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AN EXAMINATION OF ECCENTRIC VERSUS CONCENTRIC UNILATERAL RESISTANCE EXERCISE ON IPSILATERAL AND CONTRALATERAL MOTOR CONTROL STRATEGIES ACROSS AN 8 WEEK TRAINING PERIOD

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NATHAN PAUL WAGES
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AN EXAMINATION OF ECCENTRIC VERSUS CONCENTRIC UNILATERAL RESISTANCE EXERCISE ON IPSILATERAL AND CONTRALATERAL MOTOR CONTROL STRATEGIES ACROSS AN 8 WEEK TRAINING PERIOD

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF HEALTH AND EXERCISE SCIENCE

BY

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Dr. Michael G. Bemben, Chair

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Dr. Rebecca D. Larson

_____
Dr. Christopher D. Black

_____
Dr. Daniel J. Larson

_____
Dr. Michael R. Markham

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Abstract

Traditionally, contralateral training interventions have been applied in the unilateral limb to examine the potential short-term "cross-over" responses and long-term "cross education" adaptations in the contralateral limb. Despite the completion of a multitude of studies, there is still a nescience regarding differences in training adaptations based solely upon specificity of training phase (e.g., concentric [CON] vs. eccentric [ECC] exercise). **PURPOSE:** To compare the training adaptations elicited from CON vs. ECC resistance exercise to evaluate the ipsilateral and contralateral limb's responses and adaptations. **METHODS:** Twenty healthy, college-aged (18-35 years old) men (N = 10) and women (N = 10) volunteered to participate in this investigation. Participants were required to unilaterally resistance train three days per week for a total of eight weeks. Participants were randomly assigned into either CON or ECC training groups and were asked to perform bicep curls for five sets of ten repetitions (to momentary fatigue) per training visit with their dominant limb only. Ipsilateral and contralateral limb responses and adaptations were evaluated in two week increments following the initial familiarization visit. Cross-sectional area (CSA), maximal dynamic strength, maximal isometric strength, and force fluctuations during submaximal contractions (30%, 50%, and 70% of maximal voluntary contraction [MVC]), as well as surface electromyographic (EMG) and mechanomyography (MMG) signals were collected during all evaluation visits. **RESULTS:** When ECC and CON unilateral exercises are performed in isolation, ECC training causes a greater stimulus for promoting neurophysiological adaptations (e.g., greater increase in CSA, maximal dynamic and isometric strength, and a decrease in force fluctuations [e.g., greater

improvement in force steadiness]) across time. Furthermore, these neurophysiological adaptations are not only greater in the trained (ipsilateral) limb, but it also appears that they are greater in the untrained (contralateral) limb through inter-limb transfer of sensorimotor adaptations. **CONCLUSIONS:** Our results further support the findings from previous research which indicated that ECC unilateral training was a better stimulator for contralateral responses and adaptations when compared to CON unilateral training. Therefore, we have concluded that our results were attributed to an increase in neural drive and a decrease in corticospinal inhibition, which would cause greater cross-over responses and cross-educational adaptations due to a larger percentage of neural impulses remaining on the ipsilateral side of the body and not crossing over (at the medulla oblongata) to the contralateral side.

Chapter I

Introduction

1.1. Background

Since 1662, when René Descartes (Descartes, 1662) published his perceptive observations regarding the coordinated contractions between opposing muscle groups, a multitude of studies have further examined these interdependent interactions. As new studies developed over time, researchers began to label the two opposing muscle groups "antagonistic pairs". Specifically, the muscle group performing the action or movement was termed the "agonist" (from the Latin word agnista, meaning contender) and the muscle group opposing that action or movement was termed the "antagonist" (from the Latin word antagnista, meaning competitor). Furthermore, it has been demonstrated by several studies (Sherrington, 1896; Sherrington & Hering, 1898; Sherrington, 1898) that during certain conditions, agonist activation is accompanied by antagonist relaxation, or inhibition (i.e., during concentric [CON] exercise). This contraction-relaxation phenomenon is often referred to as reciprocal innervation, reciprocal relaxation, or reciprocal inhibition (Sherrington, 1896; Neilsen & Kagamihara, 1992; Geersen *et al*., 2011). However, there are other conditions where the opposing muscle is involuntarily active (i.e., during eccentric [ECC] exercise) and when this situation occurs, this phenomenon is referred to as "co-activation" (Tilney & Pike, 1925; Person, 1958).

The terms "CON" and "ECC" originates back to Hill (1925), when he first defined two types of muscle contractions. He proposed that the first type of muscle contraction be labeled "isometric", and defined it as "where muscle length does not

change during contraction". The second type he labeled "isotonic", and defined it as "where tension remained unchanged or could also vary while the muscle's length changes". Furthermore, he proposed the sub-categorization of the isotonic contractions into "CON", which he defined as "where the muscle tension rises to meet the resistance, then remains stable as the muscle shortens"; and "ECC", which he defined as "where the muscle lengthens as the resistance is greater than the force the muscle is producing." Since Hill's (1925) article, traditional (or conventional) resistance exercise has been taught to implement a high external load in the CON and ECC phases of a repetition, over multiple repetitions, to increase muscular strength, hypertrophy, and force (Vikne *et al*., 2006).

Presently, it is common knowledge that skeletal muscles are able to develop a greater amount of force during ECC contractions, as compared to CON contractions. Accompanying this increase in force development is an increase in the associated "damage" related to that particular muscle (as seen by a reduction in voluntary strength occurring immediately after ECC exercise) (Warren *et al*., 1999). Moreover, unlike ECC exercise, CON exercise does not appear to cause muscle damage and any strength loss after CON exercise is solely because of muscle fatigue (Weerakkody et al., 2003). Furthermore, this muscle damage (due to ECC exercise) affects not only voluntary strength, but also electrically stimulated twitch and tetanic tensions, superimposed twitch tension, isometric force steadiness, contraction time, half relaxation time, maximal rate of force development and the characteristics of the angle-torque relationship (Davies & White, 1981; Newham *et al*., 1987; Sayers *et al*., 2003; Semmler *et al*., 2007; Hubal *et al*., 2007; Hubal *et al*., 2008).

The notion of contralateral training (i.e., training a particular muscle or group of muscles from one appendage to enhance muscular responses and adaptations in the homologous muscle or group of muscles in the opposing limb) is not a relatively new concept, nor is the investigation of this phenomenon. Even though this type of training has been investigated over the past century, there are still many physiological facets (i.e. neural mechanisms) that researchers do not completely understand or agree upon (Zhou, 2000; Shima *et al*., 2002; Carroll *et al*., 2006). For example, which mechanism (i.e., cortical, subcortical/supraspinal, spinal, or peripheral) does this phenomenon depend on exclusively, or is there a coupling amongst these mechanisms that act together for this contralateral response or adaptation to occur? Furthermore, even though contralateral training can increase muscular strength and force while reducing muscle atrophy, this type of training does not appear to be effective for the development of specific skill acquisition where practice is a necessity (i.e., shooting a basketball, throwing a baseball, kicking a ball, writing, etc.).

The vast majority of evidence for neural mechanisms and hypertrophy adaptations associated with contralateral training has been drawn from surface electromyography (EMG); whereas a very limited number of studies have investigated contralateral training using mechanomyography (MMG). Specifically, EMG is the non-invasive method for examining the electrical aspects, whereas MMG is a non-invasive method for examining the mechanical aspects, of muscle function from an active muscle (Orizio, 1993; Jaskólska *et al*., 2003; McKay *et al*., 2006). Moreover, MMG has been considered as the intrinsic mechanical counterpart to the motor unit's (MU) electrical signal detected on the skin's surface, as measured by EMG (Gordon &

Holbourn, 1948) and is not affected by the quality of the sensor-skin interface (i.e., sweat accumulation and skin resistance). Furthermore, the combination of surface EMG and MMG measurements have been used in various studies to examine the neural and mechanical aspects of muscle fatigue, as well as the mechanisms underlying the strength decrement immediately following ECC exercise (Bajaj *et al*., 2002; Kawczynski *et al.*, 2007; Orizio *et al*., 1989 a & b; Orizio *et al.*, 1992). Thus, the findings from these studies are important because they provide a basis for using simultaneous measurements of EMG and MMG to examine the neuromuscular aspects of muscle fatigue versus muscle damage (Weerakkody *et al*., 2003).

A limitation of using surface EMG to investigate motor control strategies is that surface EMG only provides a global measure of MU activity. Thus, research studies that want to investigate individual MU behavior may not benefit for using traditional surface EMG. However, recent developments in surface EMG decomposition technology have greatly improved the ability to examine and evaluate motor control strategies (Klein *et al*., 2000; Merletti *et al*., 2003; De Luca *et al*., 2006; Klein *et al*., 2007; Merletti *et al*., 2008). Specifically, the EMG decomposition technology developed by De Luca's group allows researchers the capability to examine up to 40 MUs from almost any level of specified isometric constant force (De Luca *et al*., 2006; De Luca & Hostage, 2010) and has been proven to be valid and extremely accurate (Nawab *et al*., 2010; De Luca & Nawab, 2011; Hu *et al*., 2013; Hu *et al*., 2014).

As previously mentioned, the fact that ECC exercise causes muscle damage, whereas CON exercise does not, is crucially important because nearly all sporting activities are composed of CON and ECC muscle actions (Beck *et al.*, 2012). The

relative contribution of each muscle action type is obviously dependent on the type of activity being performed (along with the intensity and duration of that activity). However, theory would suggest that activities with a high volume of ECC muscle actions would demonstrate a greater magnitude of strength loss than those activities with mostly CON muscle actions (Beck *et al.*, 2012). The reason for this decrement in strength is due to the muscle damage component linked with ECC exercise. Thus, training programs that emphasize an increased component of ECC muscle actions may be potentially more useful for reducing a muscle's vulnerability to damage, thereby decreasing the severity of the strength loss that occurs during rigorous competition (Beck *et al.*, 2012). Therefore, an improved understanding of the mechanisms related to ECC versus CON training may eventually lead to the development of training strategies or programs that hinder this decrease in strength, thereby improving performance toward the end of a rigorous competition activity (or between rigorous competition activities).

1.2. Purpose of Study

Despite the completion of a multitude of studies, there is still a nescience regarding differences in training adaptations between CON and ECC exercise. Therefore, we had two main purposes for this study. The primary purpose was to compare the training adaptations elicited from CON versus ECC exercise programs. The secondary purpose was to evaluate which training adaptation provides a greater cross-educational adaptation between homologous muscles.

1.3. Research Questions

This study has the potential to provide new information about differences in the muscular adaptations that result from CON versus ECC training. The following 6 research questions are those that had potential to be answered by the present study:

1. Would subjects experience a greater increase in dynamic strength from CON training or ECC training in the trained arm?
2. Would subjects experience a greater increase in isometric strength from CON training or ECC training in the trained arm?
3. Would subjects experience a greater increase in force steadiness during the plateau phase of the submaximal trapezoidal force tracing from CON training or ECC training in the trained arm?
4. Would subjects experience a greater cross-educational adaptation for dynamic strength between homologous muscles from CON training or ECC training?
5. Would subjects experience a greater cross-educational adaptation for isometric strength between homologous muscles from CON training or ECC training?
6. Would subjects experience a greater cross-educational adaptation for force steadiness during the plateau phase of the trapezoidal force tracing from CON training or ECC training?

1.4. Research Hypotheses

1. Subjects would experience a greater increase in dynamic strength from ECC training when compared to CON training in the trained arm.

2. Subjects would experience a greater increase in isometric strength from ECC training when compared to CON training in the trained arm.
3. Subjects would experience a greater increase in force steadiness during the plateau phase of the submaximal trapezoidal force tracing from ECC training when compared to CON training in the trained arm.
4. Subjects would experience a greater cross-educational adaptation in dynamic strength from ECC training when compared to CON training in the untrained arm.
5. Subjects would experience a greater cross-educational adaptation in isometric strength from ECC training when compared to CON training in the untrained arm.
6. Subjects would experience a greater cross-educational adaptation in force steadiness during the plateau phase of the submaximal trapezoidal force tracing from ECC training when compared to CON training in the untrained arm.

1.5. Significance of Study

This study has enhanced our knowledge of the acute and chronic adaptations between CON versus ECC exercise. Specifically, information regarding acute and chronic adaptations related to CON versus ECC training has been vitally important for interpreting different facets within those distinctly trained muscles. In addition to the improved understanding of the acute and chronic training adaptations, these results have provided information that is useful for implementing clinical and practical training applications.

1.6. Delimitations

1. Only ten males and ten female participants completed this study.
2. Participants were male and female college students between the ages of 18 and 35 years.
3. Participants were neither non-sedentary, nor resistance or aerobically trained.
4. Participants had no current signs/symptoms of upper body appendicular pain or discomfort.
5. Participants did not have a history of upper body appendicular pain or discomfort.
6. Participants abstained from taking training supplements of any form.
7. Participants only performed voluntary contractions within the parameters of the study.

1.7. Limitations

1. Process of participant selection was not be truly random due to a volunteer basis.
2. Participants may not have provided valid information related to upper body appendage pain or discomfort.
3. Participants may not have provided valid information related to training or sedentary status.
4. Results may only be specific to the biceps brachii muscles.
5. Participants may not have given maximum effort during all aspects of the training study.

6. Participants may have exercised outside parameters of the study.
7. We did not have a control group for general comparisons.
8. The technique and equipment used to examine MU properties had restrictions and limitations.
    a. Muscle contractions had to be isometric.
    b. Force tracing profile had to be trapezoidal in shape.
    c. Duration during isometric contractions had to be less than ≤ 32 sec.

1.8. Assumptions

1. Participants provided valid information on questionnaire.
2. All participants gave maximum effort during all aspects of the training study.
3. All participants completed all testing sessions.
4. All participants did not perform any exercise outside the parameters of this study.
5. All equipment was calibrated accurately between and across all measurements.
6. All equipment functioned properly during all testing sessions.
7. The MMG and EMG variables detected at the sensors accurately represented the behavior of the whole muscle.

1.9. Operational Definitions

Action potential: a short-lasting event in which a neuron's electrical membrane potential rapidly increases and then decreases.

Agonist:	the primary muscle responsible for an action.
Antagonist:	a muscle that opposes the action produced by the agonist.
Amplitude:	the maximum displacement of a signal wave from the equilibrium point.
Concentric:	a muscle action in which the muscle shortens while generating force.
Contralateral:	occurring on, affecting, or acting in conjunction with an appendage on the opposite side of the body.
Dominant arm:	the specific arm in which an individual throws an object.
Eccentric:	a muscle action in which the muscle lengthens while generating force.
Electromyography:	non-invasive technique that measures the electrical activity within a muscle.
Innervation Ratio:	the average number of fibers per motor unit for a given muscle.
Ipsilateral:	occurring on, affecting, or acting in conjunction with an appendage on the same side of the body.
Isometric:	a muscle action involving tension production without movement at the joint or shortening of the muscle fibers

Mean frequency:	the average number of oscillations of a signal wave over a specific period of time.
Mechanomyography:	non-invasive technique that measures mechanical activity within a muscle.
Motor unit:	a motor neuron and all the muscle fibers that it innervates.
Motor unit action potential train:	a sequence of action potentials generated by a single motor unit.
Rate coding:	the manipulation of a neuron's firing rate.
Recruitment:	the activation of (an) additional motor unit(s).
Recruitment range:	the relative level of force to which a muscle can recruit additional motor units.
Recruitment threshold:	the force level at which a motor unit is activated.
Repetition maximum:	maximum number of repetitions completed during a muscular event
Sedentary subjects:	an individual that has not participated in any form of exercise in the previous 6 months.
Size principle:	the orderly recruitment of motor units from smallest to largest as demand increases.
Strength:	the maximal amount of force or tension a muscle or group of muscles can exert against a resistance in a single effort.

Trained arm:	dominant limb; limb used to perform CON or ECC exercises
Untrained arm:	non-dominant limb; limb not used to perform CON or ECC exercises
Untrained subjects:	an individual that participates in some form of exercise ≤ 2 days per week, for less than 1 hour each day, for less than 3 months.
Voluntary activation:	level of voluntary drive during a muscular effort.

1.10. Abbreviations

1-RM	=	One-Repetition Maximum
10-RM	=	Ten-Repetition Maximum
ADM	=	Abductor Digiti Minimi
ANOVA	=	Analysis of Variance
ANCOVA	=	Analysis of CoVariance
AP	=	Adductor Pollicis
APB	=	Abductor Pollicis Brevis
BB	=	Biceps brachii
BF	=	Biceps femoris
CI	=	Confidence Interval
CNS	=	Central Nervous System
CON	=	Concentric
CPG	=	Central Pattern Generator

CSA	=	Cross-sectional Area
CVF	=	Coefficient of Variation
DFT	=	Discrete Fourier transform
DOM	=	Dominant
DOMS	=	Delayed Onset Muscle Soreness
DSDC	=	Decompose-Synthesize-Decompose-Compare
ECC	=	Eccentric
EMG	=	Electromyography
ES	=	Effect Size
FDI	=	First Dorsal Interosseous
FG	=	Fast Glycolytic
FOG	=	Fast Oxidative Glycolytic
GTO	=	Golgi Tendon Organ
HYP	=	Hypertrophy
ICC	=	Intraclass Correlation Coefficient
MEP	=	Motor Evoked Potentials
MMG	=	Mechanomyography
MNF	=	Mean Frequency
MU	=	Motor Unit
MUAPT	=	Motor Unit Action Potential Train
MVC	=	Maximal Voluntary Contraction
NDOM	=	Non-Dominant
PCA	=	Principle Component Analysis

RF	=	Rectus Femoris
RMS	=	Root Mean Square
RT	=	Resistance Training
SD	=	Standard Deviation
SO	=	Slow Oxidative
SPI	=	Second Palmer Interosseous
SPSS	=	Statistical Package of the Social Sciences
ST	=	Semitendinosus
TA	=	Tibialis Anterior
TB	=	Triceps Brachii
TMS	=	Transcranial Magnetic Stimulation
VM	=	Vastus Medialis
VL	=	Vastus Lateral

Chapter II

Review of Literature

This chapter will provide literature related to the most important aspects of the study. Specifically, the following key words (adaptation; aerobic; agonist; amplitude; anaerobic; antagonist; dominant; electromyography; fatigue; hypertrophy; mean frequency; mechanomyography; non-dominant; resistance; trained; untrained) were used within the following data bases (Academic Search Complete; ArticlesPlus; CINAHL; ERIC; Google Scholar; ProQuest; Physical Education; PubMed; SPORTDiscus; and Web of Science) to find our list of articles. More specifically, the sub-categorical literature (summaries will be provided in chronological order) will encompass research related to the agonist/antagonist interaction, motor unit recruitment/ firing rate properties, effects of visual feedback on CNS and/or exercise performance, cross-over/cross-education of homologous muscles, CON/ECC exercise, and factors that influence EMG and MMG measurements. Finally, a brief summary of literature will be provided at the end of each sub-section.

