0.90	0.93	0.98	1.00	0.98	1.00

Table 4-34: Sensitivity and specificity of specific extensor MF-ratio cutoff values

Frequency Ratio (%)	75	80	85	90	92	95	96	97	98	99	100	102	103	105	107	108	110	160
Sensitivity	1.00	1.00	1.00	0.98	0.93	0.90	0.85	0.75	0.68	0.68	**0.63**	0.45	0.38	0.25	0.18	0.15	0.08	0.00
Specificity	0.00	0.00	0.03	0.13	0.20	0.35	0.45	0.50	0.58	0.60	**0.70**	0.80	0.85	0.90	0.95	0.95	0.98	1.00
Overall error rate	1.00	1.00	0.98	0.90	0.88	0.75	0.70	0.75	0.75	0.73	**0.68**	0.75	0.78	0.85	0.88	0.90	0.95	1.00

Table 4-35: Summary of sensitivity and specificity values for the Force and EMG measures

Characteristic	Optimal Cutoff	Sensitivity	Specificity	Overall error (%)	Area under the curve (%)
Slope of force-generation phase (V/s)					
Males	1.5	0.85	0.55	60	76
Females	0.5	0.60	0.85	55	72
Flexor MF-ratio (%)	102	0.57	0.78	70	66.25
Extensor MF-ratio (%)	100	0.63	0.70	67	71

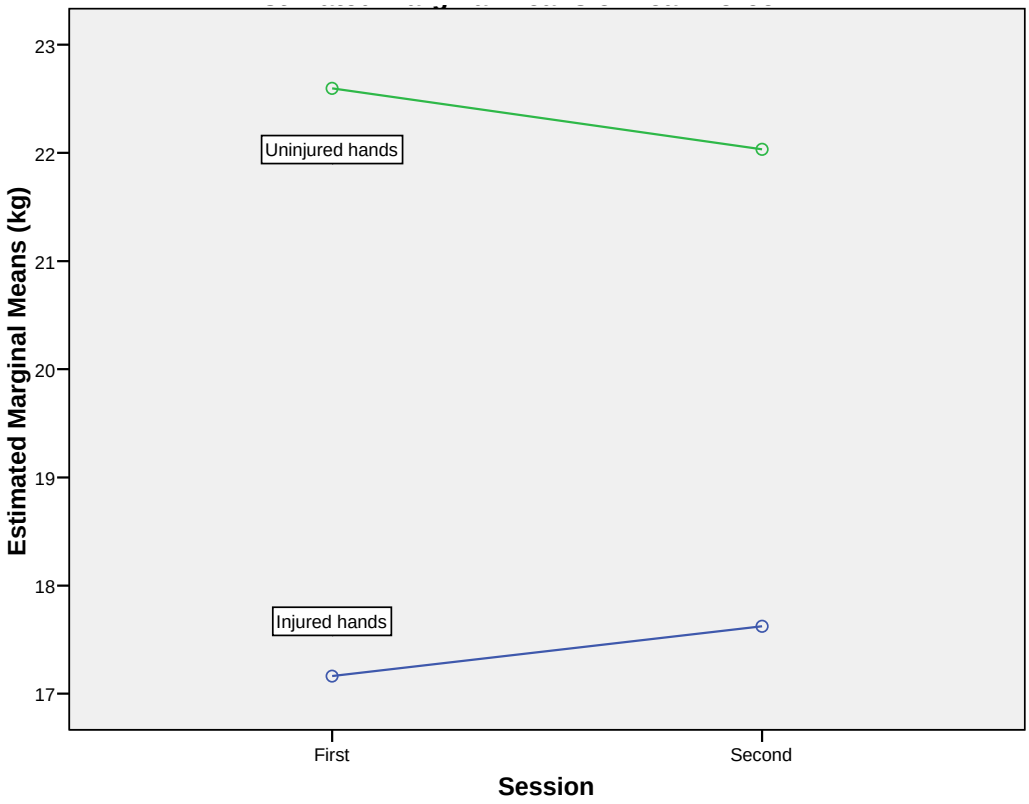


Figure 4-1: Interaction between session and injury for peak force

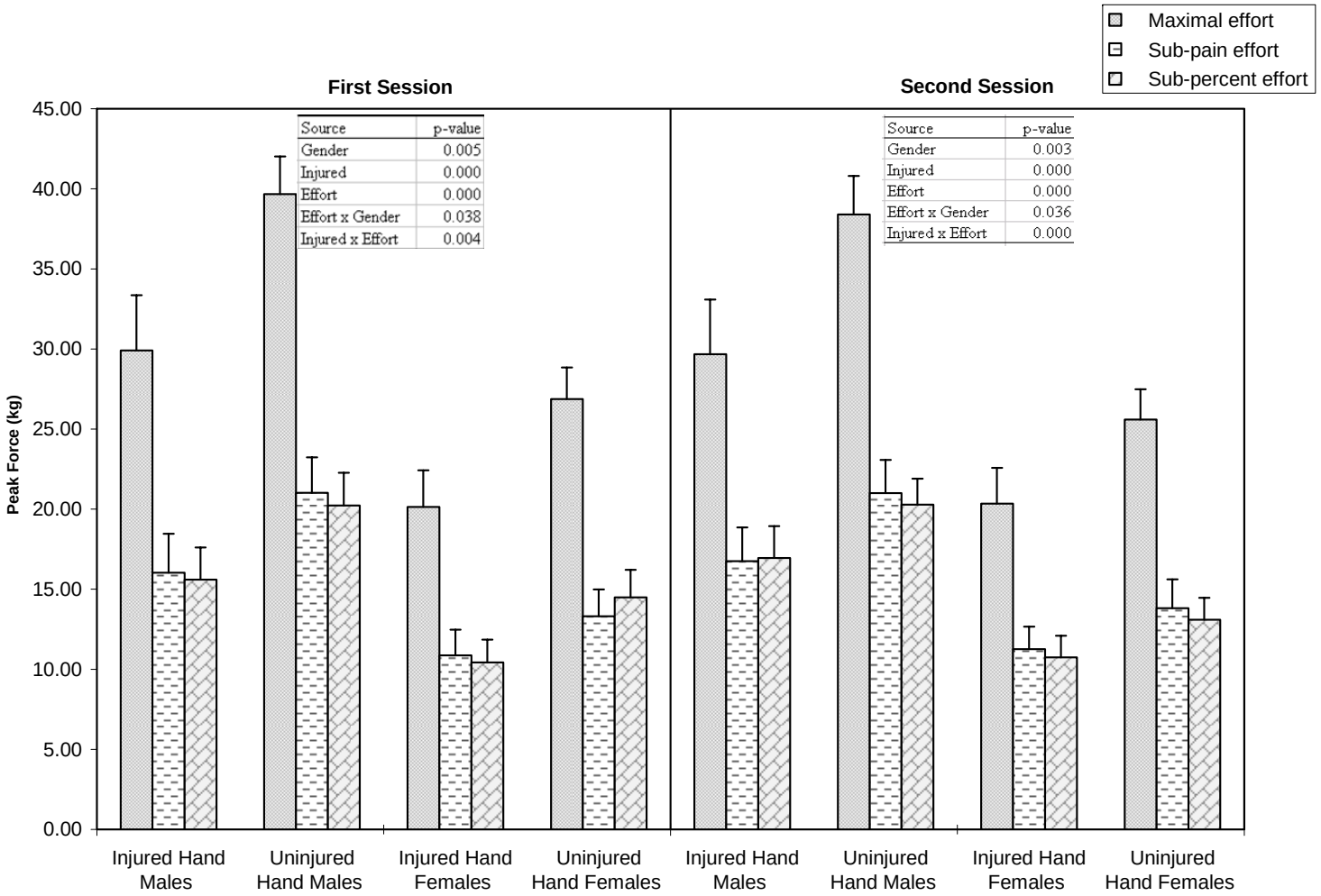


Figure 4-2: Average values of peak force for maximal and submaximal grip efforts

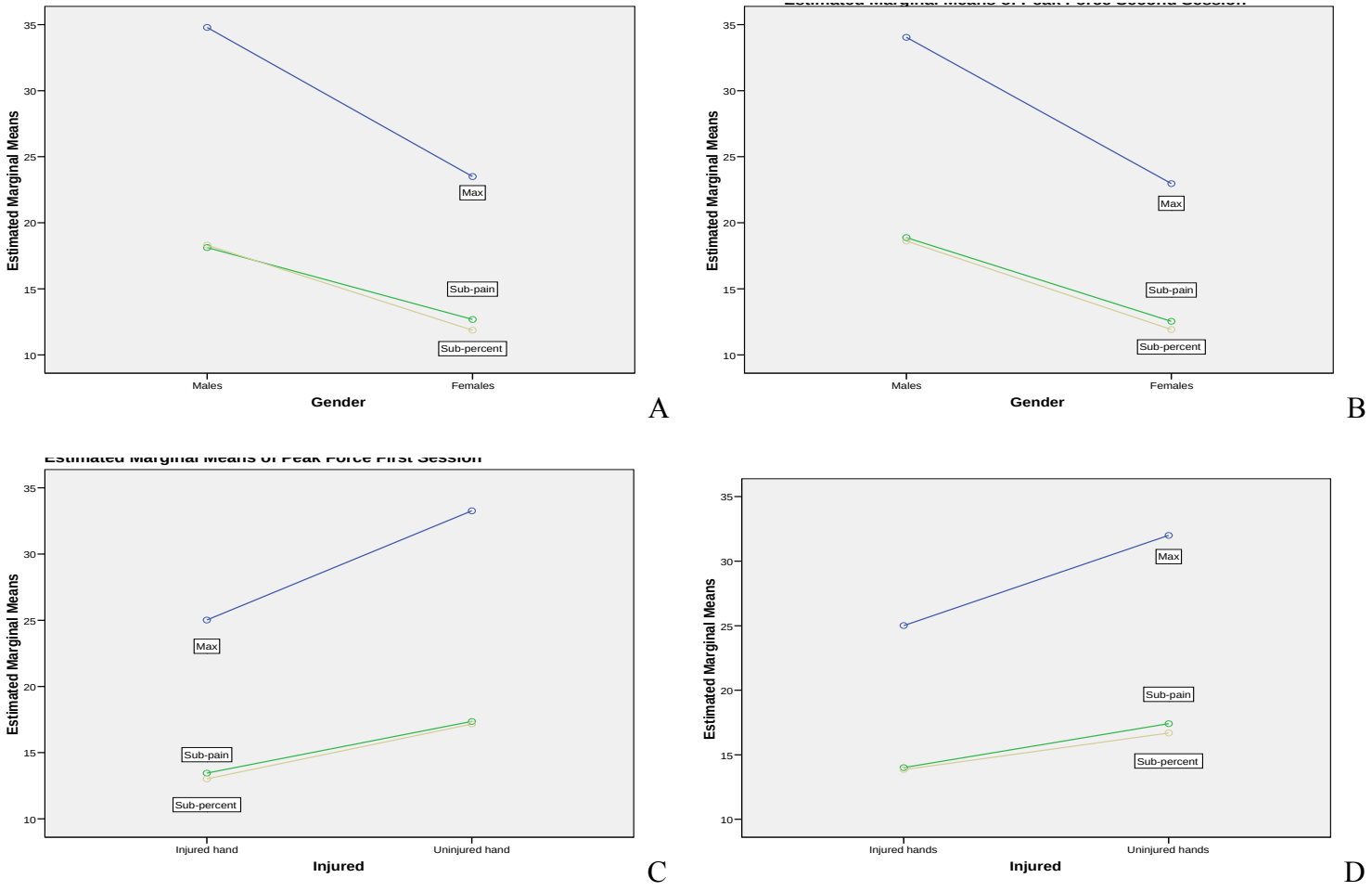


Figure 4-3: Significant interactions for peak force values. A) First session values for males and females. B) Second session values for males and females. C) First session values for injured and uninjured hands. D) Second session values for injured and uninjured hands.

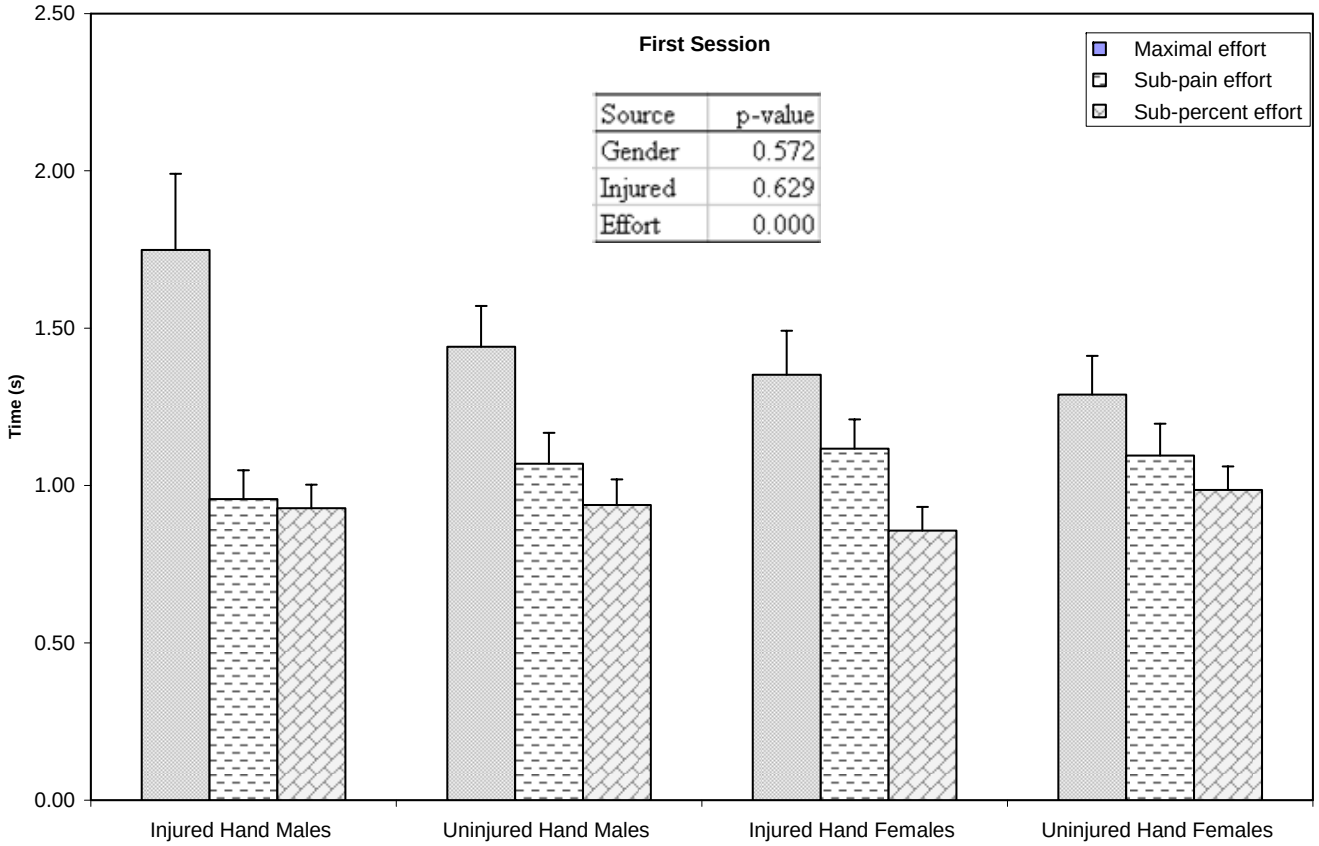


Figure 4-4: Average values of time-to-peak force

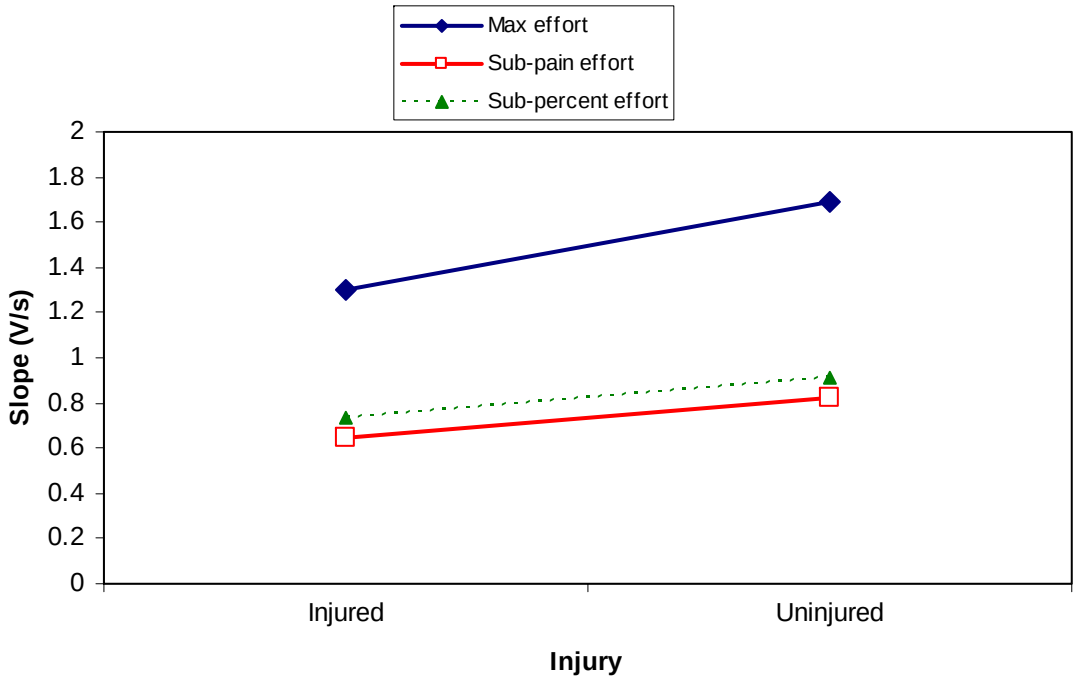


Figure 4-5: Interaction between effort and injury for slope of force-generation phase