2.1. Agonist/Antagonist Interaction

Descartes, 1662

The purpose of this investigation was to examine coordinated interactions between opposing muscle groups. Specifically, this author theorized that the shortening of an agonist muscle, which caused the muscle to expand, was brought about by the transfer of "animal spirits" derived from the collapse of the antagonistic muscle as it lengthened. Furthermore, he believed that this "spiritual transfer" was primed by the

cerebral ventricle, which directed the spirits to move from the antagonist muscle toward the agonist muscle. Most importantly, he was the first researcher to potentially explain reasons for the specific reflex actions between the afferent and efferent pathways (i.e., withdraw reflex, stretch reflex, etc.).

Bell, 1823

The purpose of this investigation was to further examine the interactions of the antagonistic pairs. Specifically, this author performed a considerable amount of experiments, using himself, living subjects, and cadavers, on reciprocal (opposing) muscle pairs. Most importantly, he hypothesized a possible neural interaction between antagonist pairs. Specifically, he stated after one of his experiments that, "The nerves have been considered so generally as instruments for stimulating muscles, without thought of their contribution in the opposite capacity, that some additional illustration may be necessary here. Through the nerves is established the connection between the muscles, not only that connection by which muscles combine to one effort, but also that relation between the classes of muscles by which one relaxes and the other contracts. I appended a weight to a tendon of an extensor muscle, which gently stretched it and drew out the muscle; and I found that the contraction of the opponent flexor was attended with a descent of the weight, which indicated the relaxation of the extensor." His statement is groundbreaking because this comment may be the first mention of the concept of a neural interaction between muscles.

Sherrington, 1892-1909

The purpose of this author's work, over a series of sequential investigations, was to further examine relationships between antagonistic pairs. Specifically, this author observed muscular afferent and efferent reflexes as it applied to the reciprocal innervation of those antagonistic pairs. More specifically, he explained the concept of reciprocal inhibition (activation of the agonist muscle elicits the inhibition [temporarily] of the antagonist muscle, but is immediately followed by a super-excitability phase for that same antagonist muscle) between antagonistic muscles. Furthermore, based off his results, he concluded that the antagonistic pair interactions were more than just mechanical (thus, agreeing with the works of Bell [1823]) and that there had to be a neural component working in conjunction with this mechanical component. Moreover, he was also the first investigator to develop the terms "muscular sense" and "kinesthetic sense" to describe the influence of the sensory organs in muscles, tendons, and joints in different limb positions, as well as the associated proprioceptive input.

Tilney & Pike, 1925

The purpose of this investigation was to examine the possible role(s) of the cerebellum in the coordinated movements between the antagonistic pairs. Specifically, these authors examined the interactions that occurred during voluntary movements, instead of during reflex movements like Sherrington's work (1892-1909). Moreover, Tilney and Pike (1925) demonstrated that the antagonistic pairs were simultaneously active (as determined by the EMG signals from the BB and TB muscles). Interestingly,

these authors were not able to reproduce the reciprocal inhibition phenomenon described by Sherrington's work (1892-1909). However, Tilney and Pike (1925) did recognize that, "with every movement, there was a DOM element (agonist muscle) and a moderator element (antagonist muscle) to check and balance the efforts of the DOM element" and despite the opposing muscles being co-activated, their associated activation levels were not equal. Furthermore, they stated that the DOM element was always greater than the moderator element and that both elements always remained proportional to one another at a constant ratio. Additionally, for these authors to determine the cerebellar role(s) for these types of muscular interactions, varying portions of the cerebellum, from monkeys and cats, were systematically removed. Moreover, due to the strategic placement of these lesions, which lead to a disassociation between the antagonistic pairs, these authors were finally able to identify the reciprocal innervation phenomenon described by Sherrington (1892-1909). Based upon their results, Tilney and Pike (1925) determined that even though the rising force curve of an antagonist muscle implies contraction, a falling force curve does not necessarily imply relaxation. Thus, these authors concluded that during a voluntary movement, antagonistic pairs are both activated, and the coordination between their antagonistic interactions was influenced by the cerebellum.

Hufschmidt & Hufschmidt, 1954

The purpose of this investigation was to examine the simultaneous responses of antagonistic muscles to a given stimulus. Specifically, the subjects began the experiment by producing a sustained low-force contraction of the BB muscle. Next,

these subjects were instructed to switch to a contraction of the TB muscle, as quick as possible, from a tactile (touch) stimulus. Interestingly, these authors found that inhibition of the BB muscle preceded the reaction of the TB muscle by approximately 50 msec and that the antagonist inhibition preceded agonist activation during the sensory-motor reaction. Furthermore, these authors deduced that the afferent conduction time to the cortex was approximately 18 msec and the efferent conduction time of approximately 12 msec, thus leaving approximately 20 msec for cortical integration. Moreover, these authors concluded that the 50 msec latency period demonstrated that the reciprocal inhibition was supra-spinal in origin.

Person, 1958

The purpose of this investigation was to examine the effects of developing a new motor habit on the coordination of an antagonistic muscle. Specifically, EMG signals were recorded from the BB and TB muscles, during an alternating, rhythmic task. Furthermore, this author found a strong co-activation for the BB and TB muscles and that training for this task led to the complete disappearance of the co-activation effect and the development of the antagonist rest period. Thus, this author concluded that the coordination of antagonist pairs plays an important role in the development of new motor habits and learned behaviors.

Patton & Mortensen, 1971

The purpose of this investigation was to further examine the reciprocal activity of antagonistic pairs. Specifically, EMG signals were detected from the BB and TB

muscles during various weighted and unweighted forearm flexion and extension exercises. More specifically, un-resisted forearm flexion demonstrated the reciprocal inhibition phenomenon described by Sherrington (1892-1909), whereas forearm extensions (or any movement with external resistance) led to a co-activation of the antagonist muscle, as described by Tilney and Pike (1925). Furthermore, Patton and Mortensen (1971) found that flexion and extension movements are not symmetrically equal, even though they are opposite, mirrored movements. Thus, these authors concluded that because flexor muscles are a more mobilizing, skillful muscle group, they must be less likely to initiate the co-activation effect.

Angel, 1977

The purpose of this investigation was to examine antagonist co-activation patterns during rapid arm movements to determine if the movements were either due to a pre-determined central motor program, a peripheral feedback and long-loop reflex, or a combination of both. Interestingly, this author found that during contractions in which the limb was not allowed to move, the antagonist muscle demonstrated little to no co-activation. Therefore, he determined that co-activation is partially affected by peripheral feedback from the specified limb. However, he reasoned that there are times in which the antagonist activity precedes the onset of movement, which is suggestive of a central component. Thus, he concluded that antagonist co-activation during rapid arm movements was the result of the ignition of a pre-existing central motor program that can be altered in response to proprioceptive feedback.

De Luca & Mambrito, 1987

The purpose of this investigation was to examine the MU firing rate properties within and among antagonistic muscles. Specifically, MU firings were detected from the flexor pollicis longus and extensor pollicis longus muscles. Furthermore, subjects were asked to perform force varying contractions during the CON and ECC directions, as well as zero-force contractions in which both muscles were co-contracting. Moreover, these authors determined that the MU firing rates were strongly cross-correlated at a zero time shift, supporting the hypothesis of common drive. Additionally, these authors found that firing rates between opposing muscles during co-contraction showed common drive, but at a lesser magnitude than when each muscle contracted separately. Thus, these authors concluded that the CNS must control the MUs for both opposing muscles as if they were one pool when both muscles are performing the same task (i.e., co-contraction).

Carolan & Cafarelli, 1992

The purpose of this investigation was to examine the training induced changes in antagonist co-activation. Specifically, subjects were asked to perform unilateral isometric leg extension training, 3 days per week, for 8 weeks, with 48 hours between visits. More specifically, EMG signals were detected from the vastus lateralis (VL) and biceps femoris (BF) muscles during pre- and post-training measurements. Interestingly, these authors found that after 1 week the antagonist co-activation decreased by 20% in the trained leg, while the untrained leg decreased its antagonist co-activation by 13%. Thus, these authors concluded that these changes in unilateral co-activation and

contralateral co-activation, due to cross-over effect, could have been due to alterations to Renshaw cells, muscle spindles, GTOs, and/or descending motor pathways.

Amiridis *et al.*, 1996

The purpose of this investigation was to examine the level of antagonist co-activation during isokinetic leg extensions. Specifically, subjects were split into two groups (highly-skilled and sedentary), while EMG signals were detected from the vastus medialis (VM), VL, and semitendonosus (ST) muscles during 14 angular velocities between -120º to 300º/sec. Furthermore, these authors found that ST co-activation during ECC muscle actions were significantly lower than that during CON muscle actions. Moreover, these authors also found that ST co-activation was significantly lower in the highly-skilled group, when compared to the sedentary group for both CON and ECC muscle actions. Thus, these authors concluded that their results support the possible presence of a tension regulating mechanism.

Burnett *et al.*, 2000

The purpose of this investigation was to examine the level of antagonist co-activation during isometric force tracing. Specifically, these authors investigated force steadiness during force tracing from 2.5% - 75% MVC. More specifically, subjects were split into two groups (young and old), while EMG signals were recorded from the first dorsal interosseous (FDI) and second palmar interosseous (SPI) muscles during these submaximal abductions. Furthermore, these authors found that the older subjects were less steady when performing lengthening contractions, when compared to

shortening contractions and that there were no differences in either type of contraction for the younger subjects. Thus, these authors concluded that there were little to no associations between antagonist co-activation and force steadiness.

Tillin *et al.*, 2011

The purpose of this investigation was to examine the agonist and antagonist neural adaptations that potentially occur within 4 weeks of unilateral resistance training. Specifically, maximal and submaximal isometric (75% MVC) knee extensions were assessed before and after 4 weeks of training. More specifically, EMG signals were collected from the rectus femoris (RF), VL, VM, and long head of the BF muscles. Furthermore, these authors found that the position of the force-agonist EMG relationship was unchanged, but the antagonist co-activation was lower during all levels of agonist activation. Moreover, their results demonstrated that strength gains in the trained leg were due to enhanced agonist activation, and a decreased antagonist co-activation for both legs. Thus, these authors concluded that the mechanisms (central and/or peripheral) responsible for the interactions between agonists and antagonist muscles can be altered with training.

Balshaw *et al.*, 2017

The purpose of the investigation was to examine the contribution of multiple underpinning neural and morphological variables, as well as pre-training strength, to the individual changes in strength after 12 weeks of resistant training. Twenty eight healthy men performed isometric knee extensor resistance exercise three days per week

for 12 weeks. Their results suggested that changes in neural drive and muscle volume, as well as pre-training strength, explained ~60% of the total variance in strength changes after resistance training, with agonist neural drive being the most important determinant. Furthermore, these authors found that antagonist co-activation and muscle fascicle pennation angle, were unrelated to strength gains possibly due to the limited sensitivity to detect their individual contributions.

Summary

The coordinated interactions between agonist and antagonist muscle groups can be extremely complex, due to the integration of multiple shared inputs (which can be central or peripheral in origin). Specifically, the central inputs can be supraspinal in origin, consisting of various descending pathways, or from solely within the spine (such as Renshaw cells and central pattern generator [CPG] interneuron networks). Furthermore, the supraspinal pathways can lead to either excitation or inhibition of the antagonist, depending on the situation, and are regulated by the motor cortex, cerebellum, and other premotor areas. Moreover, Renshaw cells can inhibit neighboring α-motorneurons and the Ia inhibitory interneurons projecting to the antagonist α-motorneurons.

More specifically, the peripheral inputs include muscle spindles (group Ia and II afferent), golgi tendon organs (group Ib afferent), and various smaller group III and IV afferents (such as chemoreceptors, nociceptors, and mechanoreceptors). Group Ia afferent neurons mono- and di-synaptically excite the agonist α-motor neurons; however, group Ia afferent neurons can also disynaptically inhibit the antagonist α-

motor neurons. Furthermore, group Ia afferent neurons are also more sensitive to a change in muscle length during dynamic conditions, when compared to slow or static conditions. Group II afferent neurons, on the other hand, can disynaptically excite the agonist α-motor neurons, and don't appear to have any appreciable connections to the antagonist muscle. Group Ib afferent neurons can disynaptically inhibit or excite the agonist α-motor neurons, but they synapse more strongly with Ib inhibitory interneurons. However, during situations requiring intentional co-contraction, the Ib inhibitory interneurons are inhibited by the CNS (disinhibition) and the lesser, Ib excitatory interneurons prevail. Interestingly, group Ib afferents are also more sensitive to tension in the tendon during a contraction, when compared to a passive stretch, even if the tension in the tendon is equitable. In fact, GTOs are sensitive enough to contractile forces that they can respond to the twitch of a single MU. The group Ib afferents also disynaptically excite the antagonist α-motor neurons, facilitating antagonist coactivation or co-contraction and to add further complexity, the disynaptic Ia and Ib excitatory pathways can actually share the same excitatory interneurons.

With regards to the group III and IV small afferent nociceptors, which respond to pain, are capable of causing a polysynaptic inhibition of the agonist α-motor neurons and excitation of the antagonist α-motor neurons. Furthermore, the small cutaneous mechanoreceptors, which are sensitive to touch or pressure, can elicit flexion or extension reflexes, or even a complex series of excitation-inhibition-excitation cycles, but the roles of agonist or antagonist interactions in these instances are relative to the task being performed. Moreover, chemoreceptors, which are sensitive to changes in O_2,

CO_2, and/or metabolic accumulates, are capable of inhibiting the agonist α-motor neurons, whereas its effect to the antagonist is unknown.

Additionally, central and peripheral sources of input are not independent processes, due to the CNS being able to regulate the Ia afferents (presynaptic inhibition), Ib inhibitory interneurons, and Ia inhibitory interneurons, as well as the peripheral afferents being able to ascend to the brain and affect subsequent motor commands (via long-loop reflexes). The integration of all these complex shared inputs ultimately regulates the coordination between agonist and antagonist muscle groups and dependent upon various input combinations. Thus, these combinations can lead to antagonist inhibition, coactivation, co-contraction, or even a preprogrammed pattern consisting of multiple phases.

2.2. Motor Unit Recruitment/Firing Rate Properties

Liddell & Sherrington, 1925

The purpose of this investigation was to examine the inhibitory relaxation mechanism that occurs due to stimulation of an ipsilateral afferent nerve. Specifically, these authors measured, using the isometric optical myograph, the crossed extensor reflex from the knee extensor of a decerebrated cat. Furthermore, their results are vastly important because this was the first investigation to recognize that a motor neuron and all of the fibers it innervates behave as a single entity. Thus, these authors concluded that since those fibers behaved as a single unit, this action should be termed a "MU", which present researchers still use to this day.

Adrian and Bronk, 1929

The purpose of this investigation was to examine the firing properties of motor neurons. Specifically, these authors performed their experiments with cats that were anesthetized and decapitated or decerebrated. Interestingly, these authors were the first researchers to detect action potentials from a single MU. Furthermore, in their discussion section, these authors state that "the gradation of force is brought about by changes in the discharge frequency in each fiber and also by changes in the number of fibers in action". Thus, these authors concluded that MUs can increase their force production by recruiting more MUs, increasing the MUs firing rates, or both, which present researchers still accepted as the process of increasing force production.

Denny-Brown & Pennybacker, 1938

The purpose of this investigation was to examine the EMG and force outputs produced from involuntary twitching. Interestingly, this investigation was significant because it was the first investigation to demonstrate an orderly recruitment of MUs (size principle). Specifically, these authors discovered that during any voluntary movement, the same MUs were always the first to discharge and that there was a consistent sequence of recruitment as intensity increased. Thus, these authors concluded that there was a size difference between the MUs and that they were recruited based off their sizes (size was assessed by the innervation ratio), which is still accepted, to this day, as the process of MU recruitment.

Gilson & Mills, 1941

The purpose of this investigation was to examine the MU firing properties during low-intensity voluntary efforts. Interestingly, this investigation was important because it implied that there was a consistency among amplitude (AMP) from single MU action potentials, regardless of the intensity of the contraction. Furthermore, these authors noted that an increase in spike AMP was either due to spatial changes in the relation of the electrode to the detected fibers, or the summation of multiple MU action potentials. Thus, these authors concluded that force was modulated by recruitment of new MUs and changes in their firing rates, rather than their AMP. Moreover, in conjunction with those findings made by Denny-Brown and Pennymaker (1938), and Gilson and Mills (1941) demonstrated the beginning of the "all-or-none" principle of MU activation.

Bigland & Lippold, 1954

The purpose of this investigation was to further examine the relationship between MU firing rate and force. Specifically, EMG signals were detected from the adductor pollicis (AP) and abductor digiti minimi (ADM) muscles during maximal and submaximal electrical stimulations applied to the ulnar nerve. Furthermore, these authors found that progressively increasing the stimulation frequency, in a step-like fashion from 0 - 100 Hz, caused the force to increase linearly with stimulation frequency until around 35 - 45 Hz. Moreover, once 35 - 45 Hz had been reached, the tension plateaued or slightly decreased. Thus, these authors concluded that 35 - 45 pulses per second (pps) were most likely the maximal firing rate for most MUs and that

the lowest threshold MUs (< 5% MVC) demonstrated the lowest initial firing rates, as well as a greater firing rate range than high-threshold MUs.

Henneman, 1957

The purpose of this investigation was to examine the intensity of stimulation required to elicit discharges in motor neurons of varying sizes. Specifically, this author found that motor neurons could be graded by their susceptibility to firing. Thus, he concluded that smaller neurons required a lower stimulation intensity to elicit firings (i.e., lower threshold), and the threshold of the neurons increased progressively with neuron size (determined by the size of action potential produced, which was linearly related to axon diameter). Additionally, his findings were similar and independent to those findings reported by Denny-Brown and Pennybaker (1938).

Henneman *et al*., 1965 a, b, & c

The purpose of these author's works, over a series of sequential investigations, was to further examine the relationship between a neuron's size and its firing properties. Specifically, these authors investigated whether motor neuron excitability was source-dependent, or if motor neurons responded to all excitability the same way, regardless of the source, to see if neuron size also dictates its susceptibility to inhibition. Furthermore, with regards to the first question, these authors found that the susceptibility of a neuron to discharge was size-dependent, regardless of the source of excitation (e.g., flexor reflex, electrical stimulation, etc.). Moreover, these authors also found that there was a size dependent effect on a neuron's susceptibility to inhibition,

although the relationship was opposite to the excitation relationship (the larger the neuron, the more susceptible it was to inhibition). However, it should be noted that the author's measure of "inhibitibility" was linked to the order in which cells were silenced by inhibitory stimulation. Thus, these author concluded that the neurons that were recruited later, were decruited earlier (i.e. recruitment threshold = decruitment threshold).

Clamann *et al.*, 1970

The purpose of this investigation was to examine MU firing properties of the BB and abductor pollicis brevis (APB) as these muscles relate to isometric tension. Specifically, action potential trains were detected with EMG signals from the BB muscle at various depths from 0.5 – 2.5 cm. Furthermore, this author found that higher threshold MUs had a lower firing rate and smaller firing rate ranges than lower threshold MUs. Thus, he concluded that the higher threshold MUs tended to be located superficially (0.5 – 1.0 cm deep), while the low threshold MUs were deeper within the muscle (1.0 – 2.5 cm).

Milner-Brown *et al*., 1973 a, b, & c

The purpose of these author's works, over a series of sequential investigations, was to examine MU properties during voluntary isometric contractions. Amazingly, these authors developed a spike-triggered averaging technique that allowed for the calculation of the contractile properties from individual MUs. Specifically, these authors were able to determine the relative contribution of twitch force from individual

MU recruited, as well as each additionally recruited MU. Furthermore, their development of the spike-triggered averaging technique allowed for the first direct evidence of the size principle, which was performed in the FDI muscle. Moreover, these authors also observed that although the higher threshold MUs can generate more force, the contribution of recruitment to increases in voluntary force declines at higher force levels. Thus, these authors concluded that at higher force levels, increases in firing rate (i.e. rate coding) was the dominant mechanism for the continuation to increase voluntary force.

Gydikov & Kosarov, 1974

The purpose of this investigation was to examine the relationship between BB muscle MU firing rates and force, and how that relationship is affected by MU recruitment threshold, size, and susceptibility to fatigue. Specifically, these authors divided MUs into two classifications based on firing patterns: tonic and phasic. Furthermore, these authors found that the tonic MUs, which were small and low-threshold, increased their firing rate with force and followed by an immediately plateau. Moreover, these authors also found that phasic MUs, which were large and high-threshold, continued to demonstrate increases in firing rate with force (i.e. no plateau). Thus, these authors concluded that tonic MUs are resistant to fatigue, while phasic MUs were extremely fatigable.

Kukulka & Clamann, 1981

The purpose of this investigation was to examine the relative contribution of firing rate changes and MU recruitment to isometric force production. Specifically, EMG signals were detected from the BB and AP muscles during isometric step contractions up to 100% MVC. Furthermore, these authors found that approximately 47% of the BB muscles detected MUs were active at 30% MVC, 67% were active by 40% MVC, and the recruitment of additional MUs continued up to 88% MVC. Conversely, these authors also found that 41% of the AP muscles detected MUs were recruited by 10% MVC, 86% were active by 30% MVC, and all of the MUs were recruited by 50% MVC. Moreover, these authors suggested that additional increases in force beyond the point of full MU recruitment were due to increases in firing rates. Thus, these authors concluded that small, distal muscles of the hand rely more on firing rate changes for their force modulation, while larger, proximal muscles rely more on MU recruitment.

De Luca *et al*., 1982

The purpose of this investigation was to examine the control of MU behavior during linearly force-varying contractions. Specifically, EMG signals were detected from the deltoid and FDI muscles during separate triangular contractions (i.e. ramp-up then ramp-down) up to 40% and 80% MVC. Furthermore, their results indicated that, at any given submaximal force level, the firing rates of earlier recruited MUs were higher than those of later recruited MUs. Moreover, the initial firing rates at recruitment were higher than the firing rates at decruitment. Thus, these authors concluded that, due to

between-muscle differences in the way firing rates increased with force, the deltoid muscle relies more on MU recruitment to generate additional force, while the FDI is more dependent on firing rate changes. In addition, it is important to note that this pattern of MU behavior would later be described as the "onion-skin" phenomenon.

Bellemare *et al*., 1983

The purpose of this investigation was to examine the individual MU firing rates during MVCs for the BB, AP, and soleus muscles. In addition, it is important to note that prior to this investigation, most studies were limited to only 75 - 80% MVC for single MU recordings. Furthermore, their results indicated that there were significantly higher mean MU firing rates in the BB (31.1 Hz) and AP (29.9 Hz) muscles, when compared to the soleus (10.7 Hz). Moreover, these authors found that the between muscle differences could be representative of the fiber type composition differences. Thus, these authors concluded that, during a voluntary effort, the firing rate for a MU will never exceed the minimum required to produce maximum force.

Broman *et al*., 1985

The purpose of this investigation was to examine the interactions between MU recruitment and firing rate changes with increases in force production. Specifically, EMG signals were recorded from the tibialis anterior (TA) and FDI muscles. Furthermore, these authors found that recruitment of a new MU lead to slight decreases in the firing rates of the already active MUs. Thus, these authors concluded that this mechanism's purpose is to allow for smooth force production by avoiding sudden

jumps in force that would occur when a new MU is recruited and that this mechanism is potentially due to the Ia afferent loop and renshaw cell recurrent inhibition.

Tax *et al*., 1989

The purpose of this investigation was to examine the MU recruitment properties during dynamic and isometric muscle actions at varying velocities and force levels. Furthermore, EMG signals were recorded from the BB, brachialis, and TB muscles. Moreover, their results demonstrated that the order of MU recruitment was the same for both dynamic and isometric muscle actions. However, there were still significant differences between the motor control strategies used for the two muscle action types. Specifically, the dynamic muscle actions were characterized by lower recruitment thresholds and higher initial firing rates than the isometric muscle actions. Thus, these authors concluded that the manner in which the CNS controls MUs is task-dependent.

Masuda & De Luca, 1991

The purpose of this investigation was to further examine the relationship between MU recruitment threshold and muscle fiber action potential conduction velocity (CV). Specifically, EMG electrodes were inserted into the TA to detect the action potentials from single MUs, and a linear surface electrode array was used to assess CV. Furthermore, these authors found that the CV of the muscle increased with the recruitment of each additional MU (during linearly increasing isometric force). Thus, these authors concluded that the higher the last recruited MUs threshold is, the

higher the muscle's CV and the higher the MUs threshold, the more it contributes to the muscle's CV.

Knight & Kamen, 2008

The purpose of this investigation was to examine the relationship between voluntary activation and maximal MU firing rates. Specifically, these authors attempted to identify the reason(s) that electrical stimulation increased force production. Furthermore, these authors hypothesized that the inability to produce maximal force voluntarily was due to incomplete recruitment, suboptimal firing rates, or a combination of both factors. Moreover, these authors found that the additional force (beyond MVC) from an interpolated twitch was significantly correlated with maximal firing rates ($r = -0.62$). Additionally, these authors also found that voluntary activation levels were significantly correlated with maximal firing rates ($r = 0.68$). Thus, these authors concluded that maximal firing rate was an important factor limiting maximal force production.

De Luca *et al*., 2009

The purpose of this investigation was to examine the effects of MU recruitment and proprioceptive feedback on common drive. Specifically, four muscles (TA, trapezius, FDI, and VL), all with varying levels of spindle densities, were investigated. Furthermore, their results indicated a strong, negative relationship between the correlation coefficient of MU firing rates (i.e. magnitude of common drive) and the muscle's spindle density ($r = -0.94$). Thus, the authors concluded that common drive

originates in the CNS and is reduced by the proprioceptive feedback from muscle spindles and GTOs.

De Luca & Contessa, 2012

The purpose of this investigation was to further examine the relationship between MU firing rates and recruitment threshold, as well as to propose a model that describes MU firing behavior. Specifically, EMG signals were detected from the VL and FDI muscles during trapezoidal isometric muscle actions of varying force levels and ramp speeds. Furthermore, the EMG signals were decomposed into their constituent MUAPTs to determine if the decomposition algorithm introduced any bias. Moreover, to determine if this algorithm introduced any bias, these authors took that decomposed signal, randomized the firing occurrences, reconstructed it with added noise, and decomposed it again. Their findings indicated that there was no bias introduced by the algorithm, the MU firing rates increased as a negative exponential function as force increased, and that the rate of rise of the firing rate trajectories were similar, regardless of the speed of the force ramp. Thus, these authors concluded, with overwhelming evidence, that there was a hierarchical control scheme that governs MU behavior, and that the firing rates of earlier recruited MUs were in fact higher than those firing rate from the later recruited MUs.

De Luca & Kline, 2012

The purpose of the investigation was to perform a meta-analysis of the literature to explore potential relationships between the firing rates and recruitment thresholds of

a MU, and the spindle properties of various muscles. Specifically, these authors found a weak, inverse relationship between the average mean firing rate of a muscle (grand mean of all MUs) and the number of spindles within the muscle, and that the relationship became more negative and linear at higher force levels. Conversely, these authors also found that there was little to no relationship at very low force levels (i.e., 1% - 10% MVC). Furthermore, these authors noted that during slowly increasing isometric contractions, the firing rates of already activated motor neurons temporarily decrease slightly with the recruitment of each additional motor neuron. Hence, these authors proposed that the decrease in firing rate was due to the slackening of the muscle spindles, therefore reducing the excitation they provided to the motor neurons. Moreover, since each spindle synapses with each motor neuron in the pool for that muscle, these authors explain that differences in the total number of spindles are a major factor for why muscles have varying firing rates and according to their model, muscles with a low number of spindles (e.g., FDI) have higher firing rates and a small range of recruitment. Thus, these authors concluded that those muscles with lower firing rates and a large range of recruitment (e.g., VL) behave that way because of the muscle's large number of spindles.

Ye *et al.*, 2015

The purpose of this investigation was to examine the relationship between MU firing rate and recruitment threshold to examine motor control strategies following different dynamic exercises (CON vs. ECC). Specifically, subjects who were not accustomed to ECC exercise performed 6 sets of 10 repetitions of maximal CON or

ECC exercise in a dynamometer in two separate visits. More specifically, between and after the exercise intervention, the EMG decomposition technique was used to decompose EMG signals from the trapezoid submaximal (40% MVC) isometric contractions. Additionally, linear regression analysis was used to examine the relationship between MU firing rate and recruitment threshold. Furthermore, these authors found that there were no significant changes in linear regression slope coefficient and y-intercept following the CON exercise, while the mean slope coefficient and y-intercept significantly decreased and increased, respectively. Moreover, these authors found that after ECC exercise, fast-twitch muscle fibers are more likely to be damaged, which potentially alters the motor control strategy. Thus, these authors concluded that increasing the firing rate of low-threshold MUs may be more important than recruiting high-threshold MUs to compensate for the exercise-induced force deficit.

Summary

Thanks to the work performed by Liddell and Sherrington, we now know that a motor neuron and all of the skeletal muscle fibers that it innervates behave as a single entity (or as a "MU"). Since this observation, the understanding of how movement and force are regulated has increased at an exponential pace. The reason for this advancement in the field of neuromuscular physiology is due to the recording of single muscle fiber activity being assumed to be reflective of the activity of the motor neuron itself. This finding, in conjunction with others, led to the eventual acceptance of the "all-or-none" principle. During this same period, Adrian and Bronk made the

observation that the gradation of force could be accomplished by two separate, but related mechanisms: the first being, the recruitment of MUs and the second being, changes in those MU's firing rates. Thus, both of the mechanisms can lead to an increase in force production across time.

The separate work of Sherrington and Adrian was so influential in our understanding of the function of neurons that they shared the Nobel Prize for Physiology or Medicine in 1932. A few years later, the work out of the laboratory of Denny-Brown, a former student of Sherrington's, further extended the understanding of MU recruitment introduced by Adrian and Bronk. It was discovered that there was an orderly recruitment of MUs, and that the order was exclusively dependent on the MUs size. Specifically, the smaller MUs, as assessed by innervation ratio, were always the earliest to become active and the larger, more powerful MUs typically entered later. Independent of the work performed by the Denny-Brown group, another young scholar with the last name of Henneman enhanced this "size principle" concept even further with the discovery that a neuron's action potential threshold was highly dependent on the size of the soma. Therefore, the orderly recruitment presented by Denny-Brown could be explained by the observation that the smaller MUs (both in soma size and innervation ratio) were more susceptible to discharge, and therefore were always recruited early in a contraction. Furthermore, due to Henneman's findings, the findings from Denny-Brown unfortunately went fairly unnoticed to this day. Hence, the "size principle" of MU recruitment, as we know, is still credited to the work Henneman's performed 19 years after the groundbreaking work performed by Denny-Brown.

The next advancement came from Milner-Brown group, whom provided the first direct evidence of the size principle. Specifically, they developed a technique to measure the tension produced by a single MU, and showed that there was a strong positive relationship between a MUs recruitment threshold and the amount of force it can produce. Furthermore, their subsequent work demonstrated additional differences between MUs of varying size (such as the AMP of the action potential, the size and speed of the resultant twitch, the axonal conduction velocity, the firing rates and the susceptibility to fatigue).

The understanding of the relationship between a MUs recruitment threshold and its mean firing rate at any given force level has been greatly advanced by the work of De Luca's group. Specifically, his work has demonstrated that earlier recruited MUs exhibit higher firing rates, and the gradual recruitment of each additional MU is characterized by progressively lower firing rates (termed the "onion skin phenomenon"). However, despite this initial separation, the firing rates of all MUs, regardless of recruitment threshold, converge to similar values at MVC. Furthermore, another important contribution from De Luca's lab is the concept that all the MUs in a given pool receive the same common drive from the brain, and it is the properties of each individual MU that dictates how it responds to that drive. Thus, by having a MU pool, this alleviates the CNS from having to control each individual MU separately. Moreover, it has also been demonstrated that not every muscle uses rate coding and recruitment in the same way to control force. For example, the smaller, more distal, muscles that are typically associated with fine motor control, such as the muscles of the hand, are characterized by a relatively short recruitment range (e.g. all of the MUs are

recruited by 50% MVC) and have to rely more on firing rate modulation (i.e. rate coding) to control force. Conversely, the larger, more proximal, muscles that are typically associated with powerful gross movements have a greater number of MUs and rely more heavily on recruitment to increase force (some larger muscles may recruit new MUs all the way up to 100% MVC). Currently, one of the more interesting topics regarding MU firing properties regards the relative contributions from central and peripheral inputs. Additionally, De Luca's group has recently hypothesized that differences in the total number of spindles embedded within a muscle may explain the between muscle differences (either heterogeneous or homogeneous muscles) in recruitment range.

2.3. Effects of Visual Feedback on CNS and/or Exercise Performance

Asmussen & Mazin, 1978

The purpose of this investigation was to examine the interaction between visual feedback and CNS activity. Specifically, subjects were asked to lift and lower weights with either their forearm flexors or finger flexors while seated in a custom-built arm ergograph. Furthermore, the subjects were instructed to perform repeated CON muscle actions while intermittingly opening or closing their eyes. Hence, total work was compared between bouts with the subject's eyes open versus those bouts with their eyes closed. Moreover, their results indicated that during fatiguing CON muscle actions of the forearm and finger flexors, more work was performed with the eyes open than with the eyes closed.

In a separate experiment, these authors had the subjects perform fatiguing CON muscle actions of the forearm flexors until exhaustion with their eyes closed. Once the subjects reached the point of exhaustion, they opened their eyes and attempted to continue to failure. Furthermore, these authors found that when complete exhaustion had been reached with the eyes closed; opening them allowed 15% - 30% more work to be performed. However, when the order was switched, none of the subjects were able to continue once their eyes were closed. Moreover, their collective results from both experiments indicated that diverting activities may have application for enhancing recovery and maintaining performance during fatiguing exercise. Thus, these authors concluded that the beneficial effects of diverting activities could potentially be explained by changes in reticular formation activity.