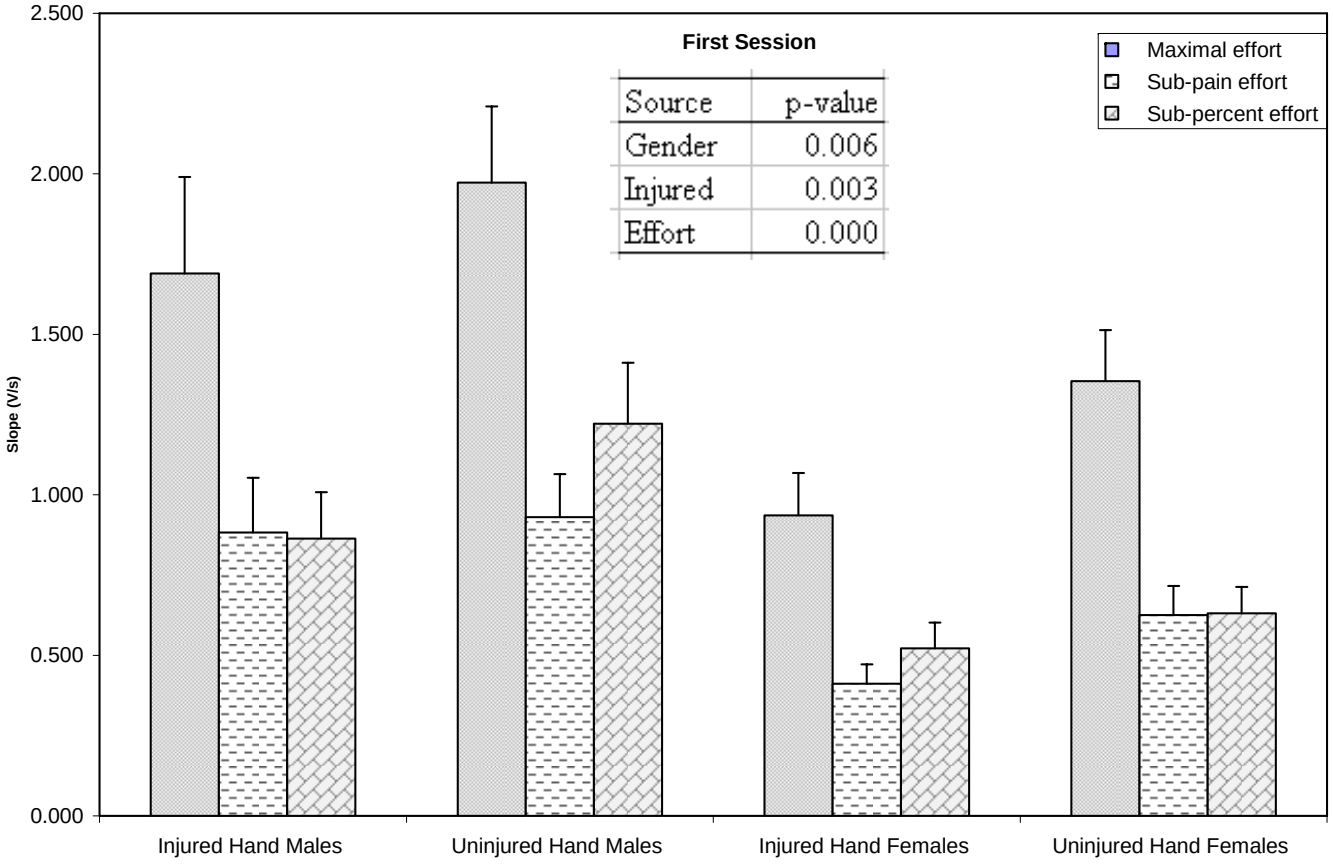


Figure 4-6: Average values of slopes of force-generation phase

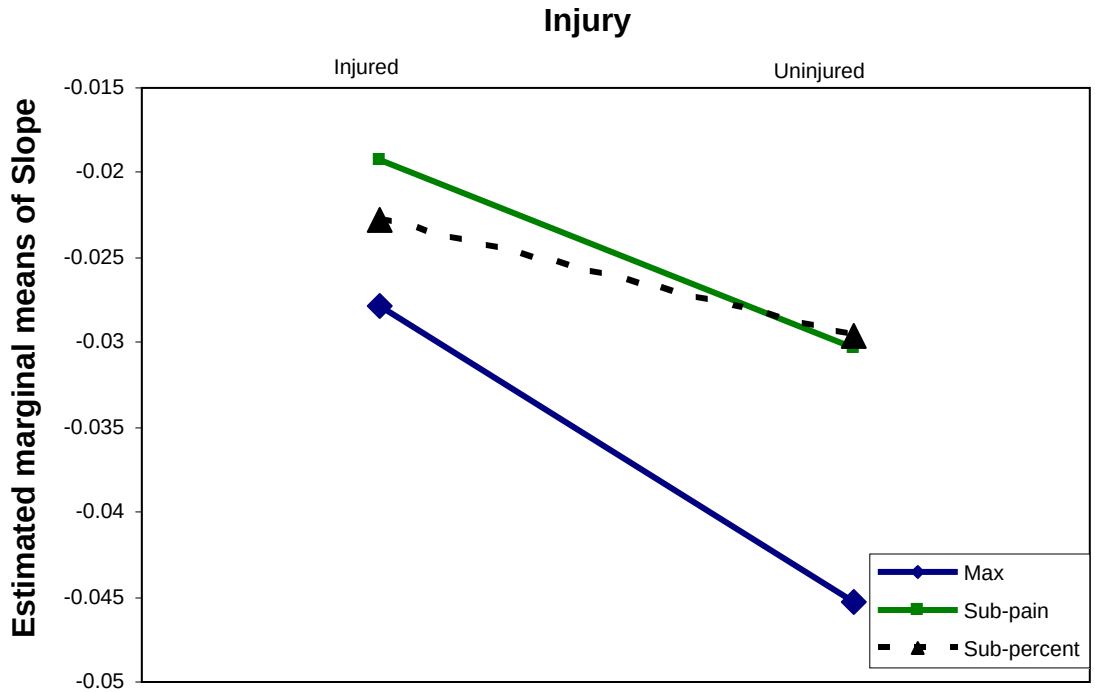


Figure 4-7: Interaction between effort and injury for slope of force-decay phase

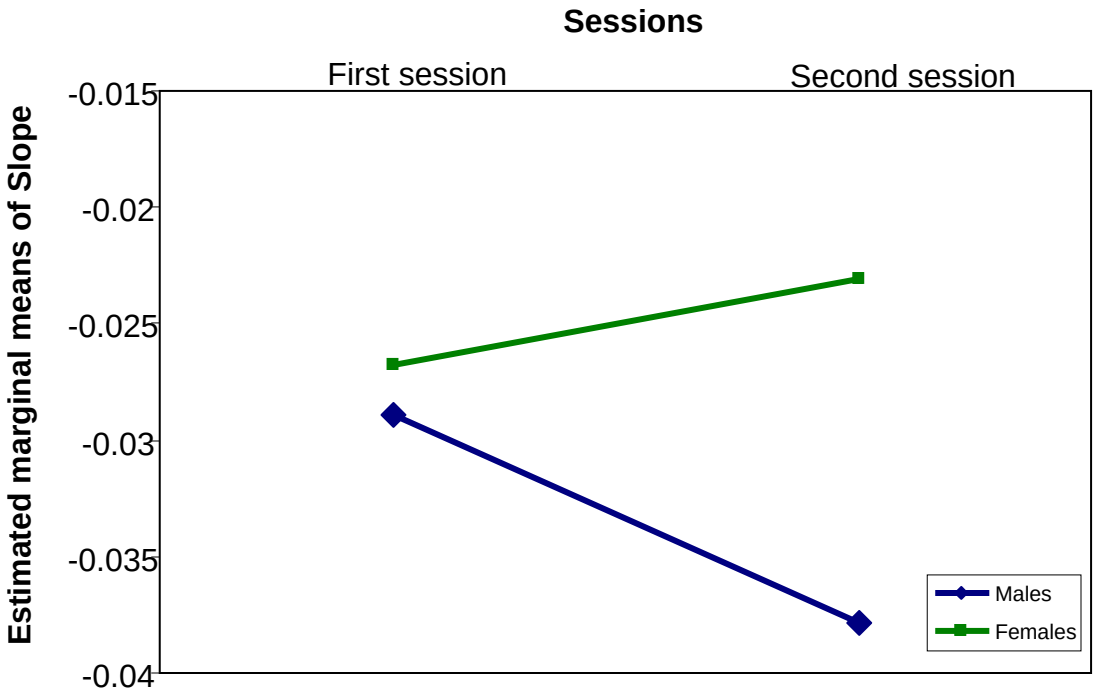


Figure 4-8: Interaction between session and gender for slope of force-decay phase

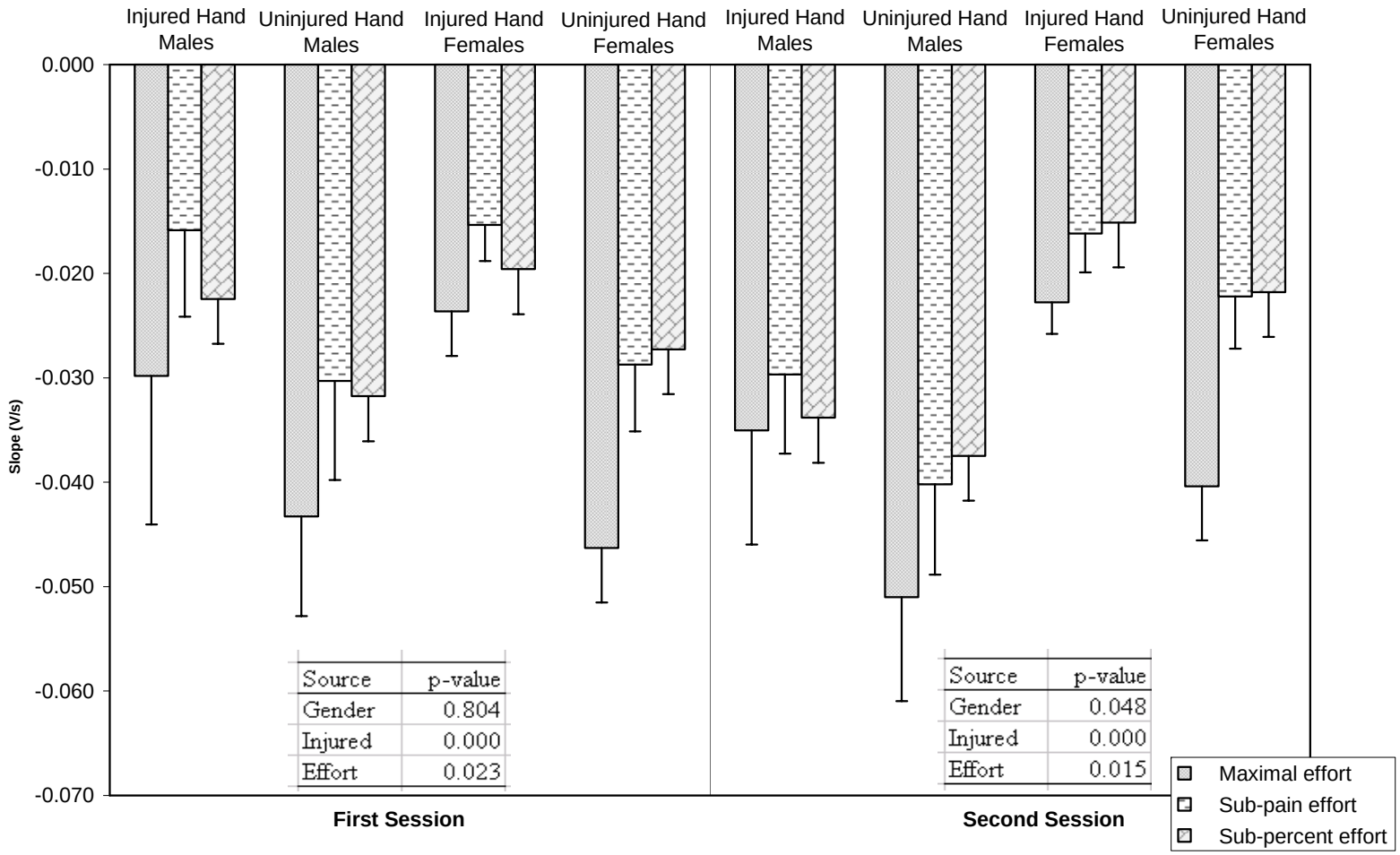


Figure 4-9: Average values of slopes of force-decay phase for maximal and submaximal grip efforts