Prablanc *et al*., 1986

The purpose of this investigation was to examine the spatial and temporal organization of hand and eye movements. Specifically, subjects were asked to complete four different conditions consisting of 80 trials per condition. More specifically, subjects were instructed to keep their gaze and the index finger of their right hand on a central target located about 54 cm in front of them on their body axis. However, when this target jumped from its central location to a randomly selected position in their right periphery, the subjects were required "to look and point to the target as quickly and as accurately as possible". Furthermore, as soon as their finger left the surface on which it was resting, their entire hand and forearm vanished from view and after completing their movement, subjects had to wait for the target to reappear at the center, before

returning their gaze and hand to the central position. Moreover, illumination of their hand was restored only at the onset of the hand return movement, when the target had returned to its central position. Therefore, subjects had no visual information about the accuracy of their pointing movement to the peripheral target, even though they could accurately return their finger to the central target under direct visual control.

Additionally, in condition 1, vision of the hand and the target disappeared when the index finger left the central position; in condition 2, the target remained in view slightly longer, disappearing 120 msec after the end of the first saccade; in condition 3, the target remained illuminated throughout the entire pointing movement; and finally, in condition 4, subjects were asked to delay their hand movement until they had completed their first eye movement toward the target until a brief tone signaled the end of their first saccade, initiating a pointing movement to the target. However, as soon as their finger moved from the central position, view of both their hand and the target disappeared. Furthermore, their results indicated that pointing movements were about 3 times more accurate when the target was present throughout the entire pointing movement, than when the target disappeared shortly after the hand movement had begun. Moreover, their data provided evidence that pointing movements made without view of the limb are not purely pre-programmed but instead, are corrected during their execution. Thus, these authors concluded that modifications to the motor program is smoothly integrated into the ongoing movement and must depend upon comparing visual information about the position of the target with non-visual information about the position of the limb.

Vuillerme *et al*., 2001

The purpose of this investigation was to examine the effects of visual feedback and muscle fatigue on postural control. Specifically, for each trial, subjects were required to balance on one leg while standing in the middle of a force platform, which allowed for measurement of displacement of the center of foot pressure. Additionally, the center of pressure was examined with the eyes opened and closed under fatigued and non-fatigued conditions. More specifically, for the fatigued trial, voluntary muscle fatigue of the plantar flexors was induced by having the subjects stand on their toes for as long as possible. Furthermore, during each trial, the subjects were instructed to open or close their eyes while attempting to balance on the force platform and the max range (mm) and speed of center of pressure (mm/sec) were examined immediately before the subject opened or closed his eyes (T1); immediately after he opened or closed his eyes (T2); and 20 seconds following T2 (T3). Moreover, their results indicated that when the subjects began the trial with their eyes closed, opening their eyes compensated for the effects of fatigue, and regardless of the degree of visual feedback, the mean ± SD center of pressure range and center or pressure speed were greater for the fatigued conditions. Thus, these authors concluded that fatigue-related factors and visual feedback play important roles in posture, and that the availability of vision allowed the subjects to appropriately modify the destabilizing effects of fatigue.

Marx *et al*., 2003

The purpose of this investigation was to examine the brain activation patterns under eyes open and closed conditions in complete darkness. Specifically, subjects

were instructed to alternately open and close their eyes for periods of 22.5 sec in response to an acoustic signal given via headphones. More specifically, the study began with the eyes closed, followed by 11 blocks in which the eyes opened and closed in an alternating fashion. Furthermore, subjects were asked to look straight ahead, remain still while functional images were acquired from 32 transverse slices of the brain and upper parts of the cerebellum. Additionally, each scanning session included two series of 120 images, each with alternating eyes open and closed conditions. Moreover, their results indicated that the two conditions results in consistent differences in the patterns of brain activation that were evident for both individual subject and group analyses. Thus, these authors concluded that the effects of eyes open versus eyes closed conditions reflected two different states of mental activity, with the first being an "interoceptive" state with the eyes closed (characterized by sensory activity and imagination) and the second being an "exteroceptive" state with the eyes opened (characterized by activation of parts of the brain responsible for attention and focus).

Sosnoff & Newell, 2005

The purpose of this investigation was to examine if age related increases in force variability were due to decreases in visual acuity and/or visual-motor information processing deficits. Specifically, subjects were split into two groups (young and old) and the visual information scale was manipulated over a 250-fold range, while subjects were asked to produce a isometric force output for a specified visually presented target (target line corresponded to 5% or 25% MVC). Furthermore, these authors found that older adults had a very small decrement in visual acuity and that there was no relation

between visual acuity and force variability. Moreover, the young adults had less relative variability and higher visual information transfer than the older group. Thus, these authors concluded that the age related declines in visual-motor information processing influence changes in neuromuscular function and the emergent differences in force variability at the behavioral level.

Baweja *et al*., 2009

The purpose of this investigation was to examine force accuracy, force variability and muscle activity during constant isometric contractions at different force levels with and without visual feedback at different feedback gains. Specifically, in experiment 1, subjects were instructed to accurately match the target force at 2%, 15%, 30%, 50%, and 70% of their MVC with abduction of the index finger and maintain their force even in the absence of visual feedback. More specifically, each trial lasted 22 sec and visual feedback was removed from 8 – 12 sec to 16 – 20 sec, while each subject performed 6 trials at each target force (half with visual gain of 51.2 pixels/N and the rest with a visual gain of 12.8 pixels/N). Furthermore, force error was calculated as the RMS error of the force trace from the target line, while force variability was quantified as the SD and coefficient of variation (CVF) of the force trace. Moreover, the EMG activity of the agonist (FDI) muscle was measured with EMG sensors placed distal to the innervation zone. Additionally, independent of visual gain and force level, subjects exhibited lower force errors with the visual feedback condition; whereas, force variability was lower when visual feedback was removed.

Thus, the EMG activity of the FDI muscle was higher during the visual feedback condition and this difference increased at higher force levels.

In a separate experiment, these authors examined whether the findings of experiment 1 were driven by the higher force levels and proximity in the gain of visual feedback. Specifically, subjects performed constant isometric contractions with the abduction of the index finger at an absolute force of 2 N, with two distinct feedback gains of 15 and 3,000 pixels/N. Additionally, in agreement with the findings of experiment 1, subjects exhibited lower force error in the presence of visual feedback especially when the feedback gain was high. However, force variability was not affected by the vastly distinct feedback gains at this force, which supported and extended the findings from experiment 1. Thus, the authors concluded that although removal of visual feedback amplifies force error, it can reduce force variability during constant isometric contractions due to an altered activation of the primary agonist muscle, most likely at moderate force levels in young adults.

Hwangbo, 2015

The purpose of this study was to identify the effects of performing squat exercises with visual feedback on the activation of the vastus medialis oblique (VMO) and vastus lateralis (VL) muscles in young adults with an increased quadriceps angle (Q-angle). This study used a motion analysis program to select 20 young adults with an increased Q-angle, who were then divided into a squat group that received visual feedback (VSG, n=10) and a squat group that received no visual feedback (SG, n=10). The intensity of exercises was increased every two weeks over a six-week exercise

period in both groups. A visual marker was attached to the patella of the subjects in the VSG, and they then performed squat exercises with a maximum of 90° of knee flexion within a route marked on a mirror. The SG performed squat exercises with a maximum 90° of knee flexion without attaching a visual feedback device. Their results suggested indicated that both groups had statistically significant increases in activation of the VL. The VSG exhibited statistically significant increases in activation of the VMO. These authors concluded that tasks with visual feedback are more effective in the activation of specified muscles during exercise.

Summary

Visual-motor function is the integration between visual perception and motor skills. Specifically, visual-motor function is the ability to perform coordinated, constructive tasks integrating visual perception and motor skills. Furthermore, due to the eyes and appendicular limbs being constantly in motion, subconscious and conscious calculations and decisions about orientation, motion, and location need to be evaluated and initiated. Thus, the parietal cortex (located above and behind the occipital and front cortexes, respectively) assists with those tasks that require the processing and integrating of somatosensory, visual, and auditory information, prior to the initiation of those specified planned movements.

Moreover, examination of the effects of increased visual information on the task performance of motor control can reveal much about the mechanism(s) underlying the visual-motor processes. Additionally, work from the past half century has suggested that with greater availability of visual information, there is a greater likelihood of

correcting for movement errors in force tracings, while not enough information will cause the performer to use more pattern generation and feed-forward processes (which causes unwanted force errors). Therefore, advances in modern computer technology has allowed isometric force tracing to become an ideal means for measuring intermittent visual processing, which in turn allows behavioral and physiological measures to be performed across multiple force outputs from a particular muscle or group of muscles. Thus, through the use of computers, and an isometric force paradigm, researchers are able to obtain reliable information about the wide range of sensorimotor functions, most notably by the influence of vision.

Furthermore, most studies agree that when visual feedback is provided in an appropriate manner, motor control strategies improve significantly in bilateral and unilateral tasks. Specifically, by using visual feedback technology, subjects are now able to make appropriate modifications, during motor control conditions, to smoothly change muscular force outputs based upon a particular force tracing paradigm. Additionally, visual feedback also causes the activation of certain parts of the brain (in addition to the parietal cortex), that are responsible for increased attention and focus, to play a more prominent role during these specified isometric contractions. Thus, due to the collaborative efforts from multiple control centers within the CNS (i.e., cerebellum, brainstem, and/or the four cortexes), information related to neuromuscular function and force variability can now be investigated on an array of behavioral levels, with a diminished error rate in force.

2.4. Cross-over/Cross-education of Homologous Muscles

Davis, 1899

The purpose of this investigation was to further examine the cross-education effect. Specifically, this author performed a considerable amount of experiments to further explore multiple aspects of cross-education. More specifically, subjects were asked to perform rapidity (i.e., finger or foot tapping), strengthening (i.e., dumbbell curls), and accuracy (i.e., fencing lunge to hit target) voluntary movements. Furthermore, this author found that there were increases in all variables for both hands/feet and hypothesized that cross-education affects the body mainly by changes in the CNS. Thus, he concluded that this phenomenon can be explained as a result of two factors: the first being the close nervous connection, through motor centers, between symmetrical muscle groups on opposite sides of the body, as well as between groups related in function or position, and the second being the development of general will power and attention (through practice).

Starch, 1910

The purpose of this investigation was to examine the trial and error method of learning on contralateral adaptations. Specifically, subjects were asked to outline a six-pointed star as seen in a mirror, with both hands. More specifically, subjects were asked to trace ½ of one outline with the left hand (untrained), followed by the right hand (trained) completed 10 outlines, and ending with two additional tracing by the left hand. Furthermore, he found that, from pre- to post-tracings, the average improvement of the right hand was 53%, while the left hand improved by 49%. Thus, these authors

concluded that there was a cross-education effect due to the left hand profiting its accuracy to approximately 90% of the gain made by the right hand.

Allen, 1948

The purpose of this investigation was to study cross-education in a motor act involving both hands and to test the efficiency of the simultaneous and successive methods of learning a perceptual motor task. Specifically, subjects were asked to draw the design with both hands individually and then together. More specifically, subjects drew a specific design, as seen only on a mirror, with their left hand (untrained) once, after which they practiced with their right hand (trained) until they made no mistakes, then again with their left hand until they made no mistakes. Next, the subjects were asked to draw the design with both hands simultaneously (still looking at the mirror only) until they made no mistakes. Furthermore, this author found that successive practice, with individual hands, was more effective than simultaneous practice in developing skill, and that the left hand was almost as accurate as the right hand from pre- to post-test tracing. Thus, these authors concluded that there was a cross-education effect from the right to the left hand, and this effect can become a learned behavior (through practice) for developing or improving a new motor task or skill.

Yasuda & Miyamura, 1983

The purpose of this investigation was to provide information regarding the effects of unilateral endurance training on the blood flow of the ipsilateral and contralateral limbs. Specifically, blood flow from both forearms was determined by

venous occlusion plethysmography before and after hand ergometer training. More specifically, subjects trained, using work loads of ⅓ and ½ of their respective maximal grips strength, 6 days a week, for 6 weeks. Furthermore, these authors found that the blood flow of the left forearm (which remained untrained) during exhaustive training of the right hand increased gradually with increasing training periods, and that after 6 weeks, grip strength, endurance and peak blood flows of the forearm increased significantly in both forearms. Thus, these authors concluded that the increase of blood flow in the untrained, contralateral limb after training was, at least in part, due to the cross-transfer effect during chronic endurance exercise training.

Bonata *et al*., 1996

The purpose of this investigation was to examine the possible effects of exercise on the excitability of the activated and non-activated primary motor cortex. Specifically, subjects performed repetitive abduction and adduction exercise with their right thumbs as fast as possible for one minute. Furthermore, these authors found that the motor-evoked potentials (MEPs) from the non-exercised muscles started to decline after 5 minutes of the exercise, and reached a significant level from 10 – 20 minutes following the exercise. Thus, these authors concluded that a depression in the primary motor cortex excitability can occur in the non-activated hemisphere after fatiguing exercise performed in the opposite limb muscles.

Grabiner & Owings, 1999

The purpose of this investigation was to examine unilateral and contralateral strength responses following performing either 75 isokinetic CON or ECC MVC with the unilateral knee extensors. Specifically, both protocols caused significant strength losses in the unilateral limb, with the greater fatigue induced by CON protocol when compared to ECC exercise. Furthermore, these authors found that CON exercise did not alter the contralateral maximal force output, but the ECC protocol significantly increased the contralateral ECC MVC. Thus, these authors concluded (without EMG data) that a bout of ECC exercise can induce an increase in maximal strength in the contralateral limb.

Todd *et al*., 2003

The purpose of this investigation was to examine the "cross-over" effect on contralateral neuromuscular performance by using transcranial magnetic stimulation (TMS). Specifically, subjects performed two different fatiguing protocols: an "alternating protocol", during which they did four consecutive 1-minute sustained elbow flexion MVCs (unilateral-contralateral-unilateral-contralateral); and a "unilateral intermittent protocol", during which they performed two 1-minute MVCs with their unilateral elbow flexors, with one minute rest provided between the contractions. Furthermore, during all MVCs, TMS was applied. Moreover, the authors found that when the 1-minute rest interval was replaced with the contralateral elbow flexor MVC, voluntary activation significantly decreased in the 2nd unilateral elbow flexion MVC. However, voluntary strength or EMG responses to TMS were not altered. Thus, these

authors concluded that although fatiguing the unilateral elbow flexor can induce the "cross-over" effect, the impact to maximal motor performance was not functionally significant.

Rattey *et al*., 2006

The purpose of this investigation was to examine the effects of fatiguing the unilateral leg extensors on the strength and EMG variables of the contralateral leg extensors. Specifically, subjects performed a 100 sec sustained MVC of their trained leg. Furthermore, the authors found that although the voluntary activation of the untrained contralateral leg extensor significantly decreased (8.7%), there were no significant decreases in isometric MVC, twitch force, or compound action potentials (M-wave). Thus, the authors concluded that central mediated mechanisms seem to be the only contributor to fatigue in the non-exercised contralateral muscle.

Martin & Rattey, 2007

The purpose of this investigation was to examine the gender differences regarding contralateral motor performance following a bout of unilateral fatigue exercise. Specifically, participants split into two groups and had their trained leg extensors fatigued (100 sec sustained MVC), followed by testing of the same muscle, or followed by testing of the contralateral, untrained muscle. Furthermore, these authors found that the fatiguing intervention induced greater strength losses in both unilateral and contralateral limbs. Moreover, these authors also found that there was a reduction in voluntary activation in both genders, with a greater deficit for men, when compared

to women. Thus, these authors concluded that there were gender differences in unilateral and contralateral maximal motor performance following the fatiguing intervention in unilateral muscle groups.

Doix *et al.*, 2013

The purpose of this investigation was to examine the time course of the cross-over effect from muscle fatigue on the non-exercised contralateral knee extensors. Specifically, subjects performed two bouts of 100 sec maximal isometric unilateral knee extensions. More specifically, these authors examined before, between two bouts of fatiguing exercise, and after the fatiguing exercise, neuromuscular functions (torque, normalized EMG AMP, and voluntary activation) of both exercised and non-exercised contralateral knee extensors. Furthermore, these authors found that while the fatiguing intervention kept impairing the ability to produce maximal force on the unilateral limb following, the cross-over effect of fatigue was only observed after the 2nd bout of fatiguing exercise. Moreover, these authors also found a significant correlation between the torque decline and a decrease in voluntary activation. Thus, these authors concluded that their results partially resolved the disagreement regarding the existence of cross-over effect from muscle fatigue in contralateral non-exercised muscles.

Ye *et al.*, 2014

The purpose of this investigation was to examine the isometric strength and EMG responses in unilateral and contralateral elbow flexors after fatiguing unilateral elbow flexors with CON vs. ECC exercise intervention. Specifically, subjects were

asked to perform 6 sets of 10 repetitions of maximal CON or ECC exercise on an isokinetic dynamometer. More specifically, these authors examined before and after the exercise intervention, isometric strength and the AMP of the EMG signals. Furthermore, these authors found significant decreases in maximal strength after the CON (17%) and ECC exercise (21%), as well as for the isometric strength in both unilateral (36%) and contralateral (4%) elbow flexors. Moreover, the normalized EMG AMP also decreased in both unilateral (21%) and contralateral (7%) limbs, respectfully. Thus, these authors concluded that CON and ECC exercise caused similar strength losses for the exercised and non-exercised arms, which suggesting the cause being related to a neural mechanism(s).

Aboodarda *et al.*, 2016

The purpose of this investigation was to investigate unilateral elbow flexion fatigue effects on the maximal voluntary force and corticospinal excitability of contralateral non-exercised BB muscle. Transcranial magnetic, transmastoid electrical, and brachial plexus electrical stimulation were used to elicit motor evoked potential, cervicomedullary motor evoked potentials, and compound muscle action potentials in the contralateral non-exercised limb. Twelve healthy subject were assessed before and after two bouts of 100-s unilateral elbow flexion or control. Three stimuli were evoked every 1.5-s during a series of 6-s isometric elbow flexion at 100%, 50%, and 5% of MVC. These authors found that unilateral exercise induced elbow flexion fatigue did not lead to cross-over central fatigue to the contralateral homologous muscle, but

enhanced the supraspinal responsiveness of the neural circuitries supplying central commands to non-exercised muscles at higher contraction intensity

Summary

First discovered over a century ago, cross-over/cross-education strength transfer is a well-known phenomenon whereby unilateral training produces an increase in strength of the contralateral, untrained, homologous muscle group. While convincing evidence to support the existence of cross-over/cross-education is abundant, little is known about the mechanism(s) responsible for this strength transfer. Furthermore, several lines of evidence have suggested that adaptations within the nervous system are a likely candidate, however the level of contribution from cortical, spinal and peripheral mechanisms are yet to be comprehensively quantified.

Furthermore, typical cross-over/cross-education effects are shown after approximately 1 - 4 weeks of training with the unilateral limb. Moreover, the increase in strength in the untrained limb is directly correlated with the strength gain in the trained limb, and is on average approximately 50% of the strength gain observed in the trained muscle. Additionally, cross-over/cross-education effects have also been demonstrated to be in both genders and in a variety of tasks in upper and lower limbs; with the greatest effects being shown with more novel or unfamiliar strength training tasks. Thus, when measuring time course affects from the perspective of the contralateral motor performance, many factors (i.e., the type of exercise, the intensity of exercise, the duration of exercise, and the volume of exercise) need to be considered

because those independent variables play an important role in affecting the contralateral, functional, motor performance between limbs.

In addition, the cross-over/cross-education effects have been proposed for the protection against muscle damage after a bout of damaging exercise to a contralateral muscle. Furthermore, there is recent evidence that suggests that different motor control strategies employed by trained and untrained muscles during motor tasks, may potentially be influenced by the neural adaptations associated with the cross-over/cross-education effects. Moreover, cross-over/cross-education effects provide a unique opportunity for enhancing rehabilitation following injury. Thus, by gaining an understanding of the neural adaptations occurring during immobilization, as well as the mechanism(s) responsible for the cross-over/cross-education effects, future research can utilize the application of unilateral training in clinical musculoskeletal injury rehabilitation.

2.5. Concentric/Eccentric Exercise

Newham *et al.*, 1983

The purpose of this investigation was to examine muscle pain and fatigue after CON and ECC muscle actions. Specifically, subjects performed a step test in which the quadriceps muscles of one leg contracted CON, while the contralateral muscles contracted ECC. More specifically, max voluntary force measurements were carried out before exercise and 2 min, 10 min, 30 min, 1 hr, 5 hrs, 24 hrs and 48 hrs post-exercise and the exercise test consisted of a step test for 15 or 20 min. Furthermore, their results indicated that pain and tenderness developed only in the muscle which had contracted

ECC and that the pain was first noted approximately 8 hrs after exercise. Additionally, maximal pain was reported at approximately 48 hrs after exercise, at which time force generation and electrical activation had returned to pre-exercise values. Moreover, these authors found that ECC contractions cause more profound changes in most aspects of muscle function than CON contractions. Thus, these authors concluded that these changes cannot be explained in simple metabolic terms, and that their results are due to mechanical trauma caused by the high tension generated in relatively few active fibers during ECC contractions.

Fridén *et al*., 1988

The purpose of this investigation was to examine the morphological changes that potentially take place following ECC exercise and to correlate those changes with intramuscular pressure readings. Specifically, subjects were asked to exercise their right lower leg ECC and their left lower leg CON. More specifically, 400 submaximal contractions were performed in each exercise regimen over a 20 min period against a load corresponding to 15% of the individual's maximal dorsiflexion torque. Additionally, tissue fluid pressures were measured by the slit catheter technique before, during, and after exercise and 48 hrs later and needle biopsies of both AT muscles were also taken 48 hrs after completion of the exercise regimens. Furthermore, these authors found that the overall morphology of the specimens revealed a greater cross-sectional fiber area (both type 1 and type 2) in the ECC exercised muscle as compared with the CON exercised muscle and the fiber type proportions were equal on both sides and type 1 fiber biased (70%). Moreover, these authors also found that this incidence correlated

significantly with the length of the time to return to resting pressure after ECC exercise (r = 0.93) and that the percentage of water content was significantly higher in the ECC exercised muscle. Thus, these authors conclude that muscle fiber swelling is a predominant feature following ECC exercise and is directly associated with delayed muscle soreness.

Tesch *et al.*, 1990

The purpose of this investigation was to examine torque, integrate EMG (IEMG) and the power spectrum density function of the EMG during the performance of repeated bouts of consecutive, max voluntary CON and ECC muscle actions. Specifically, subjects were asked to perform three bouts of 32 unilateral, maximal voluntary CON or ECC quadriceps muscle actions on separate days. More specifically, EMG signals of the VL and RF muscles, and torque were measured. Additionally, integrated EMG (IEMG), MNF and median power frequencies and torque were averaged for seven separate blocks of four consecutive muscle actions. Furthermore, these authors found that overall torque was substantially greater for ECC exercise and that at the onset of exercise IEMG of VL and RF muscles were greater for CON muscle actions. Moreover, their results indicated that the ability to maintain force during repeated bouts of maximal voluntary muscle actions at a relatively high angular velocity was remarkably greater for ECC than for CON exercise. Thus, these authors concluded that the factors responsible for fatigue and for changes in the EMG signal pattern during CON exercise were different, but not significantly different, than for ECC exercise within this study.

Kroon & Naeije, 1991

The purpose of this investigation was to examine the recovery effects after CON, ECC and isometric exercise. Specifically, subjects performed submaximal isometric, CON or ECC contractions until exhaustion with only the left arm elbow flexors at respectively 50%, 40% and 40% of the pre-fatigued MVC force. More specifically, EMG signals were measured during 30 sec isometric test contractions at those submaximal percentages. Furthermore, these authors found large differences in the EMG response after isometric, CON and ECC exercise. Moreover, these authors also found that ECC exercise evoked in two of the three EMG parameters (the EMG AMP and the rate of shift of the EMG MNF) the greatest and longest lasting (up to 7 days) response. Additionally, the EMG response after isometric and CON exercise was smaller and of shorter duration (1 – 2 days), while the initial MNF (the third EMG parameter), had already returned to its pre-fatigued value at the time of the first measurement, 0.75 hrs after exercise. Thus, these authors concluded that the responses of EMG AMP and the rate of MNF shift were similar to the responses observed in the muscle performance parameters (MVC and the endurance time), muscle soreness was most frequent and severe after the ECC contractions, and that ECC exercise evoked the greatest and longest lasting response in the EMG signal and in the muscle performance parameters.

Higbie *et al*., 1996

The purpose of this investigation was to examine the effects of CON and ECC isokinetic training on quadriceps muscle strength, cross-sectional area, and neural

activation. Specifically, subjects were randomly assigned to either the CON training (CTG), the ECC training (ETG), or the control groups (CG). More specifically, subjects were tested before and after 10 weeks of unilateral CON or ECC knee extension training. Furthermore, the average torque measured during CON and ECC maximal voluntary knee extensions increased by 18.4% and 12.8% for CTG, 6.8% and 36.2% for ETG, and 4.7% and −1.7% for CG, respectively, while increases from CTG and ETG were greater than for CG. Moreover, for CTG, the increase was greater when measured with CON than with ECC testing, while for ETG, the increase was greater with ECC than with CON testing. Additionally, the increase by ETG with ECC testing was greater than the increase by CTG with CON testing and the corresponding changes in the integrated voltage from EMG signals measured during strength testing were 21.7% and 20.0% for CTG, 7.1% and 16.7% for ETG, and −8.0% and −9.1% for CG. Hence, their results indicated that the quadriceps cross-sectional area measured by MRI (sum of 7 slices) increased more in ETG (6.6%) than in CTG (5.0%). Thus, these authors concluded that ECC is more effective than CON isokinetic training for developing strength in ECC isokinetic muscle actions and that CON is more effective than ECC isokinetic training for developing strength in CON isokinetic muscle actions. In addition, these authors also stated that gains in strength consequent to CON and ECC training are highly dependent on the muscle action used for training and testing and that muscle hypertrophy and neural adaptations contribute to strength increases consequent to both CON and ECC training.

Housh *et al*., 1998

The purpose of this investigation was to examine the effects of unilateral ECC only dynamic constant external resistance (DCER) training on the CSA and strength of the trained and contralateral quadriceps femoris muscles. Specifically, subjects were divided into a training group and a control group. More specifically, the training group exercised with their untrained limb using only ECC leg extension DCER exercise, 3 times a week, for 8 weeks. Additionally, pre- and post-training CSA and strength measurements for both the trained and contralateral limbs were determined for all subjects using MRI scans and ECC DCER strength tests, respectively. Furthermore, their results indicated that there were no significant changes in CSA for any muscles from the quadriceps femoris group for either the trained or contralateral limb. Moreover, these authors did note that there were significant increases in the ECC DCER strength for the trained and contralateral limbs. Thus, these authors concluded that the strength changes that were unaccompanied by hypertrophy changes suggested the presence of a neural adaptation.

Proske & Morgan, 2001

The purpose of this investigation was to perform a meta-analysis to focus attention on some possible indicators of muscle damage from unaccustomed ECC exercise and their possible mechanisms. Specifically, this review considers two possible initial events as being responsible for the subsequent damage; the first was damage to the excitation–contraction coupling system, while the second was disruption at the level of the sarcomeres. Furthermore, these authors stated that other changes seen

after ECC exercise (a fall in active tension, shift in optimum length for active tension, and rise in passive tension) are seen, on balance, to favor sarcomere disruption as the starting point for the damage, as well as damage to muscle fibers (i.e., disturbance of muscle sense organs and proprioception). Moreover, a second period of exercise, a week after the first, produced less damage and was a result of an adaptation process. Additionally, these authors proposed one mechanism for the adaptation that caused the increase in sarcomere number within muscle fibers and lead to a secondary shift in the muscle's optimum length for active tension. Thus, these authors concluded that the ability of a muscle to rapidly adapt, following the damage from ECC exercise, raises the possibility of clinical applications of mild ECC exercise (i.e., such as for protecting a muscle against more major injuries).

Beck *et al*., 2006

The purpose of this investigation was to examine MMG and EMG AMP and MNF vs. ECC isokinetic torque relationships for the BB muscle. Specifically, subjects performed submaximal to maximal ECC isokinetic muscle actions of the trained forearm flexors. More specifically, after determination of isokinetic peak torque (PT), the subjects randomly performed submaximal step muscle actions in 10% increments from 10% to 90% PT. Additionally, polynomial regression analyses indicated that the MMG AMP vs. ECC isokinetic torque relationship was best fit with a quadratic model, where MMG AMP increased from 10% to 60% PT and then plateaued from 60% to 100% PT. Furthermore, there were linear increases in MMG MNF and EMG AMP with increases in ECC isokinetic torque, but there were no significant changes in EMG MNF

from 10% to 100% PT. Moreover, these authors found that for the BB muscle, ECC isokinetic torque was increased to approximately 60% PT through concurrent modulation of the number of active MUs and their firing rates, whereas additional torque above 60% PT was produced only by increases in firing rates. Thus, these authors concluded that findings contributed to current knowledge of motor control strategies during ECC isokinetic muscle actions and that their results could be useful in the design of training programs.

Vikne *et al*., 2006

The purpose of this investigation was to examine the effects of CON and ECC training on performance and structural muscle parameters. Specifically, subjects participated in 12 weeks of either maximum CON or ECC resistance training of the elbow flexors. More specifically, the functional performance was measured as the maximum CON and ECC strength and angular velocity at standard loads. Additionally, the muscle CSA and CSA of single cells were used as measures of muscular hypertrophy, and the fiber type proportions were assessed by staining cells for myofibrillar ATPase. Furthermore, their results indicated that ECC and CON training increased CON strength to a similar extent (14% vs. 18%); whereas ECC training led to greater increases in ECC strength, when compared to CON training (26% vs. 9%). Moreover, the authors found that the maximum angular velocity at all loads was enhanced equally in both training groups and the CSA of both the elbow flexors (+11%) and of the type I and type IIa fibers increased only after the ECC training. In addition, the authors also found that the relative CSA occupied by the type II fibers

increased from 64% to 73% after the ECC training and there were only minor changes in the fiber type proportions. Thus, the authors concluded that for the resistance trained group, increases in CON strength and velocity performance after ECC training were largely mediated by changes in fiber and muscle CSA. However, these authors also concluded that hypertrophy alone could not explain the increase in ECC strength because the increases in strength and velocity performance after CON training could not be ascribed to muscular adaptations alone, implying additional neural factors.

Walker *et al*., 2012

The purpose of this investigation was to examine acute neuromuscular fatigue during dynamic maximal strength and hypertrophic loadings, which is known to cause different adaptations underlying strength gain during training. Specifically, subjects performed two leg press loadings, one week apart, consisting of 15 sets of 1-RM (MAX) and 5 sets of 10-RM (HYP). More specifically, CON load and muscle activity, as well as EMG AMP and median frequency, were assessed throughout each set. Additionally, maximal bilateral isometric force and muscle activity was assessed pre-, mid-, and up to 30 min post-loading. Furthermore, these authors found that CON loading during MAX was decreased after set 10, while the loading was maintained throughout HYP, and both loadings caused large reductions in maximal isometric force (MAX = 30 ± 6.4% vs. HYP = 48 ± 9.7%). Moreover, these authors also found that the decreased CON and isometric strength during MAX loading was accompanied by reduced EMG AMP, and conversely, HYP loading caused decreased median frequency only during isometric contractions. However, these authors found that during CON

contractions, EMG AMP increased and median frequency decreased in HYP. Thus, these authors concluded that there was a reduced neural drive during MAX loading and that there were more complex changes in a muscle's activity during HYP loading.

Cadore *et al.*, 2014

The purpose of this investigation was to compare the effects of CON vs. ECC training on neuromuscular adaptations in young subjects. Twenty-two healthy men and women were assigned into one of two groups (CON or ECC) and performed 6 weeks of isokinetic leg extension exercise, twice a week, starting with two sets of eight reps, and progressing to five sets of ten repetitions. Subjects were tested in the strength variables (CON, ECC, and isometric peak torque, and rate of force development), muscle conduction velocity, neuromuscular activity, vastus lateralis muscle thickness, and echo intensity as determined by ultrasonography. Their results indicated that both training types similarly improved dynamic isometric peak torque, conduction velocity, rate of force development, and muscle thickness and quality during the early weeks of training.

Beck *et al.*, 2016

The purpose of this investigation was to examine the EMG intensity patterns following unilateral CON vs. ECC exercise in the trained and untrained forearm flexors. Specifically, subjects were asked to perform a maximal isometric muscle action of the trained and untrained forearm flexors before (PRE) and immediately after (POST) a series of maximal CON isokinetic or maximal ECC isokinetic muscle actions of the trained forearm flexors. More specifically, the CON isokinetic and ECC

isokinetic muscle actions were performed on separate days and were randomly ordered. Additionally, in both cases, the subjects performed 6 sets of 10 maximal muscle actions. Furthermore, EMG signals were detected from the BB muscle of the trained and untrained limbs during the PRE and POST isometric muscle actions. Moreover, the signals were analyzed with a wavelet analysis, and the resulting intensity patterns were classified with a paired pattern classification procedure. Their results indicated that the EMG intensity patterns could be correctly classified into their respective PRE versus POST categories with an accuracy rate that was significantly better than random (20/26 patterns = 76.9% accuracy), but only for the trained limb following the ECC muscle actions. In addition, their results also indicated that ECC exercise had a significant influence on the muscle activation pattern for the forearm flexors. Thus, these authors concluded that it was possible that the muscle damage resulting from ECC exercise affects muscle spindle and/or GTO activity, thereby altering the muscle activation pattern.

Summary

"Conventional" resistance training (RT) is the most common form of resistance exercise, consisting of lifting and lowering a constant external load. Thus, conventional RT combines CON (lifting-phase) and ECC (lowering-phase) actions and according to the force–velocity (F-V) relationship, each value of force and velocity on a given curve should belong to the same level of neural activation. Yet, this requirement is not met by conventional RT as the same external load is displaced during both lifting and lowering phases. Hence, MUs must be decruited in the ECC part to enable the load to be

lowered; as such the load used for conventional RT is limited by the CON muscle action. Therefore, to ensure that the ECC component of resistance training is not under loaded, it would be necessary that both shortening and lengthening phases follow the physiological force-velocity curve, that is, the absolute load should be greater for the ECC contraction, when compared to the CON contraction.

Furthermore, ECC muscle actions are unique in the sense that they are most responsible for the muscle soreness felt 24 – 72 hours following unaccustomed exercise (explained as delayed-onset muscle soreness [DOMS]). This does not mean that CON muscle actions cannot cause low levels of muscle soreness. However, it has been well documented that activities with a high intensity and/or a high volume of ECC muscle actions elicit the greatest levels of muscle soreness. Moreover, mechanical disruption of the structural and contractile proteins is a logical explanation, for at least part, of this performance decrement with ECC exercise. However, substantial evidence suggests that there is also a neural component to ECC exercise induced strength loss, and recent investigations have reported acute decreases in EMG AMP after ECC exercise. Whether these decreases in muscle activation are due to decruitment of MUs, reductions in MU firing rates, a combination of both, or potentially some other factor remains to be seen.

Controversially, CON exercise does not appear to cause muscle damage, so any acute decrements in performance are due to more traditional fatigue related phenomena (such as metabolite accumulation and substrate depletion). Interestingly, similar decreases in EMG AMP have also been reported after CON exercise as those following ECC exercise. However, given the distinct differences between these two types of

exercise, it would not be appropriate to assume that the same mechanism is causing these decrements in muscle activation. Thus, researchers now hypothesize that muscular strength and hypertrophy with CON and ECC RT may occur with different morphological adaptations (i.e., MU activation patterns, MU firing rates, different fiber fascicle behavior, molecular responses, etc.). Hence, based off these morphological differences across time, researchers will potentially be able to determine which type of RT stimulus (CON or ECC) is considered to be the most ideal for the greatest degree of positive muscular adaptations across time.