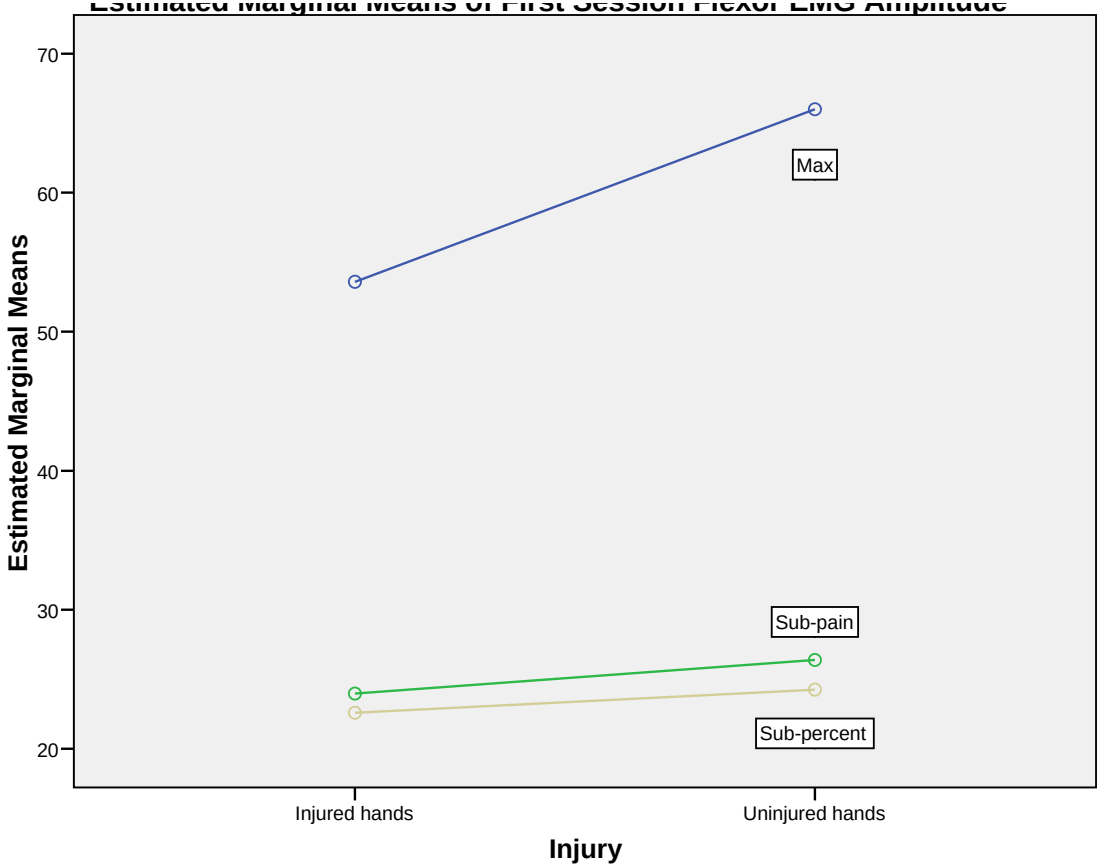


Figure 4-10: Interaction between effort and injury for flexor EMG amplitude

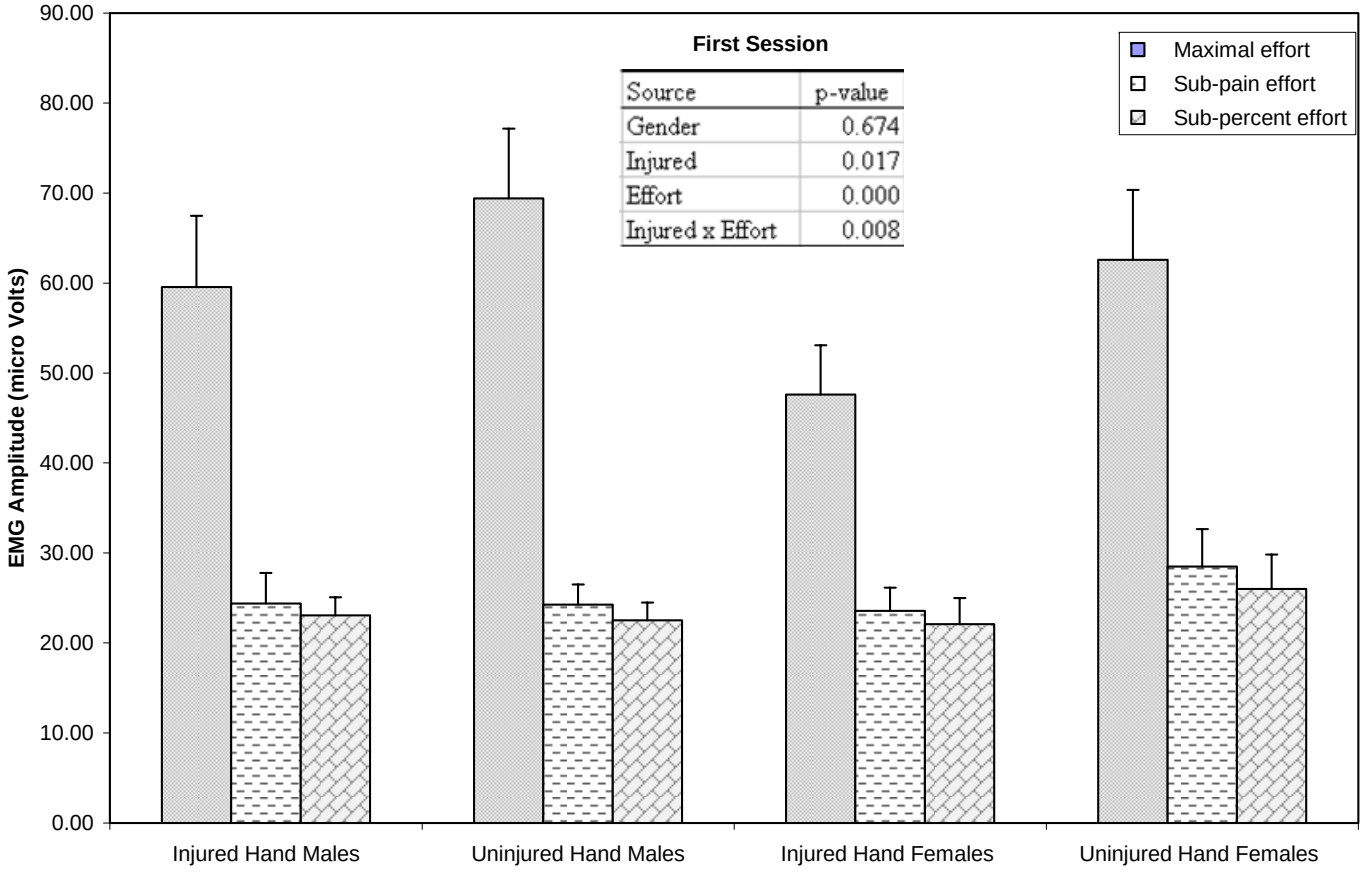


Figure 4-11: Average values of flexor EMG amplitude for maximal and submaximal grip efforts