2.6. Factors that influence EMG and MMG Measurements

Eason, 1960

The purpose of this investigation was to examine if the ability to maintain a constant force as a muscle progressively fatigues was accomplished by the recruitment of additional MUs. Specifically, subjects performed sustained isometric muscle action of the trained forearm flexors at 25%, 50%, or 75% MVC until exhaustion on twelve separate occasions and then performed a second sustained muscle action with either the contralateral or previously fatigued forearm flexors. More specifically, EMG signals were detected during each muscle action from the forearm flexors. Furthermore, their results indicated that there was a linear relationship between initial EMG AMP and force and that the EMG AMP increased with time for each subject. Moreover, this author found that the rate of increase for EMG AMP was significantly greater for the 50% and 75% MVC muscle actions compared to that for the 25% MVC trial and that there were no significant differences between arms for any of the dependent variables.

Thus, these authors concluded that the residual effects from the sustained muscle actions were specific to the fatigued forearm flexors and that the increase in EMG AMP for each trail was a result of the recruitment of higher threshold MUs.

Lindstrom *et al*., 1970

The purpose of this investigation was to examine the relationship between muscle fiber action potential CV and EMG MNF during fatiguing muscle actions. Specifically, subjects participated in the investigation and were required to perform several fatiguing isometric muscle actions of the trained forearm flexors while EMG signals were detected. More specifically, the EMG signals were recorded on FM tape, and MNF analyses were performed with a spectrum analyzer. Furthermore, their results indicated that the initial CV values ranged from 3.5 to 4.8 m/s, and declined as the muscle progressively fatigued. Moreover, this decline in CV was accompanied by a shift in the EMG power spectrum toward lower frequencies. Thus, these authors concluded that during fatiguing muscle actions, the decline in pH resulted in reduced CV for the active muscle fibers, which in turn altered the shape of the EMG power spectrum.

Viitasalo & Komi, 1975

The purpose of this investigation was to examine the reliability and constancy of recordings of EMG signal characteristics from the measurements taken during submaximal and maximal contraction of the RF muscle. Specifically, the following EMG variables were studied, integrated EMG (IEMG) various band-widths of the

power spectral density function, MNF, and rise time, AMP and number of spikes of the averaged motor unit action potentials (AMUAP). Furthermore, their results indicated that for most of the variables studied, the reproducibility of measurements were better within the test session (reliability) than between the different test days (constancy) and the reliability values for IEMG, MNF and AMUAP AMP were rather high (r = 0.77 – 0.92). Thus, these authors concluded that MNF and number of spikes in AMUP showed good constancy values (r = 0.73 – 0.93) and that these parameters can be recommended for use in EMG studies where recordings are repeated over a period of several days.

Orizio *et al*., 1989 a & b

The purpose of the first investigation (Orizio *et al*., 1989a) was to examine the relationship between MMG AMP and isometric force throughout the entire force spectrum. Specifically, subjects performed a series of randomly ordered isometric muscle actions of the trained forearm flexors from 10% to 100% MVC, in 10% increments. More specifically, MMG signals were detected from the BB muscle with a piezoelectric contact sensor during each muscle action. Furthermore, their results indicated that MMG AMP increased linearly from 10% - 80% MVC, but decreased at 90% and 100% MVC. Thus, these authors concluded that this finding reflected the fact that beyond 80% MVC, increases in force were due primarily to increased firing rates for the active MUs, and that the greater intramuscular pressure limited the degree of muscle fiber vibrations.

In their follow-up investigation (Orizio *et al*., 1989b), these authors examined MMG and EMG AMP responses during exhaustive isometric muscle actions at several

submaximal force levels. Specifically, following several familiarization sessions, the subjects were asked to perform sustained isometric muscle actions of the right forearm flexors at 20%, 40%, 60%, and 80% MVC on four separate days. More specifically, during each muscle action, MMG and EMG signals were detected on the BB muscles. Furthermore, their results indicated that the means times to exhaustion were 480, 134, 68, and 39 sec at 20%, 40%, 60%, and 80% MVC, respectively. Moreover, during the sustained action of 20% MVC, MMG AMP increased linearly across, at 40% MVC, MMG AMP showed only a very slight increase across time, and during the sustained muscle actions at 60% and 80% MVC, MMG AMP decreased curvilinearly. Additionally, what was particularly noteworthy was that EMG AMP increased across time for all the target force levels. Thus, these authors concluded that the different patterns of response for MMG AMP were due to differences in recruitment of MUs and changes in their firing rates, as well as different levels of intramuscular pressure and stiffness and that the MMG signal may provide more useful information than EMG regarding motor control strategies during sustained isometric muscle actions.

Dalton & Stokes, 1991

The purpose of this investigation was to examine the linearity of the MMG AMP vs. dynamic torque relationship. Specifically, subjects lifted and lowered weights with their right forearm flexors while MMG and EMG signals were detected simultaneously from the BB muscle. Moreover, the subjects performed the muscle actions with loads corresponding to 0, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, and 8.5 kgs, while the CON and ECC portions of the movement were analyzed separately. Furthermore,

their results indicated that EMG and MMG AMP increased linearly for both CON and ECC testing modes. Moreover, their results also indicated that MMG AMP values for the CON muscle actions were consistently greater than those for the ECC muscle actions. Thus, these authors concluded that MMG AMP may be used to detect changes in torque during dynamic muscle actions.

Marchetti *et al*., 1992

The purpose of this investigation was to examine the MMG AMP and frequency responses between the VL and soleus during supra-maximal electrically stimulated isometric twitches. Specifically, the VL and soleus were electrically stimulated on two separate occasions, while the MMG signal was detected with a piezoelectric contact sensor. Furthermore, their results indicated that the MMG median frequency values for the VL were significantly greater than those for the soleus. Additionally, for each subject, the mean time to peak MMG AMP was significantly greater for the soleus compared to that for the VL. Thus, these authors concluded that the differences between the MMG responses for these two muscles were related to fiber type differences.

Kupa *et al*., 1995

The purpose of this investigation was to examine the relationships among EMG median frequency, CV, muscle fiber type, and CSA. Specifically, the soleus and extensor digitorum longus (EDL) muscles were excised from six animals with their corresponding branches of the sciatic nerve intact. Similarly, following a tracheotomy,

eight animals had their diaphragm removed with the left phrenic nerve intact. More specifically, EMG signals were recorded during 20 sec electrically elicited tetanic muscle actions from the EDL, soleus, and diaphragm muscles. Additionally, the CSAs from each muscle were measured, along with the fibers from each muscle being classified as fast-glycolytic (FG), fast-oxidative glycolytic (FOG), and slow-oxidative (SO), based on mATPase, succinate dehydrogenase, and α-glucose-6-phosphate dehydrogenase activities. Furthermore, their results indicated that the muscles with a greater percentage of FG fibers showed higher initial values for EMG median frequency and CV. Moreover, FG fibers were associated with a greater reduction in median frequency and CV during the electrical stimulation and their multiple regression analyses indicated that fiber-type composition could be predicted based on initial median frequency and the decline in median frequency during the electrical stimulation. Thus, these authors concluded that the initial EMG median frequency values and the decline in CV during fatigue were related to both muscle fiber type composition and CSA. In addition, it is important to note that their findings support the possibility of utilizing surface EMG technologies to obtain a non-invasive electrophysiological muscle biopsy for estimating muscle fiber composition.

Orizio *et al*., 1999

The purpose of this investigation was to examine changes in the MMG and force signal characteristics before, and immediately after fatigue, as well as during 6 min of recovery, when changes in the contractile properties of muscle occur. Specifically, fatigue was induced by sustained electrical stimulation. More specifically,

these authors evaluated the reliability of the MMG as a tool to follow the changes in the mechanical properties of muscle caused by fatigue. Furthermore, these authors found that due to fatigue, the parameters of the force peak, the peak rate of force production and the peak of the acceleration of force production ($[d^2 \boldsymbol{F}]/d\boldsymbol{t}^2$), as well as the MMG peak-to-peak (p-p) decreased, while the contraction time and the half-relaxation time (½-RT) increased. Moreover, these authors also found that the attenuation rate of the force oscillation AMP and MMG p-p at increasing stimulation frequency was greater after fatigue and with the exception of ½-RT, all force and MMG parameters were restored within 2 min of recovery. In addition, their results indicated a high correlation between MMG and ($[d^2 \boldsymbol{F}]/d\boldsymbol{t}^2$) in un-fatigued muscle and during recovery. Thus, these authors concluded that the MMG signal reflects specific aspects of muscle mechanics and can be used to follow the changes in the contractile properties of muscle caused by localized muscle fatigue.

Komi *et al*., 2000

The purpose of this investigation was to examine the effects of velocity and muscle length on EMG AMP and median frequency during maximal CON and ECC muscle actions. Specifically, subjects were asked to perform muscle actions with their right forearm flexor, while remaining seated in a custom-built isokinetic dynamometer. More specifically, subjects performed maximal CON and ECC isokinetic muscle action at four different velocities (57˚, 115˚, 172˚, and 229˚/sec) and at joint angles corresponding to 55˚, 110˚, and 165˚ between the arm and forearm. Additionally, for all the dynamic muscle actions, EMG signals were detected from the BB, brachioradialis,

and TB muscles while the subjects were instructed to activate their forearm flexors approximately one sec before the dynamometer's lever arm was initiated. Furthermore, for the dynamic muscle actions, isokinetic peak torque and EMG AMP and median frequency were examined for a five separate portion of the range of motion (66˚, 88˚, 110˚, 132˚, and 154˚). Similarly, these EMG parameters and MVC strength tests were determined for each of the isometric muscle actions and their results indicated that regardless of movement velocity and muscle action type, the greatest isokinetic peak torque values occurred at 110˚. Moreover, for each velocity, the ECC torque values were greater than those for the CON muscle actions at all portions of the range of motion, except when the forearm flexors were at their greatest length (154˚). Nevertheless, the EMG AMP results for each muscle showed that the greatest values were demonstrated for the CON muscle actions, followed by the isometric and ECC testing modes, respectively, and that they were generally greatest at slower movement velocities and shorter muscle lengths. In addition, the highest EMG median frequency values for each muscle occurred during the CON muscle actions performed at the faster movement velocities. Thus, these authors concluded that max ECC isokinetic muscle actions are associated with greater peak torque values than those for CON and isometric muscle actions. However, these authors noted that the EMG AMP and median frequency results were highly dependent on movement velocity and muscle length and that these results did not support the contention that fast-twitch muscle fibers are selectively recruited during ECC muscle actions performed at high velocities.

Perry *et al*., 2001

The purpose of this investigation was to examine the relationships for MMG AMP, MMG MNF, EMG AMP, and EMG MNF versus power output during incremental cycle ergometry. Specifically, subjects were asked to perform an incremental test to exhaustion on a cycle ergometer. More specifically, the test began at 50 watts and the power output was increased by 30 watts every 2 min until the subject could no longer maintain 70 rev/min. Additionally, the MMG and EMG signals were recorded simultaneously from the VL muscle during the final 10 sec of each power output. Furthermore, the MMG AMP, MMG MNF, EMG AMP, EMG MNF, and power output were normalized as a percentage of the maximal value from the cycle ergometer test. Moreover, these authors performed a polynomial regression analyses and found that the MMG AMP increased linearly across power output, but there was no change in MMG MNF, and that EMG AMP and MPF were fit best with quadratic models. Hence, their results demonstrated dissociations among the time and frequency domains of MMG and EMG signals, which may provide information about motor control strategies during incremental cycle ergometry. Thus, these authors concluded that the patterns for AMP and frequency of the MMG signal may be useful for examining the relationship between MU recruitment and firing rate during dynamic tasks.

Madeleine *et al*., 2001

The purpose of this investigation was to examine if systematic, complementary knowledge could be obtained from EMG and MMG signals. Specifically, EMG and

MMG activities were recorded from the FDI muscle during slow CON, isometric, and ECC contractions at 0%, 25%, 50%, 75% and 100% of the MVC. Furthermore, these authors found that the combination of the EMG and MMG recordings during voluntary CON, isometric ECC contractions showed significant different non-linear EMG/force and MMG/force relationships. Moreover, these authors also found that the EMG RMS values increased significantly from 0% to 50% MVC during CON and isometric contractions, and up to 75% MVC during ECC contractions, while the MMG RMS values increased significantly from 0% to 50% MVC during CON contraction. Thus, these authors concluded the non-linear relationships depended mainly on the type and the level of contraction together with the angular velocity and the type of contraction, the contraction level, and the angular velocity influenced the electromechanical efficiency evaluated as the MMG to EMG ratio. Additionally, these authors further concluded that the EMG and MMG signals provide complementary information about the electrical and mechanical activity of the muscle and that there are different activation strategies used during different graded isometric and anisometric (non-isometric) contractions.

Cramer *et al*., 2002

The purpose of this investigation was to examine the responses of peak torque (PT), mean power output (MP), MMG and EMG AMP, and MMG and EMG MNFs of the VL, RF, and VM muscles during dynamic muscle actions. Specifically, subjects performed maximal, CON, isokinetic leg extensions at velocities of 60˚, 120˚, 180˚, 240˚, and 300˚/sec on a Cybex 6000 dynamometer. More specifically, piezoelectric

MMG sensors and EMG electrodes were placed over the VL, RF, and VM muscles. Furthermore, these authors found no sex related differences among the velocity related patterns for PT, MP, MMG AMP, MMG MNF, or EMG MNF. However, these authors did find that there were sex related differences in the patterns of EMG AMP across velocity. Moreover, their results indicated similar velocity related patterns of increase of MP and MMG AMP for all 3 muscles and of EMG AMP for the VL and VM in the women. Additionally, these authors also found velocity related decreases for PT and EMG MPF for the VL muscles, while EMG AMP for all muscles in the men and for the RF in the women. Nevertheless, EMG MPF for the RF and VM remained unchanged across velocity. Thus, these authors concluded that there were sex and muscle specific, velocity related differences in the associations among MU activation strategies (EMG AMP and MNF) and the mechanical aspects of muscular activity (MMG AMP and MNF). In addition, these authors also stated that the MMG signals may prove useful to practitioners for monitoring training induced changes in muscle power output.

Petrofsky & Laymon, 2005

The purpose of this investigation was to examine the interrelationships between the EMG AMP and frequency, muscle tension, muscle fatigue, and muscle temperature. Specifically, subjects immersed their arms and legs in water at 24°, 27°, 34°, and 37° C for 20 min. More specifically, muscle temperature, MVC, endurance for a fatiguing contraction at 40% MVC, and EMG were assessed in the handgrip, BB, quadriceps, and gastrocnemius muscles. Furthermore, their results indicated that the MVC was 44.8% lower for all muscles examined at the coldest muscle temperature, and for all

temperatures the relationship between EMG AMP and tension for brief isometric contractions was nearly linear. However, the increase in the AMP of the EMG signal with muscle fatigue was reduced for the coldest muscle temperatures. Moreover, the frequency components of the EMG signal and MU CV were largely unaffected by muscle tension, but were inversely related to muscle temperature, with a 10° C reduction in temperature resulting in a 32 Hz reduction in the center frequency. Additionally, during fatiguing contractions at a tension of 40% MVC, the percent reduction in frequency was similar for all muscle temperatures, being reduced by about 20% from the beginning to the end of the contractions. Thus, the authors concluded that EMG AMP can be used to assess muscle use in most physiological conditions, but the frequency components of the EMG are so related to temperature as to make its use more restricted.

Nonaka *et al*., 2006

The purpose of this investigation was to examine MMG and the force relationship during isometric ramp contractions of BB muscles to identify sex differences in the MMG responses. Specifically, subjects were asked to exert an isometric elbow flexion torque from 5% to 80% MVC at a constant rate of 10% MVC per second, while the MMG signal was normalized to muscle CSA, as measured by ultrasound imaging. Furthermore, their results indicated that MVC and CSA were significantly different between the two sex groups (males > females) and that there were no sex difference in the MVC relative to muscle CSA (MVC/CSA). Moreover, the RMS AMP of the MMG (RMS_{MMG}) was significantly greater in the male group than

the female group and the RMS_{MMG} relative to muscle CSA was also different between the two sex groups (males > females). Additionally, the sex difference in the RMS_{MMG}/CSA was more pronounced with increasing torque, while the torque levels at which the inflection points in the MMG AMP were located were different between the two sexes. However, the MNF of the MMG in the female group increased monotonously (having little inflection), which was different from that in the male group. Thus, the authors concluded that the sex differences in MMG responses and MU activation strategies resulted from the predominant activity of the MU with slow twitch fibers and an effective fused tetanus in females.

Stock *et al*., 2010

The purpose of this investigation was to examine the relationships among MMG AMP, power output, and bar velocity during the free weight bench press exercise. Specifically, subjects were asked to perform bench press muscle actions as explosively as possible from 10% to 90% of their 1-RM, while peak power output and peak bar velocity were assessed with a TENDO Weightlifting Analyzer. More specifically, during each muscle action, MMG signals were detected from the right and left pectoralis major and TB muscles, while the CON portion of the range of motion was selected for analysis. Furthermore, their results indicated that power output increased from 10% to 50% 1-RM, followed by decreases from 50% to 90% 1-RM, but MMG AMP for each of the muscles increased from 10% to 80% 1-RM. Thus, these authors concluded that during the free weight bench press exercise, MMG AMP was not related to power output, but was inversely related to bar velocity, and directly related to the

external load being lifted. Additionally, these authors also stated that the MMG signals could potentially help estimate force/torque production from individual muscles during dynamic, constant, external, resistance muscle actions.