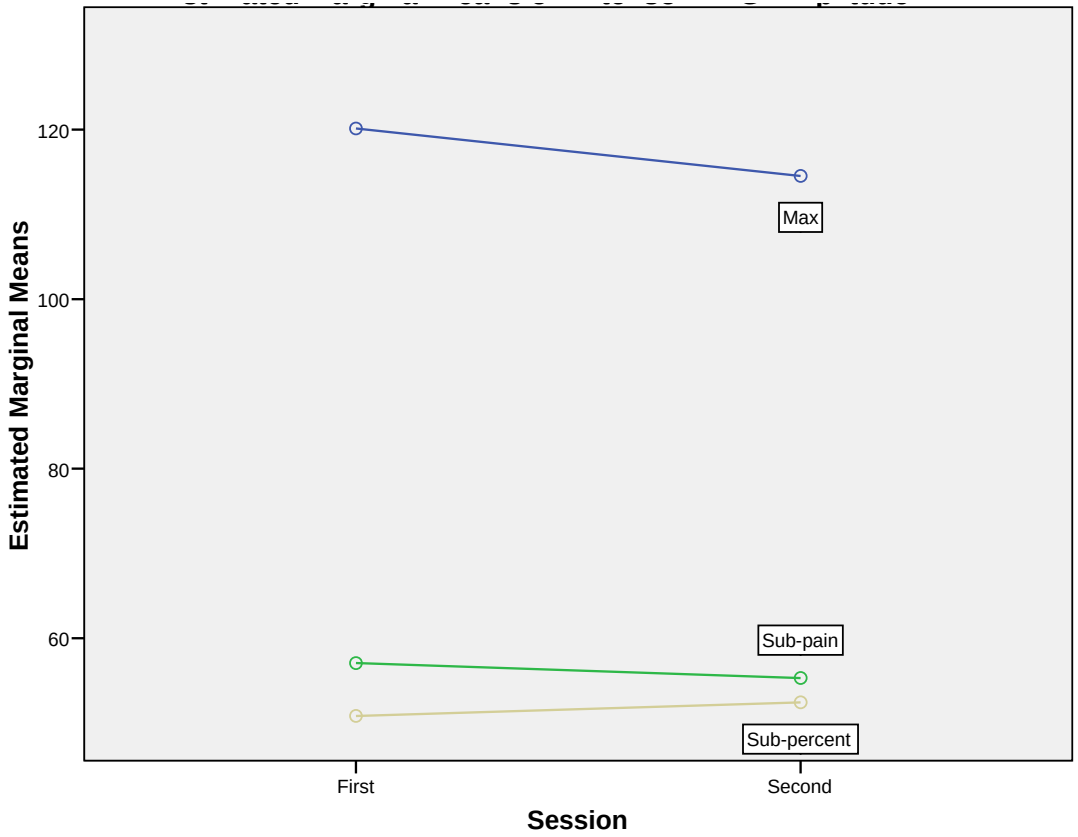


Figure 4-12: Interaction between effort and session for extensor EMG amplitude

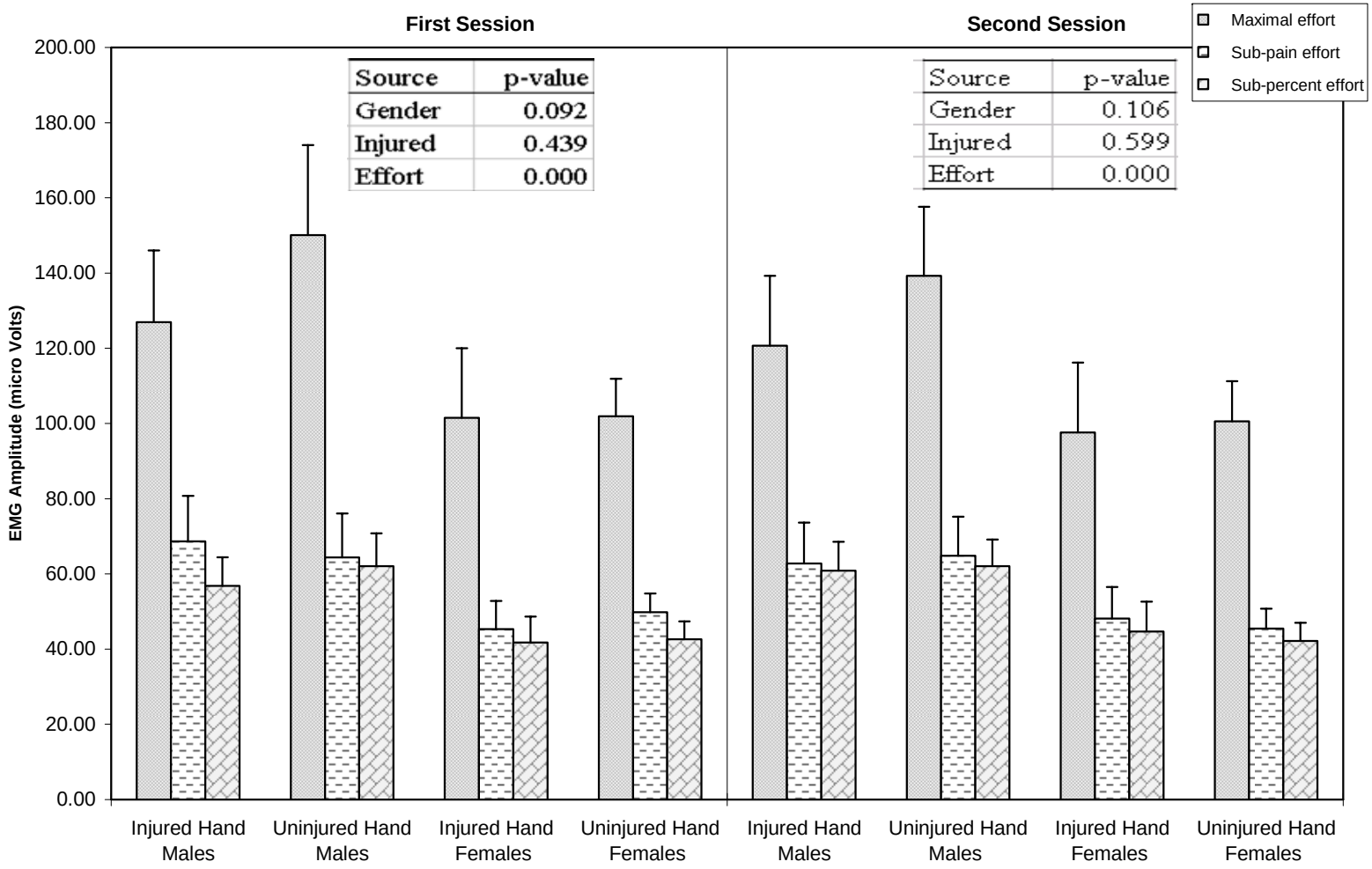


Figure 4-13: Average values of extensor EMG amplitude

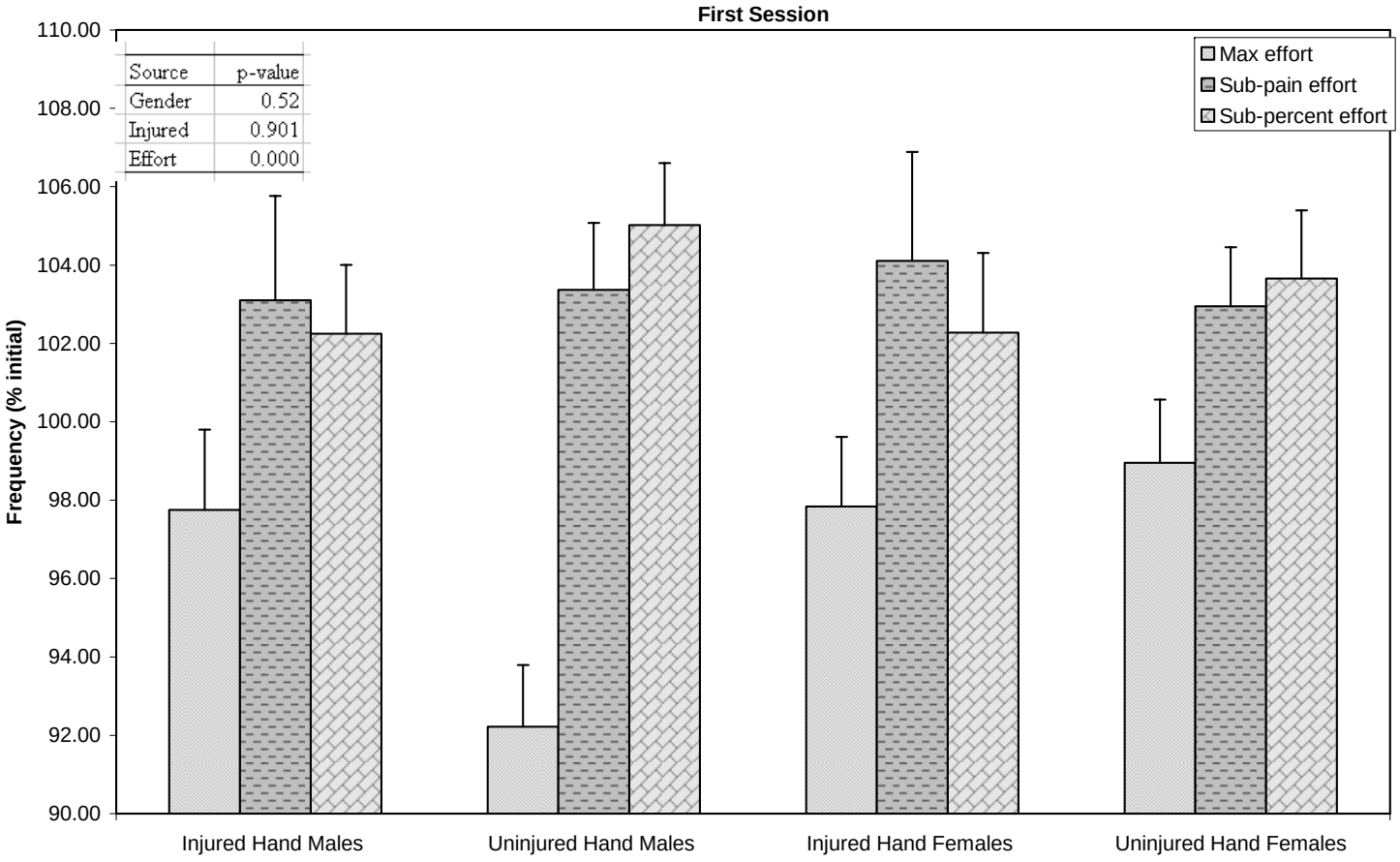


Figure 4-14: Average values of flexor MF-ratio

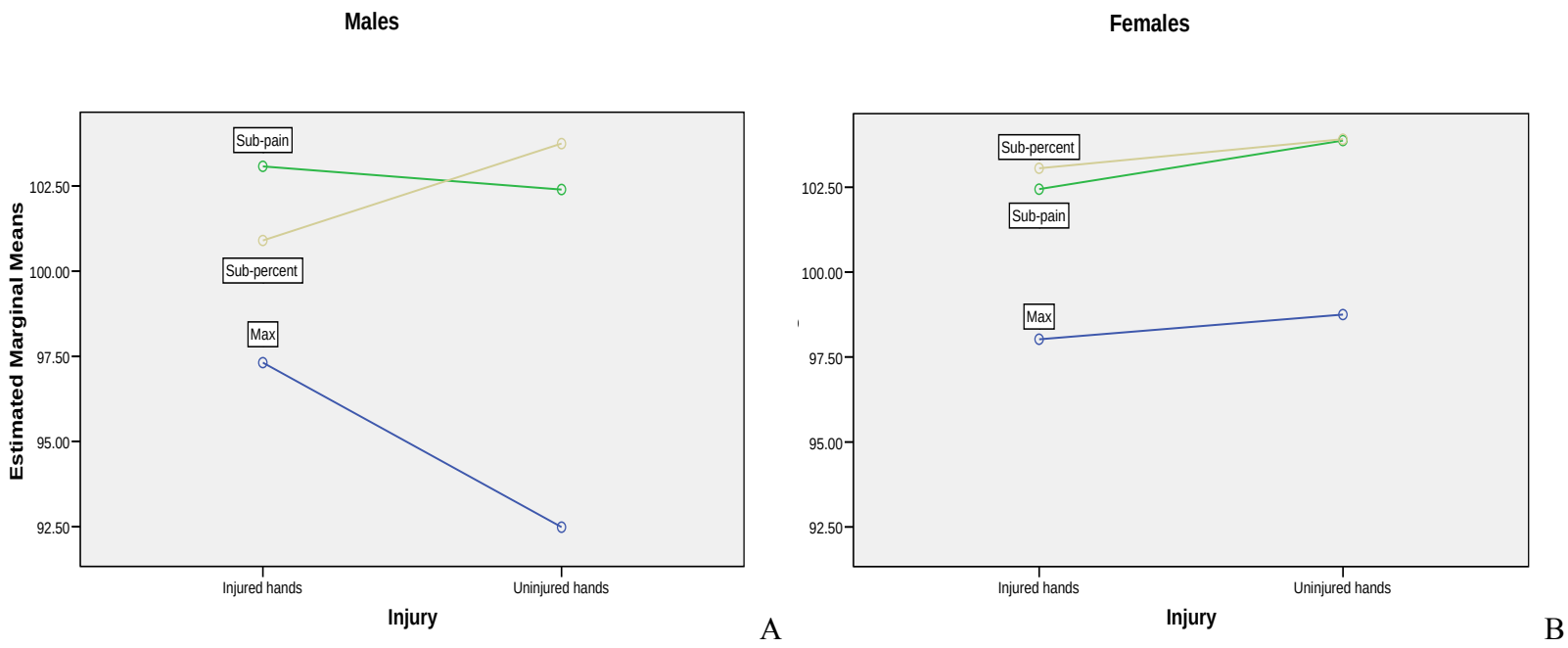


Figure 4-15: Interaction between injury, effort, and gender for flexor MF-ratio. A) Estimated marginal means for males. B) Estimated marginal means for females.

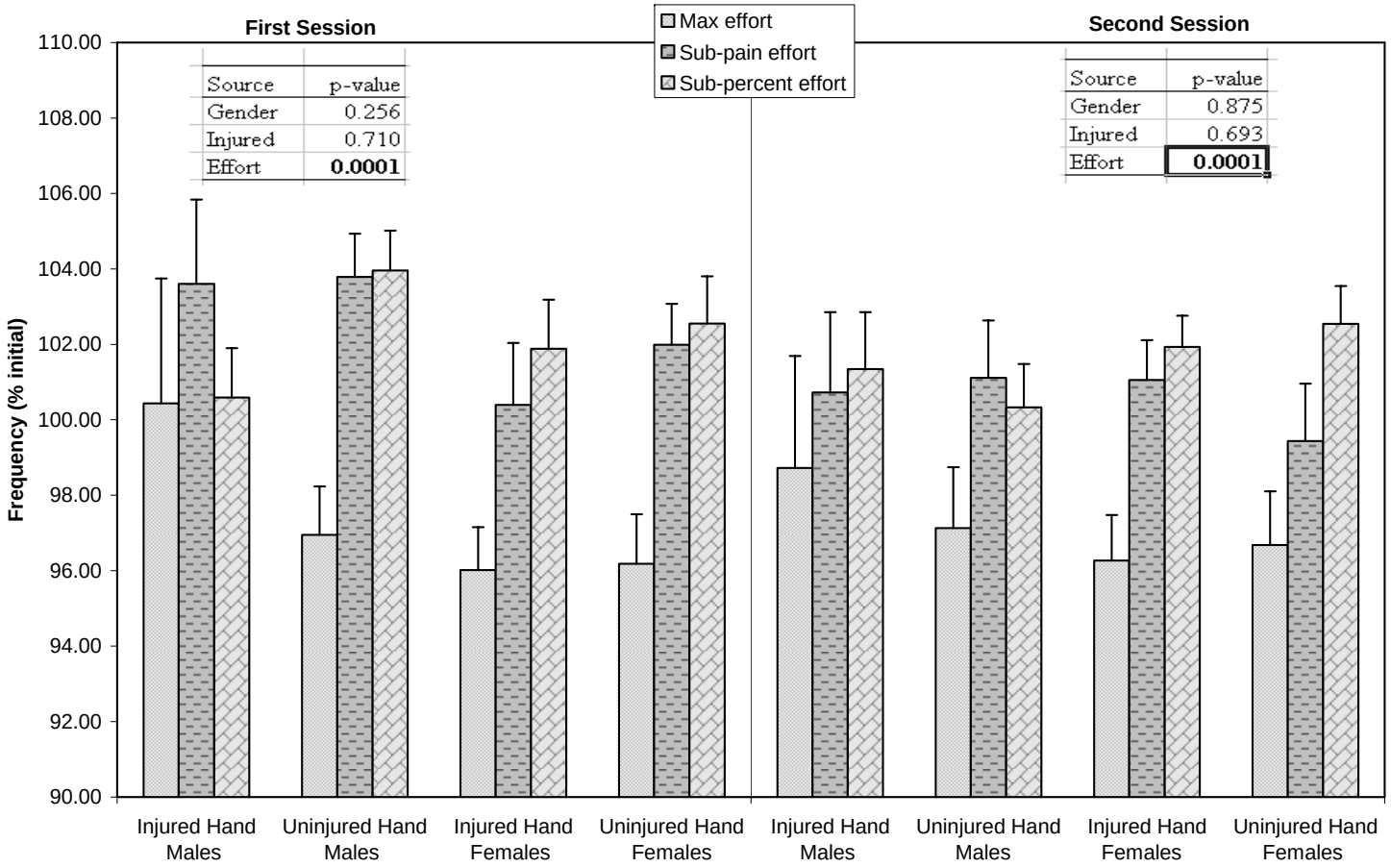


Figure 4-16: Average values of extensor MF-ratio

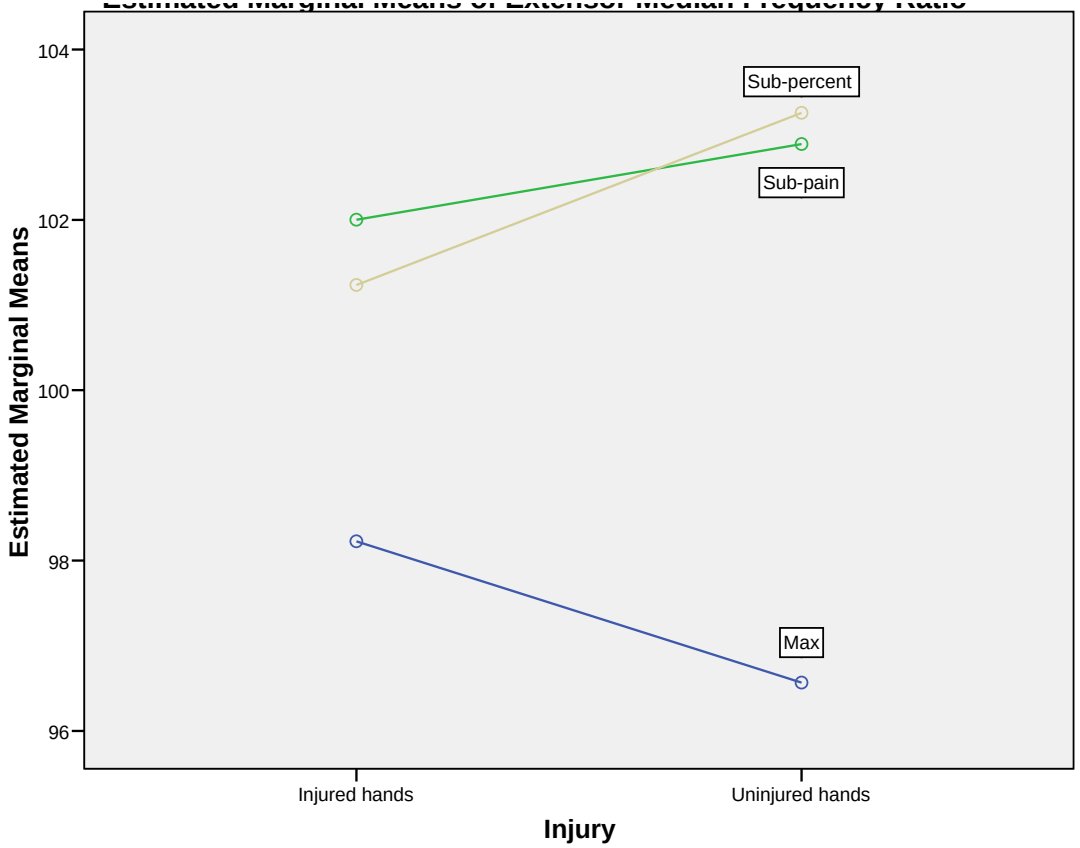


Figure 4-17: Interaction between injury and effort for the first session values of extensor EMG MF-ratio

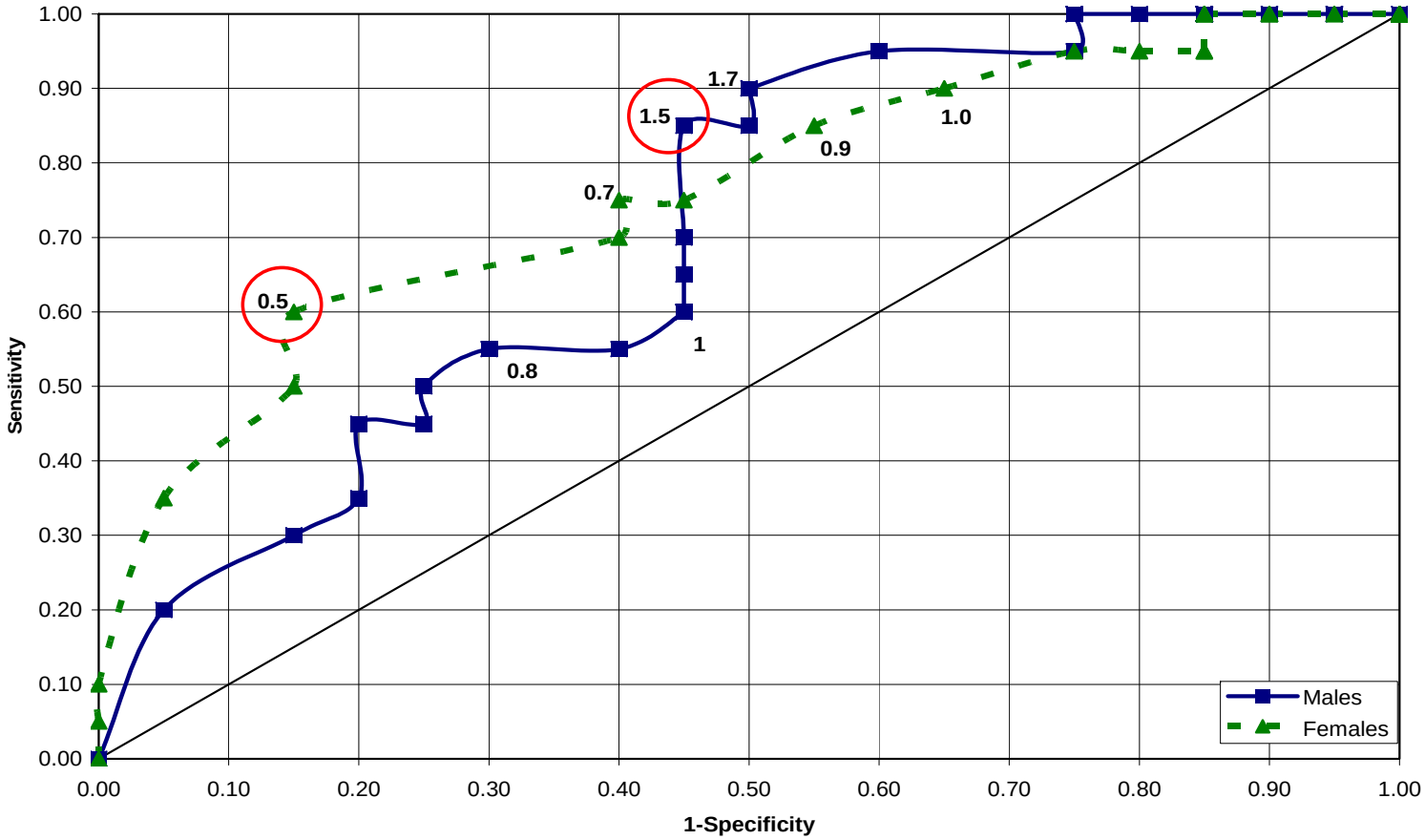


Figure 4-18: ROC curve for slope of force-generation phase

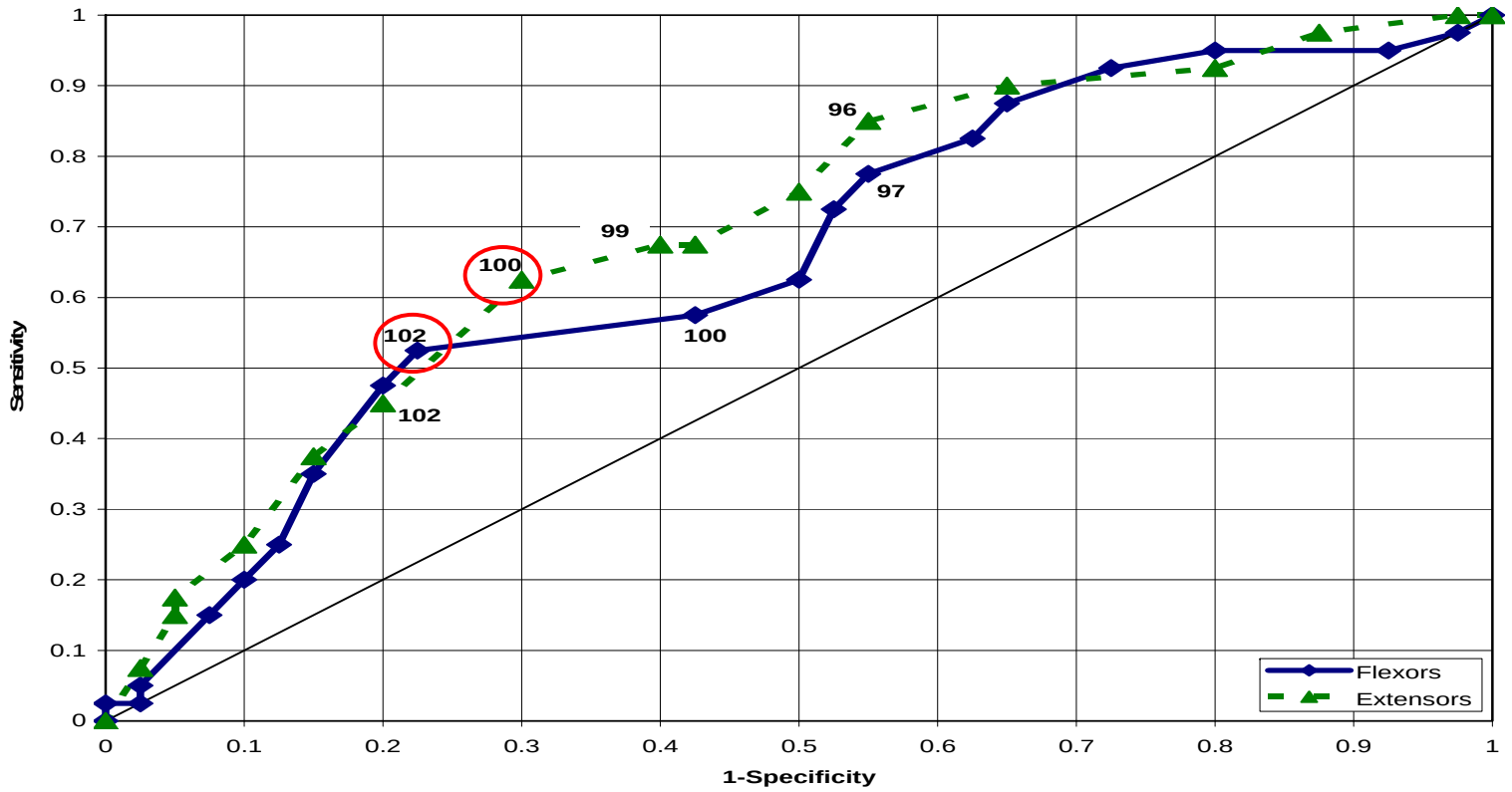


Figure 4-19: ROC curve for MF-ratio of forearm flexor and extensor muscles

CHAPTER 5
DISCUSSION

Upper extremity musculoskeletal disorders and injuries (UEMDs) may result in compromised grip strength.[1] Grip strength depends on the size, type, rate and number of contracting muscle fibers.[2] Reduced grip strength (weakness of grip) brought about by injury may be due to either a reduction in the rate and number of contracting muscle fibers[3], or changes in muscle-fiber-type.[3-7] Reduced grip strength may also occur in presence of pain.[8-10] Pain has been associated with decreases in: voluntary muscle activity[11-17], electromyographic (EMG) activity[11, 12], motor unit discharge rates[14, 15], γ-motor neuron activity[16], speed of force generation[17], and endurance time.[13]

Maximal voluntary grip strength scores of people with UEMDs are used by clinicians[18] to determine the extent of injury[19], disease process[20], and progress in rehabilitation.[21] Grip strength is a valid indicator of musculoskeletal pathology and recovery from such pathology only when people exert a sincere, maximal voluntary effort.[22-27, 64-66, 83, 84, 102, 206] Weakness of grip strength may be brought about by an injury but also could be due to exertion of submaximal effort. Submaximal effort may be exerted during evaluation and treatment for a variety of reasons, either intentional or unintentional. Unintentional submaximal effort may be exerted as a result of pain, fear of pain and fear of re-injury. Intentional submaximal effort may be exerted for secondary gain, such as money, benefits, or attention. To improve rehabilitative care, clinicians need to be able to distinguish between a maximal voluntary grip effort (exerted by a client with true weakness of grip) and a submaximal grip effort.

Force-time curve (F-T curve) characteristics[28, 29, 55, 101, 102] and electromyographic (EMG) properties[30-32] have been used to differentiate between maximal and submaximal grip effort. Furthermore, the Force-Time Curve test (F-T Curve Test)[102] has shown promise in determining sincerity of effort. The F-T Curve Test includes the slopes of the force-generation phase and the force-decay phase. So far, the F-T Curve Test has been shown to be valid in healthy people.[102] However, the validity of the F-T Curve Test has not been examined in people with UEMDs. Therefore, the primary purpose of this research project was to examine if the F-T Curve Test is valid in people with UEMDs. Another purpose of this study was to examine other F-T Curve characteristics and EMG properties are valid sincerity of effort measures in people with UEMDs.

We examined the ability of four F-T curve characteristics (peak force, time-to-peak force, slope of force-generation phase, and slope of force-decay phase) and two EMG properties (amplitude and median frequency ratio) to differentiate between maximal and submaximal effort in people with UEMDs. A valid test has to first be reliable.[92] Therefore, we examined the test-retest reliability of the various measures mentioned above and found that they ranged from $r = 0.3$ to $r = 0.97$, with time-to-peak force having the worst reliability. A valid test also means that it can differentiate between maximal and submaximal effort. We found all six measures to be significantly different between maximal and submaximal effort. However, to be clinically valid a test must be effective; i.e. it should not misclassify many patients. We examined the effectiveness of the above measures by identifying the optimal combination of sensitivity and specificity based on the overall error rates, receiver operating characteristic (ROC) curve, and the area under

the ROC curve. Based on these analyses, the most valid and effective measure of sincerity of effort in this study was the slope of the force-generation phase.

We found significant gender differences for the slope of the force-generation phase. Therefore, we calculated separate ROC curves for males and females. The area under the curve was greater for women (76%) than for men (72%), which indicated a greater ability to discriminate between maximal and submaximal efforts for women. In a previous study on healthy subjects, we found that the slope of the force-generation phase was more effective for women than for men.[102] For healthy women, the slope cutoff value of 1.2 V/s yielded the most optimal combination of sensitivity (0.8) and specificity (0.93) and the lowest overall error rate (0.27). Also, the area under the curve was 92%.[102] In contrast, in the present study for women with UEMDs, the slope cutoff value of 0.5 V/s yielded the most optimal combination of sensitivity (0.6) and specificity (0.85) and the lowest overall error rate (0.55). Also, the area under the curve was 76%.

Despite the high reliability and significant differences between maximal and submaximal efforts, the slope of the force-generation phase does not possess adequate sensitivity and specificity values to be considered clinically valid. Based on previous findings[102], our hypothesis was that a sensitivity value of at least 80% combined with a specificity value of at least 90% would be adequate clinically.

Force-Time Curve Characteristics

In the present study, we examined the ability of Force-Time curve (F-T curve) characteristics to identify differences between maximal and submaximal effort. The F-T curve graphically represents the force generated by a contracting muscle over a period of time during a single strength trial.[29] The vertical axis (Y-axis) represents change in force of muscular contraction and the horizontal axis (X-axis) represents time of muscular

contraction. The typical F-T curve generated during a maximal voluntary isometric contraction (MVIC) consists of three phases: 1) the force-generation phase or the initiation phase that involves rapid or gradual development of force, followed by 2) the peak force, and finally 3) the force-decay phase or the maintenance phase that involves a steady rate of force that may decrease gradually over time indicating onset of fatigue.[95, 96, 210-212] The characteristics of the F-T curve Test that we examined were its peak force, time-to-peak force as well as its slopes of the force-generation phase and force-decay phase.

Some F-T curve characteristics, such as peak force and the slope of the force-generation phase, have been found to change with strength training.[98, 99, 215, 229, 232] Strength training causes a muscle to undergo both rapid neural adaptations and gradual hypertrophic adaptations. Increases in slope of the force-generation phase was associated with a stronger neural drive, whereas, increases in peak force were primarily associated with muscle hypertrophy.[98, 99, 215, 228, 229, 232]

Differences between Maximal and Submaximal Effort

For the F-T curve characteristics, we expected 1) peak force to be greater for maximal versus submaximal effort, 2) the time-to-peak force be greater for maximal versus submaximal effort, and 3) slopes of the force-generation phase as well as force-decay phase to be steeper for maximal versus submaximal effort. The findings of the present study confirmed our hypotheses. We assigned submaximal effort using 2 different ways. One was to instruct the subject to exert 50% of maximal effort. The other was to exert submaximal effort based on an imagined level of pain. Because no significant differences were found between the 2 submaximal efforts, we discuss both at once as submaximal effort.

We found peak force to be greater, time-to-peak force to be longer, and slope of force-generation phase to be steeper for maximal than for submaximal efforts. Although peak force showed significant differences between maximal and submaximal efforts, it is not a good measure of sincerity of effort because peak force indicates strength of a contraction.[98, 99, 215, 229, 232] Obviously, maximal effort is stronger than submaximal effort and injured hand is weaker than uninjured hand. Time-to-peak force and the slope of force-generation phase were found to be significantly different between maximal and submaximal efforts and thus may be valid sincerity of effort tests. According to Kroemer and Marras[188], during maximal contractions, the central nervous system recruits all available fibers at their highest firing rates. Conversely, during submaximal contractions, continuous feedback signals control muscle output by modifying muscle fiber firing rate and muscle fiber recruitment. Further, motor units fire synchronously during maximal or near maximal efforts and fire asynchronously during submaximal efforts.[233] Therefore, a faster buildup of force occurs in maximal effort than submaximal effort.[29, 101, 188] Consequently, a maximal grip effort results in a greater peak force as well as a steeper slope of force-generation phase. Also, greater peak force exerted during maximal effort requires a longer time to reach this higher force, which results in a longer time-to-peak force.

We also found the slope of force-decay phase to be steeper for maximal versus submaximal effort. The differences in steepness of slope of force-decay phase can be explained on the basis of the onset of fatigue.[95, 96, 210-212] During maximal effort all motor units are activated maximally and simultaneously. Consequently, when motor units fatigue there are no “fresh” motor units that can be activated to take over.[188, 189, 192-194] In

contrast, a submaximal force can be maintained by activation of fewer motor units that fire asynchronously. In other words, as one motor unit is deactivated, another is being activated and there is a reserve of "fresh" motor units to maintain the required submaximal muscle tension. Therefore, there is a greater drop in force during maximal effort than submaximal effort, which results in a steeper slope during the force-decay phase of a maximal effort than of a submaximal effort.[215, 368]

Differences between the Injured and Uninjured Hands

For the F-T curve characteristics, we expected 1) the slope of the force-generation phase to be steeper for uninjured versus injured hands, 2) the slope of the force-decay phase to be steeper for injured versus uninjured hands, 3) peak force to be greater for uninjured versus injured hands, and 4) time-to-peak force faster for uninjured versus injured hands. Our findings for the slope of force-generation phase and peak force were as expected but for time-to-peak force and slope of force-decay phase were not as expected.

We found that the uninjured hands had steeper slopes for both the force-generation phase and the force-decay phase. The injured hands exhibited gentler slopes of force-generation phase probably because people with injuries have a slower rate of force production.[211] We expected a steeper slope during the force-decay phase for the injured hands because people with musculoskeletal conditions experience greater fatigue and inability to maintain force.[369-373] However, we found that the uninjured hand showed greater fatigue as indicated by a steeper slope during the force-decay phase. We propose an explanation that is based on the assumption that people with injuries are protective of their injured hand. They may experience pain, fear of pain, and/or fear of re-injury and thus they may not exert true maximal voluntary contraction with their injured hand. The

interaction showing that uninjured hand force decreases during the second session but injured hand increases supports this notion.

Gender Differences

We found that the slopes of force-generation phase were steeper for males than females. Gender differences in the slope of force-generation phase may be due to differences in muscle strength. Demura et al.[207-209] found the F-T curve characteristics (such as rate of force development) to be larger in stronger subjects[208], and different between males and females.[209] Males also produce greater forces[374-376] at faster rates.[213] Gender differences in F-T curve characteristics may be due to larger muscle cross-sectional area, higher concentration of anabolic hormones, and higher voluntary neural activity of muscles.[220, 377]

For the slope of the force-decay phase, gender differences in slope were found only for the second session and not for the first session. During the second session, we found steeper slopes for males versus females. Gender differences in the slopes of the force-decay phase may be due to gender differences in ability to maintain static grip force. Yamaji et al.[378] examined gender differences in ability to maintain grip force over six minutes at different effort levels (20-100% of maximal voluntary contraction, MVC).The authors reported that for efforts greater than 40% MVC, females maintained the effort level for a longer time or at a higher force level. It is also possible that females are less motivated to exert true maximal voluntary contraction and thus fatigue less as they have more “fresh” motor units to recruit.

Electromyographic Properties

In the present study, we evaluated the electromyographic (EMG) properties of forearm flexor and extensor muscles during isometric grip contractions. Both forearm

flexor and extensor muscles have been reported participate in isometric grip.[359, 379-384] The forearm flexors generate the gripping force, while the extensors stabilize the wrist.[359, 383, 385] The properties of the EMG signal that we examined were its amplitude and median frequency ratio (MF-ratio).

The amplitude of the EMG signal represents the magnitude of muscle activity. As the force being generated by a muscle increases, it results in an increase in the EMG amplitude. Increase in amplitude predominantly occurs due to increases in number of active motor units.[237, 245] Also, an injury to the hand or arm decreases the EMG amplitude by reducing the ability to produce force.

The frequency of the EMG signal represents how rapidly motor units are firing. One method of describing the frequency of EMG signal involves using spectral analysis to compute its median frequency (MF). The MF represents which motor units are predominantly active. Fast twitch motor units dominate the higher frequency spectrum and slow twitch dominate the lower frequency spectrum.[255, 260, 386] In other words, muscles with a greater percentage of type II fibers or fast twitch motor units exhibit greater values of MF.[386] An increase in muscle force results in an increase in MF, and therefore a shift of the power spectrum to a higher frequency region. That is, as contraction level increases, larger motor units are recruited, and thus the power spectrum shifts to a higher frequency region.[248, 251] A sustained forceful contraction often causes muscular fatigue, which shifts the power spectrum to a lower frequency region.[254-260] The shift of the power spectrum to a lower frequency occurs due to motor unit de-recruitment. The replacement of fast twitch motor units, which fatigue more quickly, with lower frequency fatigue-resistant units causes a decrease in the higher frequency spectrum.[255,

[260] Fatigue has been shown to result in an increase in the lower frequency spectrum[255] and a decrease in the higher frequency spectrum,[255, 263, 264] which translates into a shift of the power spectrum towards the lower frequencies.[260] Further, muscles with a greater percentage of fast twitch motor units exhibit a greater reduction in MF.[386] Thus, MF can indicate an increase in muscular force when it shifts to the higher frequency spectrum and muscular fatigue when it shifts to lower frequency spectrum.

The process of calculating median frequency (MF) involves a mathematical conversion called Fourier Transformation, which identifies different frequencies forming the EMG signal. The power of each frequency, i.e. the quantity of each frequency in the signal, can also be identified using Fourier Transformation.[120, 121] The plot of frequency along the X-axis versus the power of the frequency along the Y-axis results in a graph that is commonly termed as the power spectrum or the frequency spectrum.[121] The MF represents the frequency that divides the power spectrum into two regions with equal power, i.e. the parts of the spectrum above and below the MF have equal distributions of power.[105]

In presence of pathological conditions, the decline in MF with development of fatigue varies markedly with the type of motor units recruited.[210, 387-389] A smaller shift to the lower frequency region as a result of fatigue has been observed in people with Amyotrophic lateral sclerosis[210] and Parkinson's disease.[390] The smaller shift has been attributed to selective atrophy of type II (fast glycolytic, fast oxidative) muscle fibers, which fatigue more quickly, and/or higher prevalence of type I (slow twitch oxidative) muscle fibers.[210, 390] In contrast, a greater shift in MF associated with earlier onset of fatigue has been observed in people with chronic heart failure[391], peripheral arterial

disease[392], and chronic neck pain.[393] The greater shift in MF has been attributed to selective atrophy of type I muscle fibers or hypertrophy of type II muscle fibers.[391-393] Therefore, a greater or smaller shift in MF may be observed in people with a pathological condition than healthy people as expressed by changes in muscle fiber type.

For the current study, we calculated the amplitude of the EMG signal as the average rectified amplitude for the duration of the grip. We computed the MF for two separate 1-second intervals, the first interval beginning at peak force (called the median frequency of the first interval) and the second interval forming the last second of the force-decay phase of the F-T curve (called the median frequency of the last interval). We then computed the MF-ratio of the last to first intervals, to reflect changes in median frequency between the beginning and end of the grip contraction. The MF-ratio represents the extent of fatigue or de-recruitment of motor units.

Differences between Maximal and Submaximal Effort

For the EMG properties, we expected 1) the amplitude to be greater for maximal versus submaximal effort, and 2) the MF-ratio to be smaller for maximal than for submaximal effort. The findings of the present study confirmed our hypotheses.

The EMG amplitude was significantly greater for maximal versus submaximal efforts. EMG amplitude is not a valid measure of sincerity of effort because it correlates to the amount of force exerted by a muscle. Obviously, maximal effort results in greater muscle force than submaximal effort and an injury may reduce the ability of a muscle to produce force.

We examined the shift in the MF spectrum during 6-seconds of isometric grip contraction. MF indicates which motor units are predominantly firing.[255, 260] We found both the flexor and extensor MF-ratios were smaller for maximal effort than for

submaximal effort. During maximal effort, the MF-ratio actually decreased probably due to replacement of some of the fast twitch motor units with lower frequency fatigue-resistant units.[255, 260] Conversely, during submaximal effort, the MF-ratio increased, probably as a result of an increase in recruitment and firing rate of motor units. The maintenance of a submaximal muscle force over 6 seconds gradually requires a greater number of motor units or increased firing of already recruited motor units. As the contraction persists, larger (and more) motor units are recruited, and thus the power spectrum shifts to a higher frequency region.[248, 251] Therefore, a combination of both recruitment and rate coding results in shift of the power spectrum to the higher frequency region.[248] MF-ratio has the potential to form a valid measure of sincerity of effort as it indicates a shift of MF during a grip strength trial.