Qi *et al*., 2011

The purposes of this investigation were to apply wavelet and principal component analysis (PCA) to quantify the spectral properties of the EMG and MMG signals during isometric ramp and step muscle contractions, when the MUs are recruited in an orderly manner, and to compare the recruitment patterns of MU during isometric ramp and step muscle contractions. Specifically, participants performed ramp and step isometric contractions, while EMG and MMG signals were recorded from BB muscle. More specifically, the EMG and MMG signals were decomposed into their intensities in time–frequency space, using a wavelet technique and the EMG and MMG spectra were then compared using PCA and ANCOVA. Additionally, wavelet combined PCA offers a quantitative measure of the contribution of high and low frequency content within the EMG and MMG signals. Furthermore, the ANCOVA indicated that there were no significant difference in EMG total intensity, EMG_{MNF}, first and second principal component loading scores (PC-I and PC-II) between ramp and step contractions. However, the MMG_{MNF} and MMG PC-I loading scores were significantly higher during ramp contractions than during step contractions. Moreover, these authors found that EMG and MMG signals may offer complimentary information regarding the interactions between MU recruitment and firing rate that control muscle

force production. Thus, these authors concluded that different MU recruitment strategies are used by the muscle when contracting under different conditions.

Camic *et al*., 2014

The purpose of this investigation was to examine the patterns of responses for torque, MMG and EMG AMP, and MMG and EMG frequency across 30 repeated maximal ECC muscle actions of the leg extensors. Specifically, subjects performed an ECC fatigue protocol at 30°/sec with MMG and EMG signals recorded from the VL muscle. Furthermore, their results indicated there were significant decreases in MMG frequency (linear, $\boldsymbol{r}^2 = 0.395$), EMG frequency (linear, $\boldsymbol{r}^2 = 0.177$), and torque (linear, $\boldsymbol{r}^2 = 0.570$; % decline = 9.8 ± 13.3%). Moreover, their results also indicated there were increases in MMG AMP (linear, $\boldsymbol{r}^2 = 0.783$); and there were no changes in EMG AMP ($\boldsymbol{r}^2 = 0.003$). Nevertheless, these authors found that the neural strategies used to modulate torque during fatiguing ECC muscle actions involved decruitment of MUs, reduced firing rates, and synchronization. Additionally, these authors also found that the decreases in ECC torque were more closely associated with changes in MMG frequency than EMG frequency. Thus, these authors concluded that MMG frequency, compared with EMG frequency, more accurately tracked fatigue during repeated maximal ECC muscle actions.

Summary

EMG is the recording of the MU action potentials that activate skeletal muscle fibers as detected by sensors placed on the skin overlying the muscle belly.

Specifically, the EMG signal reflects muscle activation and is influenced by the number of active MUs and their respective firing rates. More specifically, the EMG signal may be influenced by several factors including, but not limited to, electrode and amplifier properties, conduction velocity, muscular length, muscular mass, thickness of subcutaneous fat between the MMG sensor and the surface of the muscle, sweat accumulation, and/or skin resistance. Therefore, EMG signals are often considered a global measure of MU activity, which contains information regarding both peripheral and central properties of the neuromuscular system. However, MMG has been defined as the recording of low frequency lateral oscillations of muscle fibers that occur during a contraction and have suggested that these oscillations are manifested through: the gross lateral movement of the muscle at the initiation of the contraction, smaller subsequent lateral oscillations occurring at the resonant frequency of the muscle, and dimensional changes in the active fibers. Additionally, MMG has been considered as the intrinsic mechanical counterpart to the MUs electrical signal, as measured by EMG, and is not affected by the quality of the sensor-skin interface (i.e., sweat accumulation and skin resistance). More specifically, the MMG signal may be influenced by several factors including, but not limited to, the active stiffness of the fibers modulated by the number of MUs recruited, the firing rates of the active MUs, muscular tension, muscular length, muscular mass, intramuscular pressure, viscosity of the intra- and extracellular fluid surrounding the fibers, intramuscular temperature, and/or the thickness of subcutaneous fat between the MMG sensor and the surface of the muscle.

Furthermore, although it may initially appear that the surface EMG and MMG signals provide similar information about neuromuscular function, recent studies have

argued that both signals provide unique information that can be used simultaneously as non-invasive measures to examine motor control issues. Perhaps the greatest disparity between the EMG and MMG signals exists in their force related patterns of responses. EMG–force relationships are usually characterized as linear or quadratic increases in EMG signal across the force spectrum has suggested that the EMG–force relationship reflects the concurrent increases in MU recruitment and firing rates that regulate muscle force output. On the other hand, MMG-force relationships tend to display a cubic increase in MMG signals across the force spectrum, which is different from most EMG patterns. Therefore, in contrast to the EMG–force relationships, the patterns of responses demonstrated during the MMG-force relationship may be able to distinguish between the contributions of MU recruitment and rate coding as the MU activation strategies that increase muscle force production. Specifically, it has been suggested that the AMP content of the EMG and MMG signals are related to MU recruitment/decruitment, whereas EMG and MMG frequencies are associated with the global firing rate of unfused, activated MUs. Additionally, even though the AMP and frequency components of the EMG and MMG signals have been used to discriminate between muscle fiber types, monitor physical training programs, and identify changes in force production and muscle action velocity, these signals have also been useful for examining numerous neuromuscular disorders, including, but not limited to, cerebral palsy, myotonic dystrophy, craniomandibular disorders, chronic and severe low back pain, diaphragmatic fatigue, and skeletal muscle atrophy. Thus, using both types of measurements provides complementary knowledge to provide a better, more reliable,

globalized picture of the motor control strategies, within a particular muscle, during different exercise modalities.

Chapter III

Methods

This chapter will provide a brief description of the research design and the exercise protocol. The study's sensor description, preparation, placement and processing will be explained. Finally, data analyses and the associated equations for effect sizes will be described.

3.1. Subjects

Twenty healthy, college-aged (18-35 yr olds) men (N = 10) and women (N = 10) volunteered to participate in this investigation. All potential subjects contacted the primary investigator using the tear away attachments from the flyers that were placed around the Norman campus. All subjects completed an informed consent form and a pre-exercise health and exercise status questionnaire, as well as were given a copy of the informed consent form to keep for their records. The purpose of these forms were to ensure that the rights of the participants were protected and to screen out participants that may be at risk for injury. Furthermore, this study conformed to the standards set by the Declaration of Helsinki and was approved by the University's Institutional Review Board prior to data collection.

3.2. Research Design

This study incorporated a true experimental research design. Specifically, this study used a randomized repeated measures protocol (pre-, mid-, and post-tests) investigating within and between subjects comparisons. This study required 30 separate

visits to the Biophysics Laboratory on the University of Oklahoma, Norman campus, and each visit was separated by a minimum of 48 hours. The Familiarization Visit (1st visit) consisted of a maximal voluntary contraction (MVC) testing of the forearm flexors (BB muscle), as well as practicing the trapezoidal force tracing procedures from the DOM (determined by which arm the subjects chose to throw a ball) and NDOM arms. Furthermore, there were a total of 15 right hand and 5 left hand DOM individuals, respectively. The Evaluation Visits (Visits 2, 9, 16, 23, and 30) consisted of a MVC testing of the BB muscle and force tracings of 30%, 50%, and 70% MVC for the DOM and NDOM arms. The Training Visits (Visits 3rd - 8th, 10th - 15th, 17th - 22nd, and 24th - 29th) consisted of CON or ECC exercise of the BB muscle for only the DOM arm.

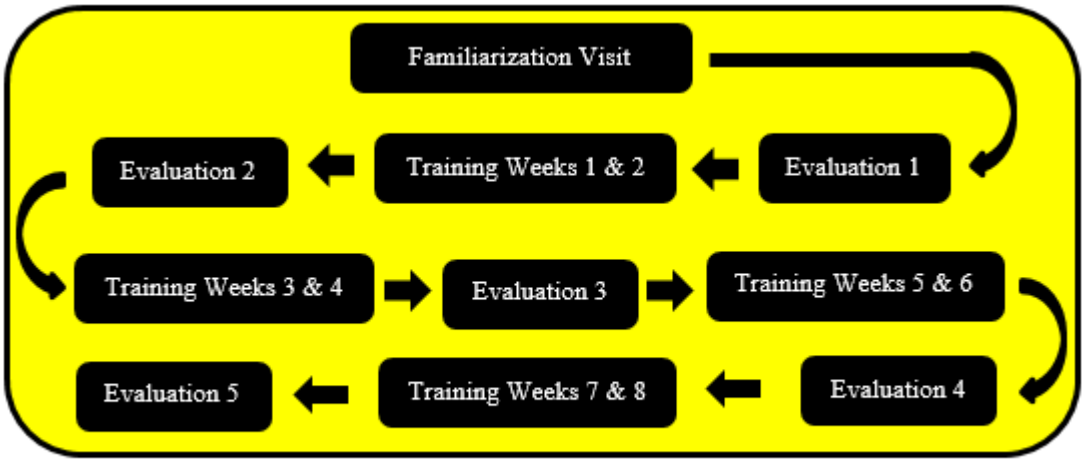


Figure 1. Experimental Design of the Investigation

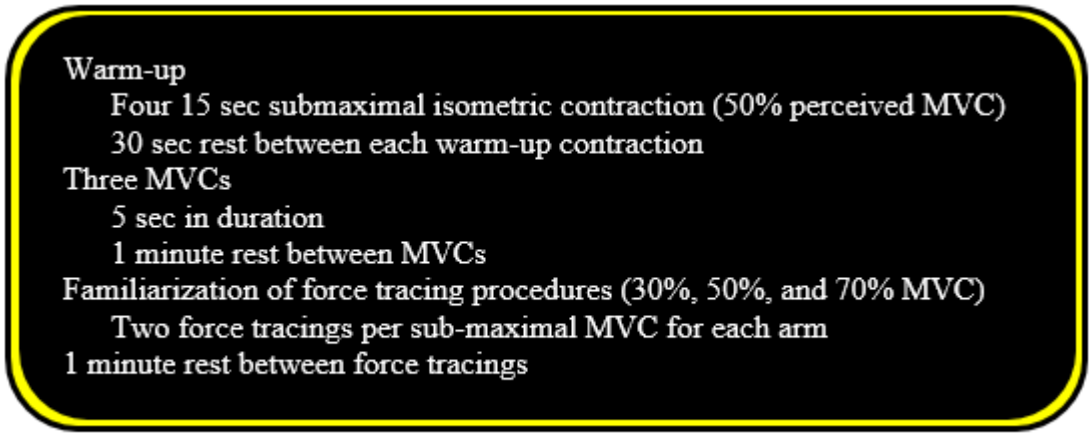


Figure 2. Familiarization Visit Summary

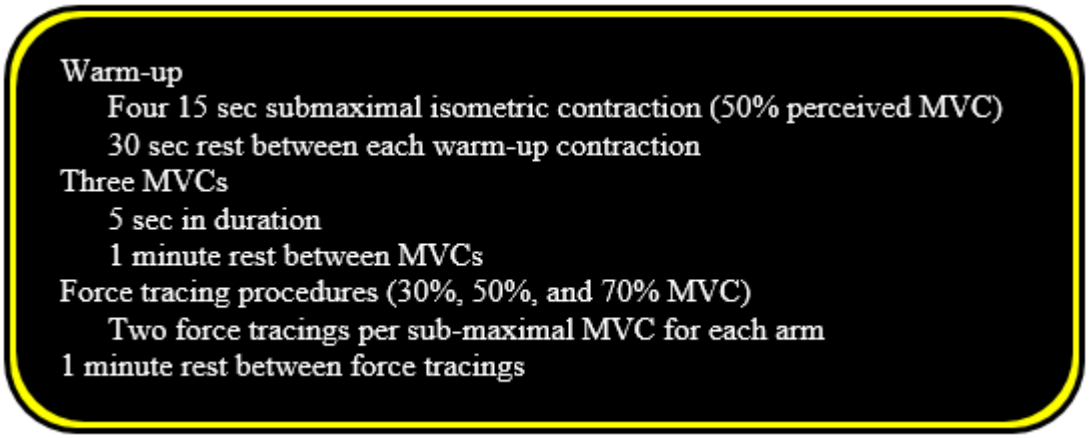


Figure 3. Evaluation Visit Summary

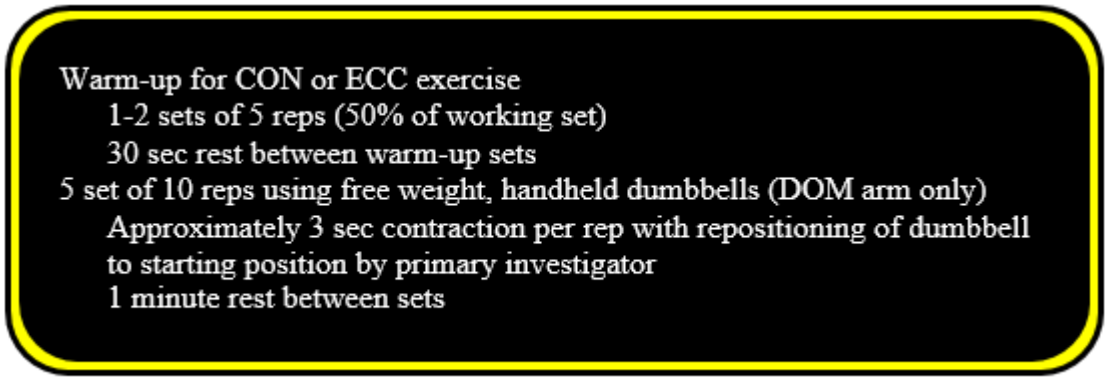


Figure 4. Training Week Visit Summary

3.3. Instrumentation/Measurement Protocols

Before any study data collection began, there was pilot testing of all EMG and MMG sensor placements and exercise procedures. Based off this pilot testing (and previous literature), *a priori* sample size estimation using G*Power 3.1 software indicated that for an alpha level of 0.05 and a power level of 0.80, a sample size of approximately 20 participants was appropriate (e.g., 10 [5 Male and 5 Female] participants in each group).

3.4. Isometric Strength Assessment

The subjects were seated at a table with their trained and untrained arms placed in a custom-built, isometric strength testing apparatus. The subject's arm was flexed 90º at the shoulder with the elbow resting on a soft pad. The forearm was flexed 90º at the elbow and a soft cuff was secured around the subject's wrist. The cuff was secured to the apparatus perpendicular to the forearm with a load cell (Model SSM-AJ-500, Interface Inc., Scottsdale, AZ) to measure isometric force (N). Forearm flexion force was measured when the subject was facing the apparatus. Following the warm-up exercise of four, 15 sec submaximal isometric muscle actions at approximately 50% perceived MVC, the subjects performed three, 5 sec MVCs of the forearm flexors. Each MVC was separated by 1 min of rest, and the highest force value from the 3 trials being designated as the subject's MVC.

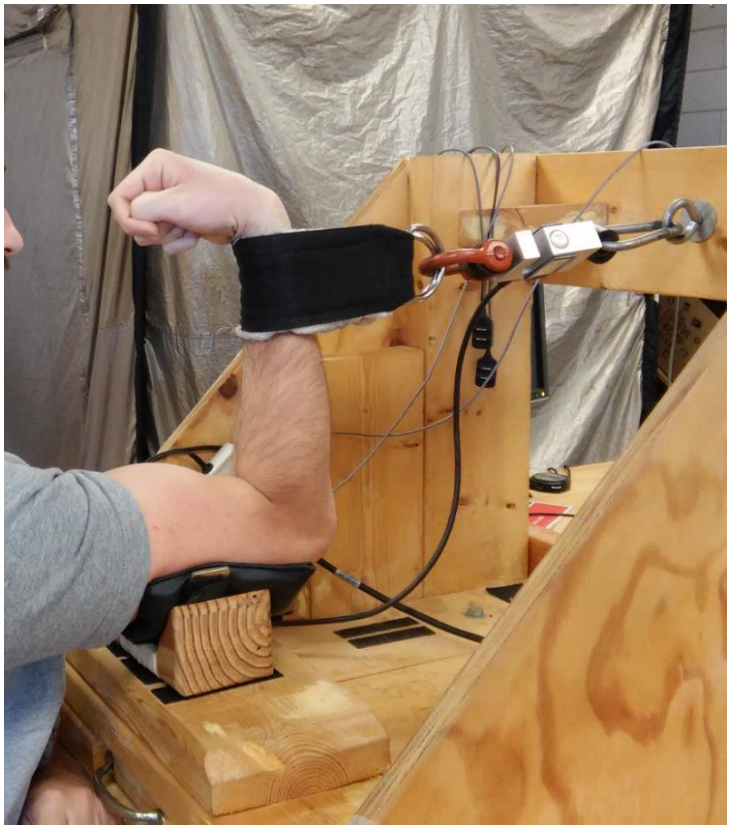


Figure 5. An example of the subject's arm position during all submaximal isometric muscle actions

3.5. Submaximal Muscle Actions

Submaximal, isometric trapezoid muscle actions were performed at 30%, 50%, and 70% of the subject's MVC. Furthermore, for all submaximal isometric MVCs, there was a relaxation period before the positive linear and after the negative linear force tracings. Thus, the 30% trapezoid force tracing required a linear force increase from 0% to 30% MVC over a period of 3 sec, a constant force hold at 30% MVC for 10 sec, and a linear force decrease from 30% to 0% MVC over a period of 3 sec (total time = 22 sec). The 50% trapezoid force tracing required a linear force increase from 0% to 50% MVC over a period of 5 sec, a constant force hold at 50% MVC for 10 sec, and a linear force decrease from 50% to 0% MVC over a period of 5 sec (total time = 26 sec).

The 70% trapezoid force tracing required a linear force increase from 0% to 70% MVC over a period of 7 sec, a constant force hold at 70% MVC for 10 sec, and a linear force decrease from 70% to 0% MVC over a period of 7 sec (total time = 30 sec). Visual feedback of the real-time force level was provided to the subjects along with a target template of the trapezoid. This feedback helped minimize error and ensure that the subject was as close to the target force template as possible.