Differences between Injured and Uninjured Hands

For the EMG properties, we expected 1) the amplitude to be greater for uninjured versus injured hands, and 2) the MF-ratio to be smaller for injured versus uninjured hands. The findings of the present study did not confirm all our hypotheses.

Flexor EMG amplitude was significantly greater for the uninjured hands. Uninjured hands can produce greater force as they have greater number of motor units available. Therefore, uninjured hands have a greater EMG amplitude.[245] However, extensor EMG amplitude was unexpectedly not significantly different between the 2 hands. One reason could be because of differences in diagnosis. But, we did not collect information on diagnosis. Therefore, we are not certain regarding the cause of no difference in extensor amplitude.

Regarding MF-ratio, the interaction effects of injury were significant but the main effects were not significant. The decrease in flexor MF-ratio between submaximal and

maximal efforts was greater for uninjured vs. injured hands in males but not in females. Also, the decrease in extensor MF-ratio between submaximal and maximal efforts was greater for uninjured vs. injured hands. It was unexpected that the decrease in MF-ratio was greater for the uninjured hand than the injured hand. The difference in MF-ratio between injured and uninjured hands may be present because subjects did not exert their maximal voluntary contraction with their injured hands as a protective mechanism. A smaller shift to the lower frequency as result of fatigue has been attributed to selective atrophy of type II (fast glycolytic, fast oxidative) muscle fibers and/or higher prevalence of type I (slow twitch oxidative) muscle fibers.[210, 390] However, our study participants had a diverse group of musculoskeletal conditions. It is not clear if these conditions resulted in selective atrophy of type II fibers and/or higher prevalence of type I fibers. Therefore, a smaller decrease in MF-ratio with injured hands most likely occurred because people with injuries may be protective and not exert maximal voluntary contraction with their injured hands.

Gender Differences

Gender differences existed for flexor MF-ratio but not for flexor amplitude, extensor amplitude, and extensor MF-ratio. For flexor MF-ratio, the interaction effect of gender was significant but the main effect was not significant. The decrease in flexor MF-ratio between submaximal and maximal efforts was greater for uninjured vs. injured hands in males but not in females. In other words, males fatigued more with the uninjured hands, whereas, females fatigued the same with injured as well as uninjured hands. The cause of these differences is not clear. It is possible that females are less motivated to exert true maximal voluntary effort and thus fatigue to the same extent with injured and uninjured hands, as they have more “fresh” motor units to recruit. In contrast, it seems

that males are protective of their injured hands. Males may experience pain, fear of pain, and/or fear of re-injury and thus may not exert true maximal voluntary effort with their injured hand and thus fatigue less with their injured hands.

On examining maximal effort exerted with the uninjured hands, we found that the flexor MF-ratios were smaller for males versus females. This difference in uninjured hands suggests an existence of gender differences in forearm flexor muscle fatigability, i.e. males fatigue more than females. Gender differences in elbow flexor fatigability have been related to the level of absolute force exerted during an isometric contraction.[394] Hunter et al.[394] found that women had longer endurance times, which indicates less fatigability, because the maximal voluntary contraction force was smaller for females. Indeed, in our study, greater peak forces with uninjured hands were exerted by males versus females. Therefore, gender differences in fatigability of forearm flexor muscles during maximal isometric grips seem to be related to force exerted during a maximal voluntary contraction.

Force-Decay Phase

When examining the region of the F-T curve from peak force to the end of contraction, we found that the changes in the slope of the force in the slope of the force-decay phase corresponded to the changes in EMG signal as expressed by the flexor MF-ratio. We found steeper slopes of force-decay phase and smaller MF-ratios for 1) maximal versus submaximal effort, 2) uninjured versus injured hands, and 3) males versus females. Steeper slopes and smaller flexor MF-ratios for maximal versus submaximal effort may be explained on the basis of differences in onset of fatigue, which has been associated with ability of a muscle to maintain force[95, 96, 210-212] as well as shift in the median frequency to a lower frequency region.[254-260] Further, steeper slopes and

smaller MF-ratios for uninjured versus injured hands suggest that uninjured hands fatigued more than injured hands. One possible explanation is that people exert less effort with their injured hands as a protective mechanism and therefore experience less fatigue. Furthermore, steeper slopes and smaller flexor MF-ratios for males versus females suggest that males fatigue more than females, which could be because females are better able to maintain forces than males.[378] It is also possible that females are less motivated to exert true maximal voluntary contraction and thus fatigue less as they have more "fresh" motor units to recruit.

Reliability and Validity

The usefulness of an assessment depends on its reliability, i.e., its ability to measure an attribute or behavior consistently and free of error. Test-retest reliability of an assessment indicates that an assessment obtains the same results with repeated administrations of the test.[92] According to Portney and Watkins[92], "reliability coefficients of measurements used for decision making or diagnosis of individuals need to be higher, perhaps at least 0.9 to ensure valid interpretations of findings" (p. 65). Portney and Watkins[92] also suggest that an index greater than 0.9 is a guideline and not an absolute standard. Further, as a general guideline, coefficients below 0.5 represent poor reliability, coefficients from 0.5 to 0.75 represent moderate reliability, and coefficients above 0.75 represent good reliability.[92]

We found that the slope of the force-generation phase and the MF-ratios to have acceptable levels of test-retest reliability. We expected the F-T curve characteristics and EMG properties to consistently measure grip efforts as expressed by high test-retest reliability ($r \geq 0.9$). Based on the guidelines provided by Portney and Watkins[92], we found acceptable levels of reliability only for peak force, slope of force-generation phase, and

almost all EMG properties ($r \geq 0.7$). Therefore, the slope of the force-generation phase, as well as the flexor and extensor MF-ratios are sufficiently reliable measures of sincerity of effort. A reliable sincerity of effort test is appropriate for clinical use only if it is valid.[92]

A valid sincerity of effort test should reveal significant differences between maximal and submaximal efforts. We found significant differences between maximal and submaximal effort for the following measures: time-to-peak force, slopes of the force-generation phase and force-decay phase, and MF-ratios of EMG signal for flexors and extensors.

A sincerity of effort assessment could be classified as a "diagnostic" test as its purpose is to distinguish between the presence and absence of a feigned effort.[102] According to Portney and Watkins[92], "the validity of a diagnostic test is evaluated in terms of its ability to accurately assess the presence and absence of the target condition" (p. 93).[92] To be valid, a diagnostic test must also be effective; i.e., possess acceptable levels of sensitivity and specificity.[92] In absence of adequate sensitivity and specificity values, either a feigning individual may be incorrectly classified as sincere (low sensitivity) or a sincere individual may be wrongly identified of being insincere (low specificity). Specificity becomes more important than sensitivity when the risks associated with misdiagnosing maximal effort are substantial.[92] As results of a sincerity of effort test impact continuation of rehabilitative services and workers compensation, it is better to make a mistake in the direction of low sensitivity. Unfairly misclassifying a sincere person as feigning can be very damaging to the individual and promote clinically unfair decisions.[28, 64-67, 83, 93, 102, 206] It seems less damaging to misclassify people giving a

deliberate feigned effort than to mistakenly classify a person giving a true maximal effort as feigning.[80]

The sensitivity of a sincerity of effort test indicates the percentage of people who were classified as exerting a submaximal effort and really exerted a submaximal effort (true positives). The specificity indicates the percentage of people who were classified as exerting a maximal effort and really exerted a maximal effort (true-negatives). An inverse relationship exists between specificity and sensitivity: increasing the specificity (by reducing the false-positive rate) results in a decrease in sensitivity and vise versa. Therefore, when interpreting sensitivity and specificity results, one has to find a cutoff value that yields the most optimal combination of sensitivity and specificity.[27, 28, 64-67, 83, 93, 102, 206]

One method of finding the best combination of sensitivity and specificity involves calculating the overall error rate by using the formula (1-sensitivity) + (1-specificity). In other words, the overall error rate for a specific cutoff value represents the percentage of combined errors (false-positive plus false-negatives). Therefore, the lowest overall error rate identifies the cutoff value with the best combination of sensitivity and specificity.[27, 28, 64-67, 83, 93, 102, 206] In the present study, we found that the overall error rate for the slope of force-generation phase of the force-time curve ranged from 55% to 60%. We also found the overall error rates for the MF-ratios ranged from 68% to 70%. These error rates are too large to render these measures valid in detecting submaximal effort. These error rates are just as bad as the error rates identified for the clinically relevant sincerity of effort tests including the five rung grip test, coefficient of variation, and rapid exchange grip test (Table 1-1). The error rates of the clinically relevant tests range from 47% to

69%.[27, 65, 93] They are also larger than the slopes of the force-time curve for healthy people, which ranged from 7% to 33%.[102] Therefore, the force-time curve characteristics and the EMG properties of a 6-second grip exertion do not seem to provide an effective means of distinguishing between maximal and submaximal efforts in people with upper extremity injuries.

Another method of finding the best combination of sensitivity and specificity is plotting a receiver operating characteristic (ROC) curve.[110] The ROC curve is a plot of false-positive rates (1-specificity) along the X-axis against true-positive rates (sensitivity) along the Y-axis resulting from application of many arbitrarily chosen cutoff points. Therefore, the ROC curve demonstrates the effectiveness of using different cutoff values.[110] That is, the ROC curve shows the accuracy of detecting sincerity of effort over a range of cutoff values.[27, 28, 64-67, 83, 93, 102, 206] For the present study, the cutoff values were different values of the slopes of the force-generation phase, as well as flexor and extensor MF-ratios. The ROC curve allows a researcher to decide which cutoff point is the most beneficial for a certain diagnostic test.[92] Using the ROC curve facilitates choosing a cutoff value that is not arbitrary, but rather is based on the best combination of sensitivity and specificity.[92] When using the ROC curve to choose the best cutoff value for a sincerity of effort test, it is better to err in the direction of lower sensitivity and higher specificity so that a true maximal effort will not be misclassified as a submaximal effort.[27, 28, 64-67, 83, 93, 102, 206] Due to significant gender differences in the slope of the force-generation phase, we generated separate ROC curves for males and females. ROC curves were not generated for time-to-peak force due to low reliability and slope of force-decay phase due to poor sensitivity and specificity values.

The ROC curve for the force-generation phase in the present study revealed that the most optimal combination of specificity and sensitivity values for the injured hand of men was at the slope cutoff value of 1.5 V/s. When using the slope of 1.5 V/s as a criterion for determining sincerity of effort, 15% of the men who exerted submaximal effort were incorrectly identified as exerting a maximal effort (1-sensitivity) and 45% of the men who exerted maximal effort were mistakenly identified as exerting a submaximal effort (1-specificity). The overall error rate for this criterion was 60%. In a previous study, we also found the slope of 1.5 V/s as the optimal slope value among healthy men. However, only 20% of the men who exerted submaximal effort were incorrectly identified as exerting a maximal effort and only 13% of the men who exerted maximal effort were mistakenly identified as exerting a submaximal effort. The overall error rate for this criterion was 33%.[102] The most optimal cutoff value for injured women in the present study was 0.5 V/s. When using this cutoff value as a criterion for determining sincerity of effort, 40% of those who exerted submaximal effort were misclassified as exerting a maximal effort and 15% of those who exerted maximal effort were mistakenly identified as exerting a submaximal effort. The overall error rate was 55%. With healthy subjects, we found an optimal cutoff value of 1.2 V/s for women, which resulted in incorrectly identifying 20% of those who exerted submaximal effort and 7% of those who exerted maximal effort with an overall error rate was 27%.[102] In the present study, the overall error rate was almost double for both men and women with UEMDs than the error rate reported for healthy people.[102] This discrepancy between the two studies could be explained by the probable protective response of injured people who may avoid exerting maximal voluntary contraction due to pain, fear of pain and/or fear of re-injury. This is

supported by the significant session by injury interaction term for peak force (Figure 4-1), which indicated that the uninjured hand force exertion decreased in the second session while the injured hand's force exertion increased. This suggests that while the uninjured hand experienced fatigue the injured hand did not. This further suggests that the force exertion of the injured hand in the first session was not maximal.

The ROC curves generated for the EMG properties revealed similar effectiveness for the median frequency ratio of flexor and extensor muscles. High overall error rates, however, do not deem them to be good sincerity of effort tests. The ROC curve for the flexor muscle MF-ratio revealed that the most optimal combination of specificity and sensitivity values for the injured hand was for the MF-ratio cutoff value of 102%. When using this cutoff as a criterion for determining sincerity of effort, 47% of the people who exerted submaximal effort were incorrectly identified as exerting a maximal effort and 22% of the people who exerted maximal effort were mistakenly identified as exerting a submaximal effort with an overall error rate of 70%.

The ROC curve for the extensor muscle MF-ratio revealed that the most optimal combination of specificity and sensitivity values was at the MF-ratio cutoff value of 100%. When using this cutoff as a criterion for determining sincerity of effort, 37% of the people who exerted submaximal effort were incorrectly identified as exerting a maximal effort and 30% of the people who exerted maximal effort were mistakenly identified as exerting a submaximal effort. The overall error rate for this criterion was 68%. Based on our findings, if a therapist used either the flexor or extensor MF-ratio as a sincerity of effort test, he or she would incorrectly classify a large proportion of people

that they tested, which makes these measures inappropriate for clinical use as a sincerity of effort test.

Using the ROC curve, the proportional area under the curve is calculated and used as a measure of its discriminability, i.e., the ability of the test to discriminate between maximal and submaximal efforts. The area under the ROC curve is an index of the degree of separation (or overlap) between the distributions of true-positives (signal) and false-positives (noise).[110] An ideal diagnostic test has an area of 100%.[92] The greater the area under the curve, the better the ability to discriminate between maximal and submaximal efforts. In the present study, the area under the curve for the force-generation phase was greater for women (76%) than for men (72%), indicating greater ability to discriminate between maximal and submaximal efforts in women. The area under the curve for the flexor MF-ratio was 66.25% and extensor MF-ratio was 71%. In a previous study, the proportional area under the ROC curve for the force-generation phase was 92.5% for men and 92% for women.[102] Therefore, the force-time curve characteristics and the EMG properties of a 6-second grip exertion do not seem to provide an effective means of distinguishing between maximal and submaximal efforts in people with upper extremity injuries. This discrepancy between the two studies is that people with injuries are protective of their injured hand. They may experience pain, fear of pain, and/or fear of re-injury and thus they may not exert true maximal voluntary contraction with their injured hand. The interaction showing that uninjured hand force decreases during the second session but injured hand increases supports this notion.

Limitations

The limitations of this study include a heterogeneous patient population and only measuring EMG activity of forearm flexor and extensor muscles. Our findings are based

on people with upper extremity musculoskeletal conditions, with various etiologies including acute versus cumulative trauma. Further, the etiologies were different for men and women. Almost all men experienced acute trauma, whereas, half of the women experienced acute trauma and the other half experienced cumulative trauma. Therefore, the etiology could be a confounding variable for this study. Furthermore, we did not gather information regarding diagnosis because the injury-related information was provided by the patients and thus could have been inaccurate. Also, due to technical limitations, we were unable to measure the EMG activity of the intrinsic hand muscles, which participate in grip and may have identified differences between maximal and submaximal efforts. Future studies should focus on using a homogeneous patient population and examining EMG activity of intrinsic hand muscles. It is possible that testing EMG activity of intrinsic hand muscles as well as a homogeneous patient population would yield different results.

Conclusions

We found significant differences in the time-to-peak force, slope of force-generation phase as well as flexor and extensor MF-ratio between maximal and submaximal efforts. However, we did not find acceptable combinations of sensitivity and specificity for detecting sincerity of effort using these characteristics. Sensitivity and specificity analysis revealed that the slope of the force-generation phase had the best effectiveness, with the slope being a more effective assessment of sincerity of effort for women than for men. These measures yielded overall error rates of 55% to 70%. Therefore, these measures may not possess adequate sensitivity and specificity values to justify their use in the clinic.

APPENDIX A
SAMPLE SIZE CALCULATION

The primary hypothesis identified for sample size calculation was that the force-decay phase of a force-time curve (FT-curve) possesses a significantly steeper slope for maximal effort than for submaximal effort. Table A-1 lists the range of maximal and submaximal effort slope values in the preliminary study.

The extreme slope values result in the largest and smallest differences:

Largest difference = 0.39 – 0.009 = 0.381 (A-1)
Smallest difference = 0.014 – 0.16 = -0.146 (A-2)
Largest possible range of differences (Range) = 0.381 – (-0.146) = 0.527 (A-3)
We estimated the standard deviation (σd) by dividing the range by 4:

$\sigma d = \text{Range}/4 = 0.131$ V/s (A-4)

We decided to keep the bound (B), i.e. the mean difference between maximal and submaximal effort slope that is important to detect, as 0.1 V/s. We computed DELTA as:

$\text{DELTA} = B/\sigma_d = 0.1/0.131 = 0.76.$ (A-5)

We also chose a 2-tailed $\alpha = 0.05$ and $\beta = 0.2$. Although our hypothesis is unidirectional, we chose a 2-tailed α to be more conservative. Using these values, we calculated the sample size as 24. However, to take into consideration attrition due to pain/fatigue, we increased sample size to 30. Thus, 30 participants are required to detect an average difference between maximal and submaximal effort slopes of 0.1 V/s, if that difference truly exists.

Table A-1: Range of maximal and submaximal effort slope values

	Maximal Effort	Submaximal Effort
Minimum slope (V/s)	0.014	0.009
Maximum slope (V/s)	0.390	0.160

APPENDIX B
CORRELATION MATRIX FOR DYNAMOMETER CALIBRATION

Prior to beginning data collection, the calibration of the Jamar dynamometer was checked on 3 consecutive days, which when averaged resulted in Pre-data collection values. During the data collection phase, the calibration of the dynamometer was checked weekly, resulting in values Wk. 1-17. The Pearson moment correlation coefficients (*r*) between the Pre-data collection values and weekly values have been reported in Table B-1.

Table B-1: Pearson correlation coefficients (*r*) between weekly voltage outputs obtained during the dynamometer calibration process

	Pre-data collection values	Wk. 1	Wk. 2	Wk. 3	Wk. 4	Wk. 5	Wk. 6	Wk. 7	Wk. 8	Wk. 9	Wk. 10	Wk. 11	Wk. 12	Wk. 13	Wk. 14	Wk. 15	Wk. 16	Wk. 17
Pre-data collection values	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 4	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 14	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 15	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 16	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wk. 17	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

APPENDIX C
DEMOGRAPHIC QUESTIONNAIRE

University of Florida

Department of Occupational Therapy

Demographic Questionnaire

Participant ID#:_____ Date Completed:_____ Time:_____

A. DEMOGRAPHIC INFORMATION

1. Please fill out or circle the correct answer(s) for the following questions about yourself.

a.	Year of birth? _____	b.	Gender? M F
c.	Height? _____ Inches	d.	Weight? _____ lbs
e.	Dominant hand/arm? R L	f.	Injured hand/arm? R L

B. INJURY-RELATED INFORMATION

1. What injury/condition are you in therapy for?

_____

_____

2. Do you think your condition was caused by work? (Please circle one option)

YES NO

If so, please explain:_____

_____

3. Do you think your condition is aggravated by work? (Please circle one option)

YES NO

If so, please explain:_____

_____

4. What do you think is the cause of your injury?

_____

_____

5. How long have you had this condition (in years and months)?

_____Years _____Months

6. How long have you been in therapy?

_____ Weeks _____ Times per week

7. Do you experience similar symptoms on the uninjured side? (Please circle one option)

YES NO

8. Do you have any other condition that affects your hand grip? (Please circle one option)

YES NO

If so, please explain:_____

_____

9. Are you taking any pain medications?

YES NO

10. Do you have any limitations in Activities of Daily Living, such as dressing, bathing, etc.?

YES NO

11. Have you had surgery for your injury? YES NO

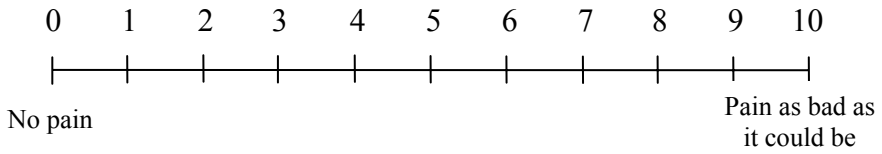
If yes, did you benefit from the surgery? YES NO

12. Have you seen any improvement with therapy? YES NO

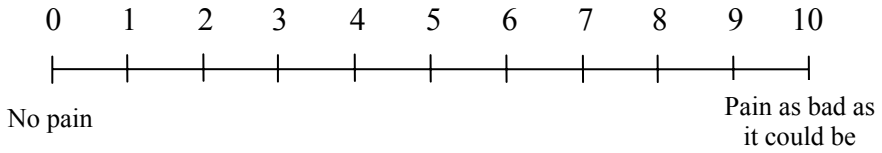
13. How successful is (was) your therapy? (Please circle one option)

a. Very successful
b. Successful (average)
c. Somewhat successful (less than average)
d. Not successful at all

14. What was the average range of pain over the last week on a scale of 0 to 10? (Please cross the line below at the most appropriate point)



15. What is the level of your current pain on a scale of 0 to 10? (Please cross the line below at the most appropriate point)



C. JOB-RELATED INFORMATION

5. What was your occupation when you were injured?

_____
_____

6. How long have you held that position?

_____

7. Please describe your duties at that position.

_____
_____

8. Are you currently working? YES NO Full-time Part-time

If part-time, how many hours? _____

9. Are you performing the same job duties as prior to your injury?

YES NO

If no, describe changes. _____

For Office Use Only	
Order #	

APPENDIX D
LETTER TO HEALTHCARE PROFESSIONALS WITH INCLUSION AND EXCLUSION CRITERIA

Orit Shechtman, Ph.D., OTR/L
Associate Professor
College of Public Health and Health Professions
Department of Occupational Therapy
Box 100164
University of Florida
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E-mail: oshechtm@phhp.ufl.edu

[Date]

[Contact information of healthcare professional]

Dear [Name of Healthcare Professional]:

Subject: Study on association between pain and grip strength, [IRB #]

It was a pleasure to talk to you on [date]. Thank you for agreeing to help us recruit participants for our study to identify an association between upper extremity pain and grip strength. This study has been approved by the Institutional Review Board at the University of Florida ([IRB Study #]). In order to be compliant with the Health Insurance Portability and Accountability Act (HIPPA), you will need to use your clinical judgment to identify individuals who meet the study criteria. Please use the following criteria to identify study participants:

- The participant should have experienced a **unilateral** traumatic or non-traumatic injury involving the **elbow or distally** in the last 1 year but not necessarily diagnosed in the last year.
- The uninjured extremity should **have not experienced** any injury in the last 5 years and currently should not be experiencing any injury-related signs/symptoms.
- The participant should be aged between 18 and 65 years.
- The participant should be able to perform 4 maximal and 8 submaximal grip efforts with their injured extremity.

- The participant should not be suffering from extreme pain. When asked verbally the level of pain generally experienced by the participant on a scale of 0-10, the participant should not experience pain intensity greater than 7.
- The participant should not have any associated illness that would compromise their grip strength.
- The participant should not be taking any medications that would compromise their grip strength.
- The participant should not have impaired cognition.

Once you have identified a study participant, please brief the individual regarding the study using the following standard instructions:

> "A study is being conducted to identify how pain affects grip strength among people with upper extremity musculoskeletal conditions. Your condition makes you eligible to participate in this study. This study involves gripping a hand dynamometer 12 times with each hand and rating your pain and perceived grip effort. If you agree to participate, you will attend one session lasting approximately 45 minutes and will be paid $20.00 for participating in the study. Please let me know if you are interested in participating and I can provide you with information to contact the research group."

If an individual agrees to participate in the study, please ask them to either contact me or Bhagwant Sindhu (Phone Number: (352)273-6057, Email: bsindhu@phhp.ufl.edu). Bhagwant is my doctoral student and he will be conducting this study. If we do not answer the phone please ask them to leave a message with their name and phone number. If you have questions regarding this study, please feel free to contact us at anytime.

We appreciate your help with this study.

Sincerely,

Orit Shechtman

APPENDIX E
RANDOMIZATION ORDER AND SHEET

	Order 1	Order 2	Order 3	Order 4
Effort 1	IM	IS	UM	US
	UM	US	IM	IS
Effort 2	IS	IS50	US	US50
	US	US50	IS	IS50
Effort 3	IS50	IM	US50	UM
	US50	UM	IS50	IM

For submaximal effort, always start with submaximal effort according to imagined pain

IS	Injured—Submaximum (Imagined Pain)
IS50	Injured—Submaximum (50% max)
IM	Injured--Maximum
US	Uninjured—Submaximum (Imagined Pain)
US50	Uninjured—Submaximum (50% max)
UM	Uninjured--Maximum

Figure E-1: Randomization orders used in the study

Table E-1: Randomization sheet used in the study

Participant #	Name	Sex	Order	Date	Time	Pre/Post Therapy	Dominant hand	Injured hand
1		Male	3					
2		Male	1					
3		Male	2					
4		Male	2					
5		Male	4					
6		Male	4					
7		Male	3					
8		Male	3					
9		Male	3					
10		Male	2					
11		Male	1					
12		Male	2					
13		Male	1					
14		Male	4					
15		Male	3					
16		Male	1					
17		Male	4					
18		Male	1					
19		Male	2					
20		Male	4					
21		Female	4					
22		Female	4					
23		Female	2					
24		Female	1					
25		Female	4					
26		Female	4					
27		Female	3					
28		Female	1					
29		Female	3					
30		Female	3					
31		Female	2					
32		Female	3					
33		Female	1					
34		Female	2					
35		Female	1					
36		Female	4					
37		Female	2					
38		Female	2					
39		Female	3					
40		Female	1					

APPENDIX F
CHECKLISTS USED DURING THE DATA COLLECTION PROCESS

During the data collection phase, we used checklists to assist us in following the correct experimental procedure. To maintain blinding, we used two different checklists. The checklist used by the research assistants indicated the level of grip effort being exerted by the study participant (Figure F-1). In contrast, the checklist used by the test administrator did not indicate the level of grip effort. The test administrator's checklist was also used to note the length of the rest period between hand grips (Figure F-2).

Participant # _____
Order 2
Session 1

Check when done																			
Task	Forms	Pain VAS Test-Retest	Participant Setup	Pain VAS Test-Retest	Practice Grip Uninjured	Practice Grip Injured	Grip Effort Instructions	Injured Sub Pain 1	Injured Sub Pain 2	Uninjured Sub Pain 1	Uninjured Sub Pain 2	Injured Sub 50% 1	Injured Sub 50% 2	Uninjured Sub 50% 1	Uninjured Sub 50% 2	Injured Max 1	Injured Max 2	Uninjured Max 1	Uninjured Max 2
Sub-tasks	ICF	VAS Instructions	Affix electrodes	Baseline Pain 2	Pain Scale	Grip		Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card
	Questionnaire	Baseline Pain 1	Positioning	For injured hand	Grip	Effort Scale		Grip 1	Grip 2	Grip 3	Grip 4	Grip 5	Grip 6	Grip 7	Grip 8	Grip 9	Grip 10	Grip 11	Grip 12
		For injured hand		Paper first	Effort Scale Instructions	Pain Scale		Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale
		Paper first		Time	Effort Scale			Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale
								Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time

Break

Check when done	
Task	Forms
Sub-tasks	Payment

Session 2

Check when done																			
Task		Injured Sub Pain 1	Injured Sub Pain 2	Uninjured Sub Pain 1	Uninjured Sub Pain 2	Injured Sub 50% 1	Injured Sub 50% 2	Uninjured Sub 50% 1	Uninjured Sub 50% 2	Injured Max 1	Injured Max 2	Uninjured Max 1	Uninjured Max 2						
Sub-tasks		Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card						
		Grip 1	Grip 2	Grip 3	Grip 4	Grip 5	Grip 6	Grip 7	Grip 8	Grip 9	Grip 10	Grip 11	Grip 12						
		Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale						
		Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale						
		Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time						

Figure F-1: Checklist used by the research assistants

Participant # _____

Session 1

Check when done																			
Task	Forms	Pain VAS Test-Retest	Participant Setup	Pain VAS Test-Retest	Practice Grip Uninjured	Practice Grip Injured	Grip Effort Instructions												
Sub-tasks	ICF	VAS Instructions	Affix electrodes	Baseline Pain 2	Pain Scale	Grip		Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card
	Questionnaire	Baseline Pain 1	Positioning	For injured hand	Grip	Effort Scale		Grip 1	Grip 2	Grip 3	Grip 4	Grip 5	Grip 6	Grip 7	Grip 8	Grip 9	Grip 10	Grip 11	Grip 12
		For injured hand		Paper first	Effort Scale Instructions	Pain Scale		Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale
		Paper first		Time	Effort Scale			Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale
								Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time
							Time (s)												

Break

Check when done	
Task	Forms
Sub-tasks	Payment

Session 2

Check when done																			
Task																			
Sub-tasks								Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card	Instructions	Cue Card	Cue Card	Cue Card
								Grip 1	Grip 2	Grip 3	Grip 4	Grip 5	Grip 6	Grip 7	Grip 8	Grip 9	Grip 10	Grip 11	Grip 12
								Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale	Effort Scale
								Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale	Pain Scale
								Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time	Time
							Time (s)												

Figure F-2: Checklist used by the test administrator

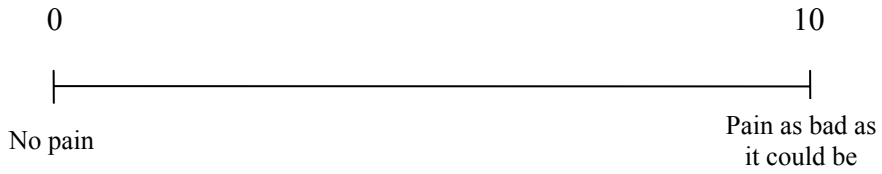
APPENDIX G
DATA COLLECTION FORM

Participant ID#:_____ Order #: **1**

Session 1
Practice 1

What is the level of your current pain on a scale of 0 to 10?

Pain

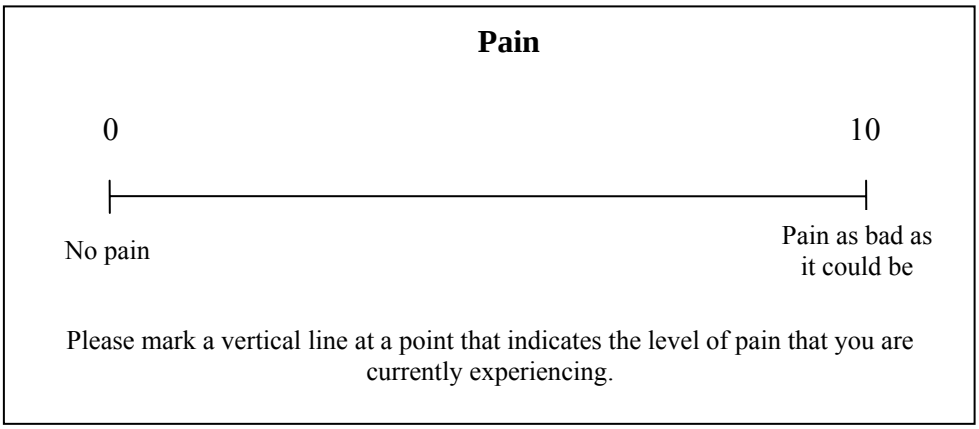


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Time (between practice 1 and 2): _____

Practice 2

What is the level of your current pain on a scale of 0 to 10?



Practice Trial – Uninjured Hand

Pain

0 10

No pain

Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Effort

0% 100%

No Grip Force

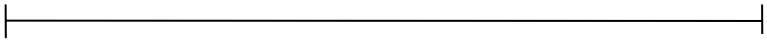
Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Practice Trial Sheet – Injured Hand

Effort

0% 100%



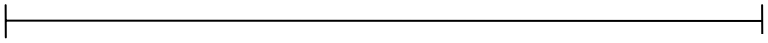
No Grip Force

Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

0 10



No pain

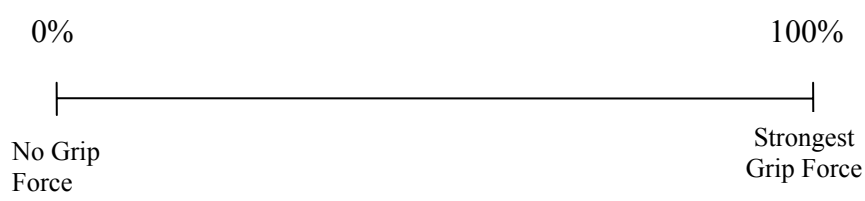
Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Maximum

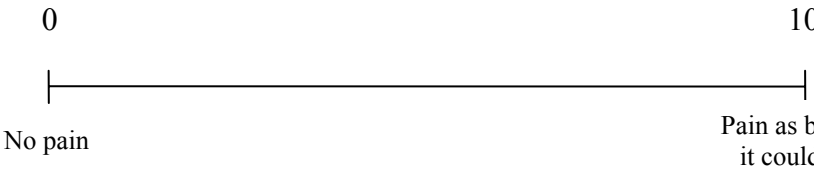
Grip 1

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

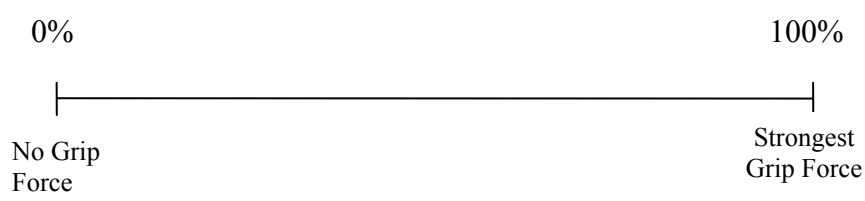


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Maximum

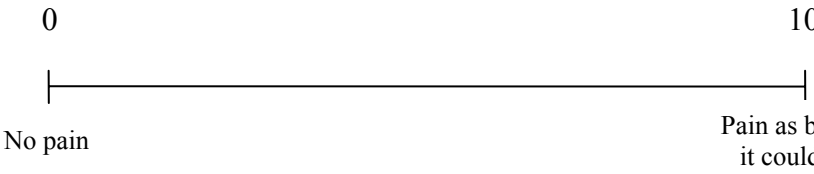
Grip 2

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

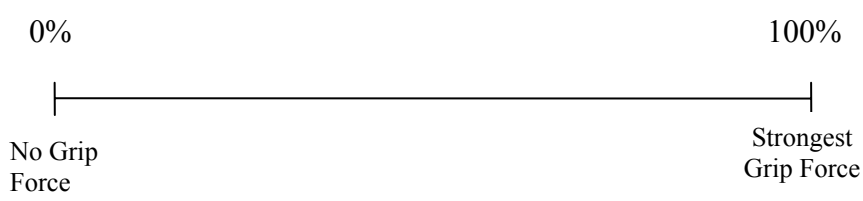


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Maximum

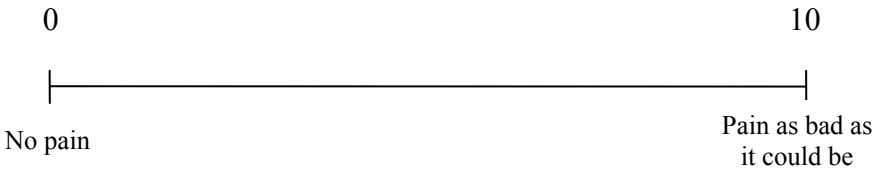
Grip 1

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

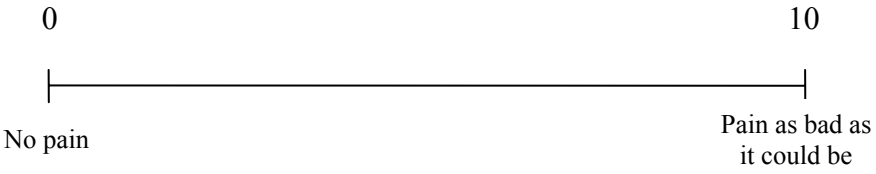
Uninjured- Maximum

Grip 2

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

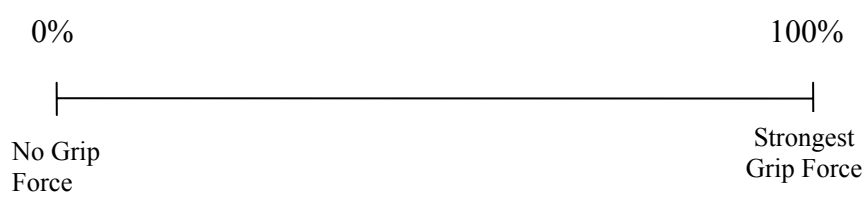


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Submaximum (Pain)

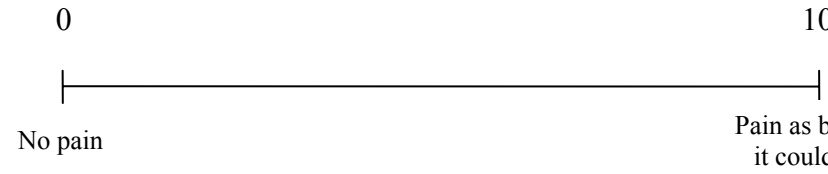
Grip 1

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

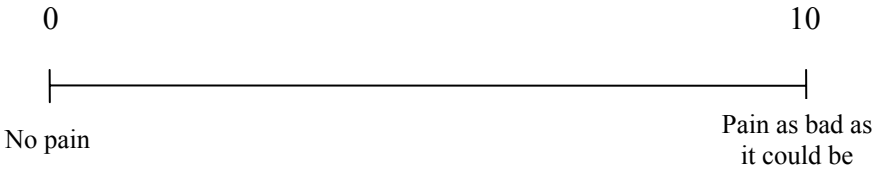
Injured- Submaximum (Pain)

Grip 2

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Submaximum (Pain)

Grip 1

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

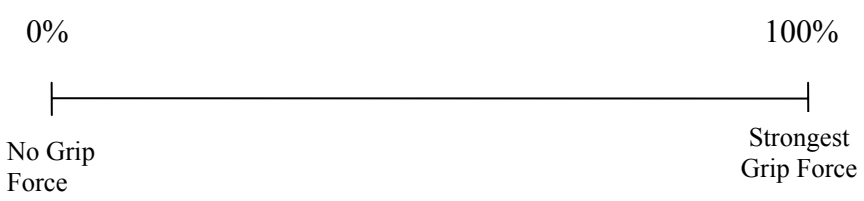
Pain

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Submaximum (Pain)

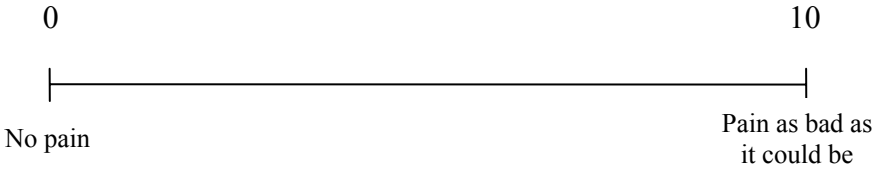
Grip 2

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

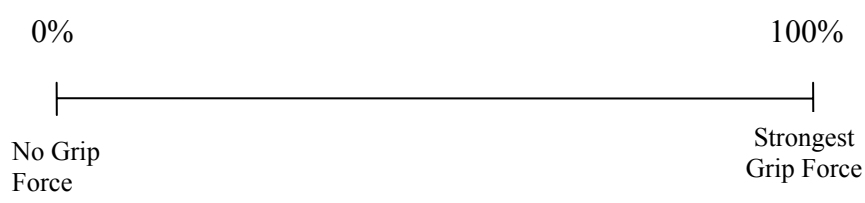


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Submaximum (50% Maximum)

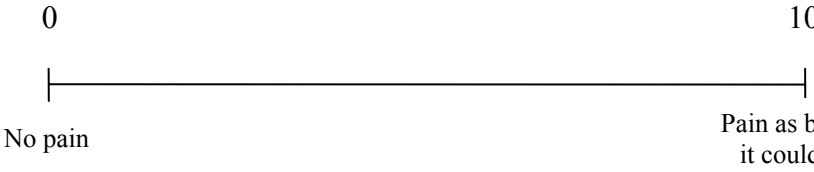
Grip 1

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

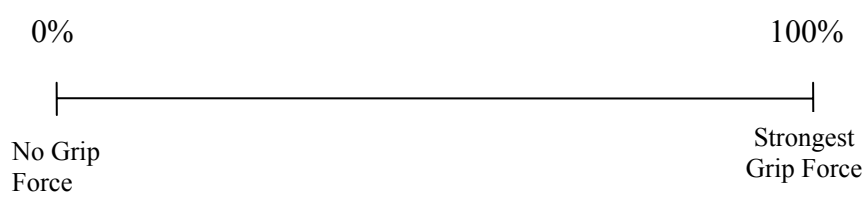


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Submaximum (50% Maximum)

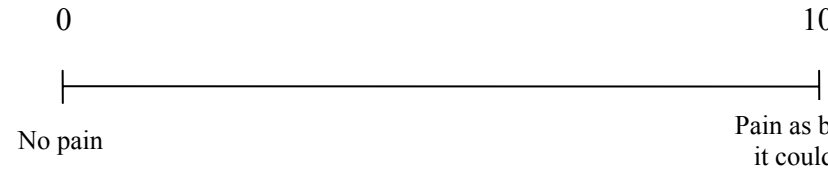
Grip 2

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

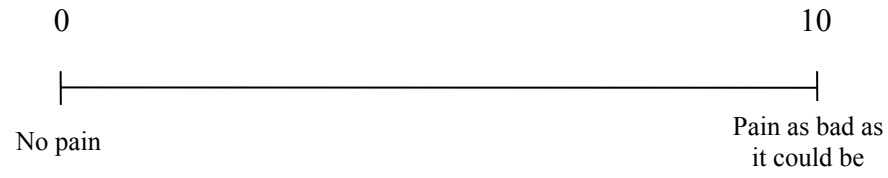
Uninjured- Submaximum (50% Maximum)

Grip 1

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

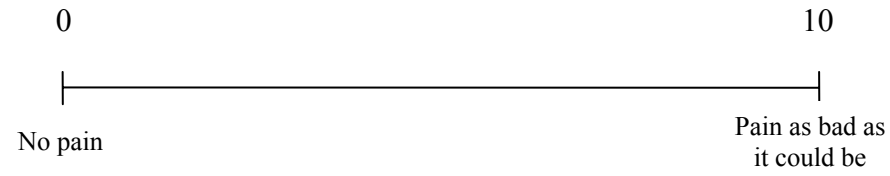
Uninjured- Submaximum (50% Maximum)

Grip 2

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Participant ID#:_____ Order #: **1**

Session 2

Injured- Maximum

Grip 1

Effort

0% 100%

No Grip Force — Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

0 10

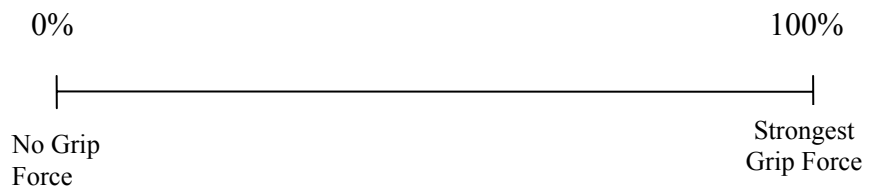
No pain — Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Maximum

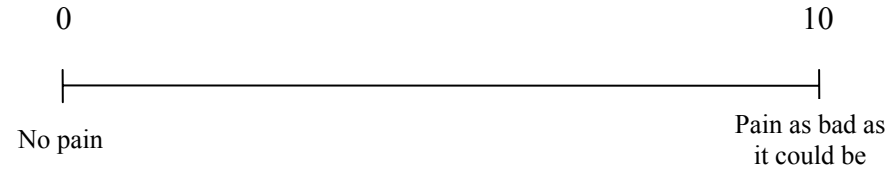
Grip 2

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

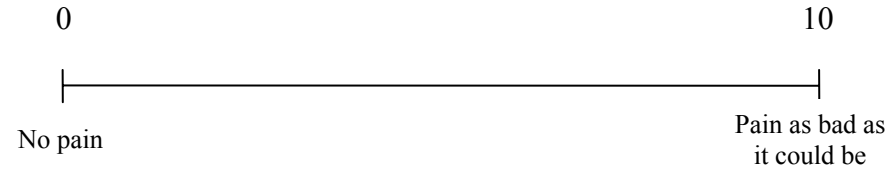
Uninjured- Maximum

Grip 1

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Maximum

Grip 2

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

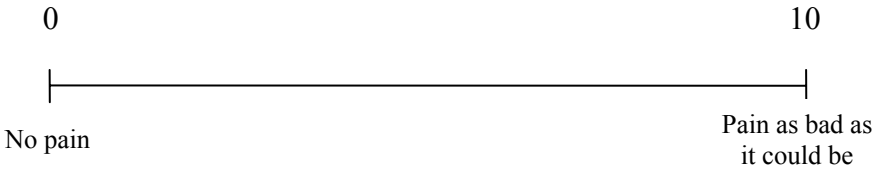
Injured- Submaximum (Pain)

Grip 1

Effort

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

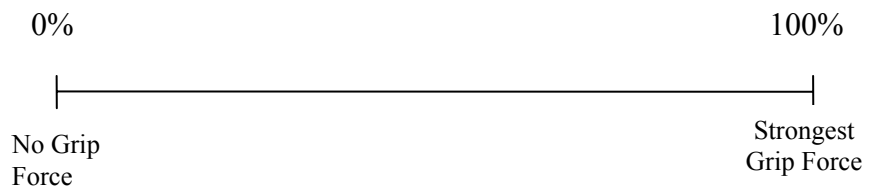


Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Submaximum (Pain)

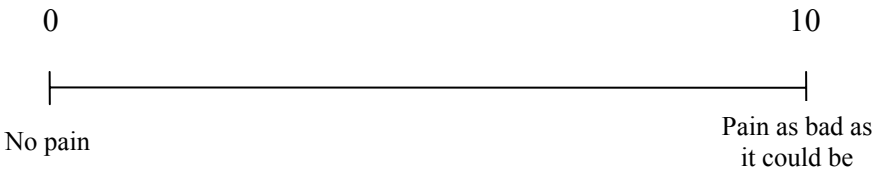
Grip 2

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain



Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Submaximum (Pain)

Grip 1

Effort

0% 100%

No Grip Force

Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

0 10

No pain

Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Submaximum (Pain)

Grip 2

Effort

0% 100%

No Grip Force

Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

0 10

No pain

Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Submaximum (50% Maximum)

Grip 1

Effort

0% 100%

No Grip Force — Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

0 10

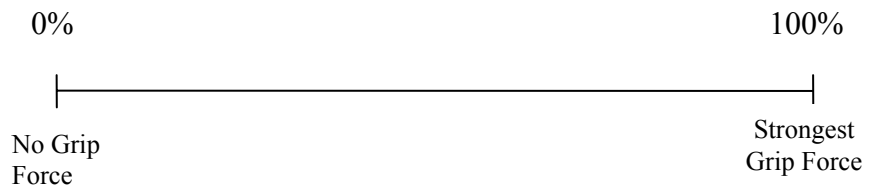
No pain — Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Injured- Submaximum (50% Maximum)

Grip 2

Effort



Please mark a vertical line at a point that indicates the level of effort you just exerted.

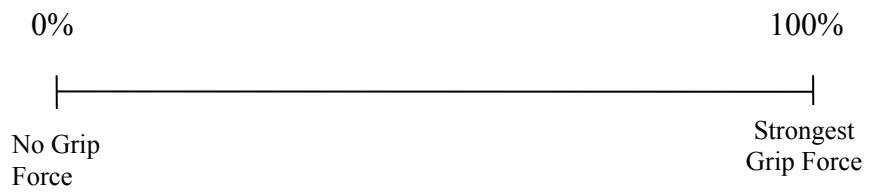
Pain

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Submaximum (50% Maximum)

Grip 1

Effort



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Pain

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

Uninjured- Submaximum (50% Maximum)

Grip 2

Effort

0% 100%

No Grip Force — Strongest Grip Force

Please mark a vertical line at a point that indicates the level of effort you just exerted.

Pain

0 10

No pain — Pain as bad as it could be

Please mark a vertical line at a point that indicates the level of pain that you are currently experiencing.

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BIOGRAPHICAL SKETCH

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