Figure 6. An example of the trapezoid template used for the submaximal isometric muscle actions. Visual feedback of the subject's real time force level was overlaid on the screen as the subject attempts to match the template.

3.6. Training Protocol

A total of 24 exercise visits were required for this study. Exercise visits encompassed either CON or ECC contractions only. Contractions were performed using free weight, handheld dumbbells (between 20 and 60 lbs) and incorporated 5 sets of 10 repetitions for the DOM arm only. The duration for each repetition lasted three seconds and following the conclusion of each repetition the primary investigator placed

the dumbbell back to the starting position. Furthermore, regardless of contraction type, subjects sat in a chair with a preacher curl pad attachment to isolate the BB muscle during exercise. However, even though both contraction groups had their arms positioned identical on the pad; their forearms began and finished in different positions. Specifically, subjects from the CON contraction only group began with their forearm extended approximately 170º and finished with their forearm flexed at approximately 60º, while subjects from the ECC contraction only group began with their forearm flexed approximately 60º and finished with their forearm extended at approximately 170º.

Figure 7. An example of subject position for CON and ECC muscle actions.

3.7. Assessment Protocol

A total of 5 assessment visits were required for this study. Specifically, there was one pre-test measurement, three mid-tests measurements, and one post-test measurement that were separated by six exercise visits between each measurement. The trained and untrained BB muscles were assessed on these visits and incorporated the same warm-up as with the familiarization visit. Following this warm-up, subjects performed three MVCs, with the highest MVC being used for submaximal trapezoidal force tracings. For each submaximal trapezoidal force tracing (30%, 50%, and 70% MVC), subjects performed each tracing twice for a total of 6 force tracing per arm.

3.8. Data Collection Procedures

Prior to all sensor placements, the skin over the BB muscle was shaved, lightly rubbed with sand paper, cleansed with rubbing alcohol, and touched repeatedly with hypo-allergenic tape to remove dead skin. Furthermore, sensors were placed in the direction of the muscle fibers, firmly secured to the skin with hypoallergenic surgical tape and outlined with a permanent marker to ensure consistent placement between all visits. In addition, a reference electrode (5.08 cm diameter Dermatrode HE-R; American Imex, Irvine, CA) was placed on the spinous process of the C^7 vertebrate at the inferior portion of the neck and was prepared in the same manner as with the BB muscle.

3.9. Electromyography

One surface EMG sensors were placed on the subject's trained and untrained arms during visits 2, 9, 16, 23, and 30. The sensor was bipolar electrode (DE-2.1 Single Differential surface EMG sensor; Delsys, Inc., Boston, MA) with a 1 cm interelectrode distance. The EMG sensor was placed over the muscle belly of the BB muscle in accordance with the specific recommendations from the SENIAM project (Hermens *et al.*, 1999). Specifically, for the BB muscle, the sensors was placed at 1/3 from the fossa cubit on the imaginary line between the medial acromion and the fossa cubit.

3.10. Mechanomyography

One MMG sensor (Entran EGAS FT-10; Measurement Specialties, Hampton, VA) was also placed on the subject's trained and untrained arms during visits 2, 9, 16, 23, and 30. The MMG sensor was also placed over the muscle belly of the BB muscle in accordance with the specific recommendations from the SENIAM project (Hermens *et al.*, 1999).

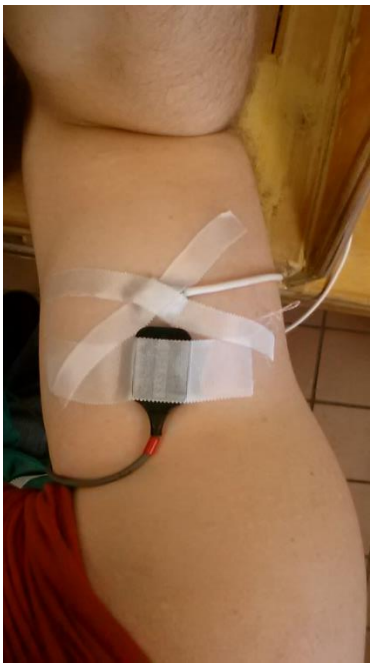


Figure 8. An example of the sensor placement on the BB. On the BB muscle the MMG sensor was located most distal, while the EMG sensor was located most proximal to the shoulder attachment.

3.11. Signal Processing

All analog (raw) EMG signals were preamplified (gain = 1,000) with a modified Bagnoli 16-channel EMG system (Delsys, Inc.), digitized at a rate of 20,000 samples/sec, by a 12-bit analog-to-digital converter (National Instruments, Austin, TX, USA), and stored in a personal computer (Dell Optiplex 755, Round Rock, TX) for subsequent analyses. The sEMG signals were then digitally band-pass filtered (4^{th}–order Butterworth) with pass frequencies, between 20 and 450 Hz.

All analog MMG signals (baseline and post-exercise) were digitized at a rate of 1,000 samples/sec, by a 12-bit analog-to-digital converter (National Instruments, Austin, TX), and stored in a personal computer (Dell Inspiron, Latitude D620, Round Rock, TX) for subsequent analyses. The MMG signals were then digitally band-pass filtered (4^{th}–order Butterworth) with pass frequencies, between 5 and 50 Hz.

The Discrete Fourier Transform (DFT) algorithm was used to derive the sEMG and MMG power spectrum (purpose was to calculate the MNF based on the equation described by Kwatney *et al.* [1970]). Lastly, sEMG and MMG signal processing was performed with two separate, custom programs written with LabVIEW programming software (version 7.1, National Instruments, Austin, TX).

3.12. Muscle Cross-Sectional Area and Specific Tension

The CSA of the trained and untrained arms were determined by the technique of estimating CSA from skinfolds and circumference measurements (Moritani & deVries, 1979). Specifically, this method involved estimating the CSA with the following equation:

$$\mathrm{CSA} = \pi \left[\frac{\mathrm{Circumference}}{2\pi} - \frac{\sum_{i=1}^{4} \mathrm{skf_i}}{4} \right]^2,$$

where *Circumference* was the circumference of the upper arm, and *skf* were the upper arm skinfold thicknesses at each of the four sites (anterior, posterior, lateral, and medial). The circumference and skinfold measurements were taken along the mid-point between the acromion and olecranon processes.

The specific tension for dynamic strength of the trained and untrained arms were determined by the following equation:

Specific Tension = Dynamic Muscular Force / CSA,

where dynamic muscular force was the weight lifted during dynamic contractions, and CSA was determined by the CSA equation list above.

3.13. Statistical Analysis

Force steadiness was quantified by calculating the force fluctuations: the coefficient of variation (CV = [SD/mean] x 100%) of the force output from the middle portion (mid flat portion of the force output, corresponding to 30%, 50%, and 70% MVC) of each submaximal trapezoidal isometric muscle action.

A four-way (group [CON vs. ECC] x muscle [trained vs. untrained] x intensity [30% MVC vs. 50% MVC vs. 70% MVC] x time [week 0 {baseline or pre} vs. week 2 vs. week 4 vs. week 6 vs. week 8 {post}]) repeated measures ANOVAs was performed to analyze the EMG and MMG data. When appropriate, follow-up analyses included: three-way repeated measures ANOVAs, two-way repeated measures ANOVAs, one-way repeated measures ANOVAs, paired samples t-tests, bivariate correlation and Bonferroni post-hoc comparisons.

A bivariate correlation was used to investigate the relationship between the normalized MMG and EMG AMP and MNF values for the trained and untrained arms across time, and paired samples t-tests were used to determined statistical significance between pre- and post-values for skinfold and circumference measurements of the trained and untrained arms.

In addition, effect sizes were determined using Cohen's *d* and eta squared (η^2). Specifically, for determining Cohen's d we used the following equation,

$$d = (Y_1 - Y_2) / S_p,$$

where the numerator (Y_1 and Y_2) was the difference between two sample means and the denominator (S_p) was the pooled SD. Cohen's proposed standards were used for the interpretation of d (i.e., small effect size, $d = 0.2$; moderate effect size, $d = 0.5$; large effect size, $d = 0.8$). Furthermore, for determining eta squared we used the following equation,

$$\eta^2 = t^2 / (t^2 + df),$$

where the numerator was the squared *t*-test statistic value and the denominator was the sum of the squared *t*-test statistic value and the degrees of freedom (*df*). Cohen's proposed standards were also used for the interpretation of eta squared (small effect size, $\eta^2 = 0.01$; moderate effect size, $\eta^2 = 0.06$; large effect size, $\eta^2 = 0.14$). All signal processing were performed with a custom program written with LabVIEW programming software (v. 7.1, National Instruments, Austin, TX). Moreover, all statistical analyses were performed using the SPSS v. 22 for Windows, with a critical alpha of $p \leq 0.05$.

Chapter IV

Results and Discussion

4.1. Descriptives

Twenty subjects participated in and completed this study. Of these 20 subjects, 10 were male and 10 were female. Furthermore, both genders were equally distributed into the two training groups (5 males and 5 females in the CON and ECC groups, respectively.

Table 1. Participant Group Characteristics

Variables	PRE-CON	PRE-ECC	POST-CON	POST-ECC
Age (yr)	23.8 ± 4.1	24.8 ± 4.6	23.8 ± 4.1	24.8 ± 4.6
Height (cm)	170.2 ± 8.2	172.0 ± 12.9	170.2 ± 8.2	172.0 ± 12.9
Weight (kg)	77.9 ± 12.0	81.4 ± 13.1	78.0 ± 12.1	80.8 ± 12.4
BMI (kg/m^2)	26.4 ± 3.8	27.4 ± 3.8	26.4 ± 3.9	27.3 ± 3.9
Trained Limb				
BB Skinfold (mm)	0.37 ± 0.18	0.49 ± 0.36	0.40 ± 0.11	0.47 ± 0.32
Med Skinfold (mm)	0.39 ± 0.17	0.51 ± 0.23	0.39 ± 0.13	0.50 ± 0.28
TB Skinfold (mm)	0.66 ± 0.33	0.88 ± 0.49	0.63 ± 0.20	0.79 ± 0.39
Lat Skinfold (mm)	0.70 ± 0.31	1.06 ± 0.43	0.66 ± 0.19	0.86 ± 0.35
Circumference (cm)	30.32 ± 5.02*	31.80 ± 3.10*	31.75 ± 5.19*	34.23 ± 2.85*
Untrained Limb				
BB Skinfold (mm)	0.35 ± 0.17	0.52 ± 0.36	0.41 ± 0.13	0.49 ± 0.30
Med Skinfold (mm)	0.39 ± 0.19	0.48 ± 0.24	0.40 ± 0.17	0.47 ± 0.25
TB Skinfold (mm)	0.67 ± 0.29	0.95 ± 0.49	0.62 ± 0.21	0.83 ± 0.42
Lat Skinfold (mm)	0.70 ± 0.34	1.05 ± 0.44	0.78 ± 0.22	0.84 ± 0.41
Circumference (cm)	29.64 ± 5.03*	31.69 ± 2.62*	30.80 ± 5.13*	33.45 ± 3.16*

* = significance from pre-to-post; ant = anterior; bb = biceps brachii; con = concentric; cm = centimeters; ecc = eccentric; kg = kilograms; lat = lateral; m = meter; med = medial; mm = millimeter; pre = week 0 (baseline) values; post = week 8 values; tb = triceps brachii; yr = year

4.2. Training Volume

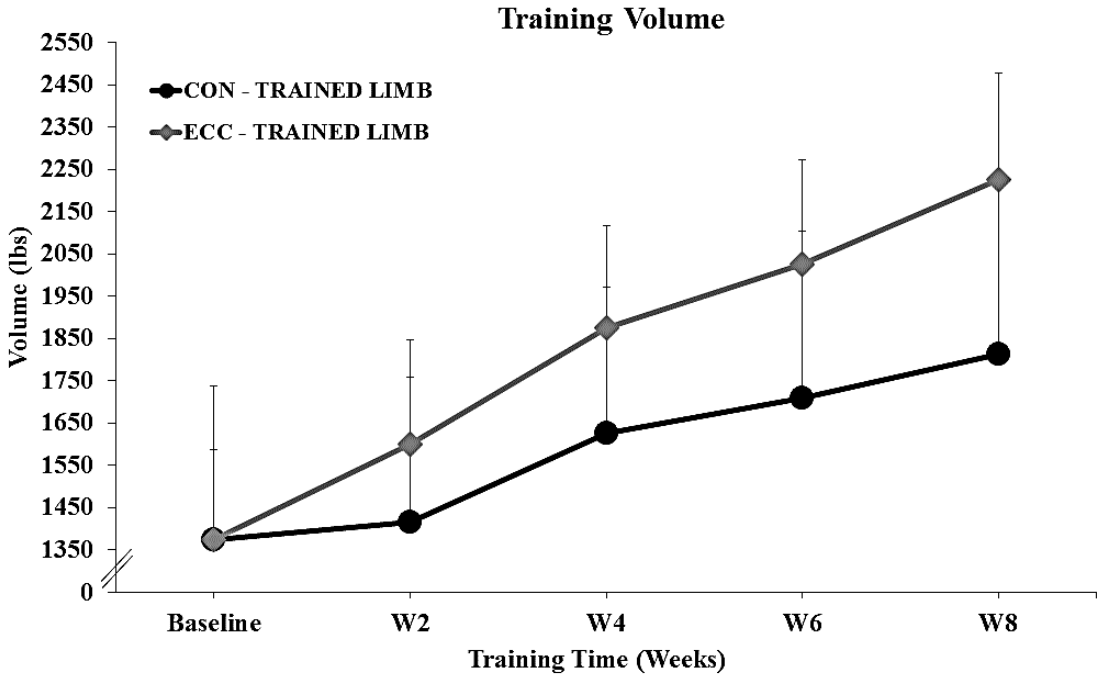


Figure 9. Changes in training volume from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the black line with black circles at each time point, while the trained arm for the ECC group is depicted by the grey line with grey diamonds at each time point.

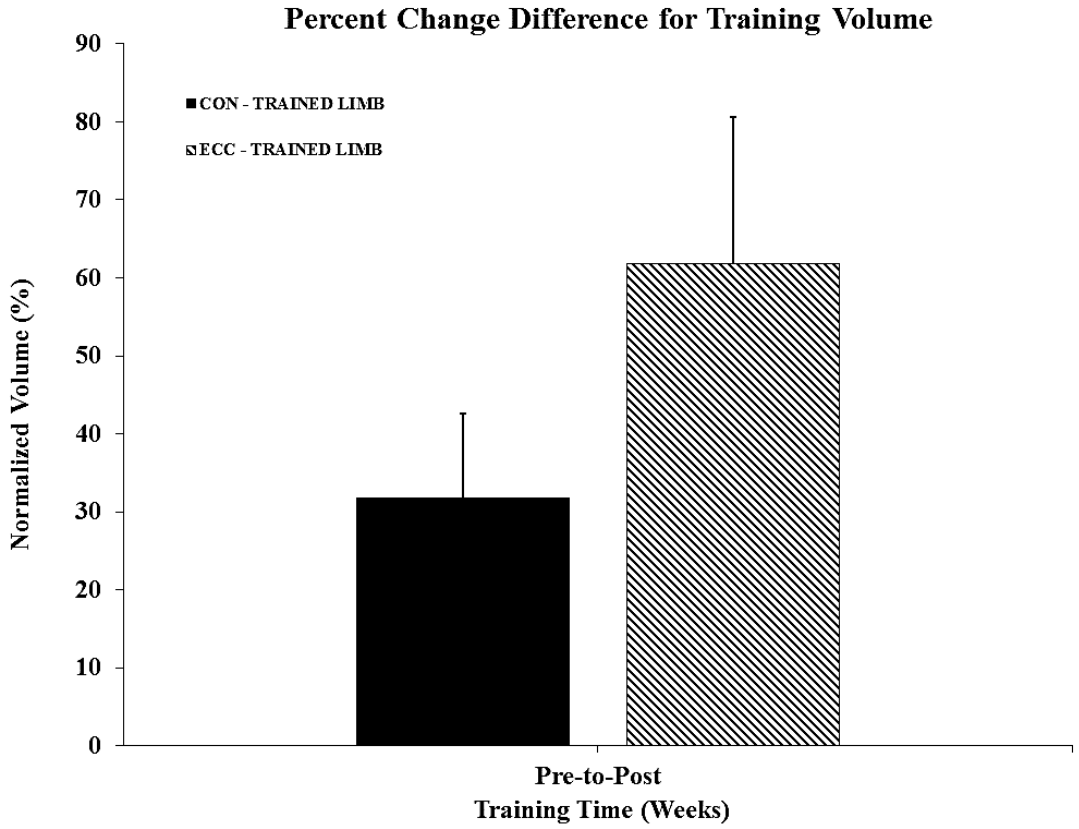


Figure 10. Percent change difference for normalized training volume from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post- measurements are shown on the graph. The trained arm for the CON group is depicted by a black rectangle (left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (right).

The results from the two-way repeated measures ANOVA for training volume indicated a statistically significant ($p < 0.050$) main effect for time ($p = < 0.001$ and $\eta^2 = 0.889$). For the main effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.745$). Follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 2. Paired Samples T-Test for Time – Training Volume for Trained Arm

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.001	0.53
Baseline vs. Week 4	< 0.001	1.21
Baseline vs. Week 6	< 0.001	1.14
Baseline vs. Week 8	< 0.001	1.71
Week 2 vs. Week 4	< 0.001	0.66
Week 2 vs. Week 6	< 0.001	0.91
Week 2 vs. Week 8	< 0.001	1.21
Week 4 vs. Week 6	< 0.001	0.27
Week 4 vs. Week 8	< 0.001	0.61
Week 6 vs. Week 8	< 0.001	0.32

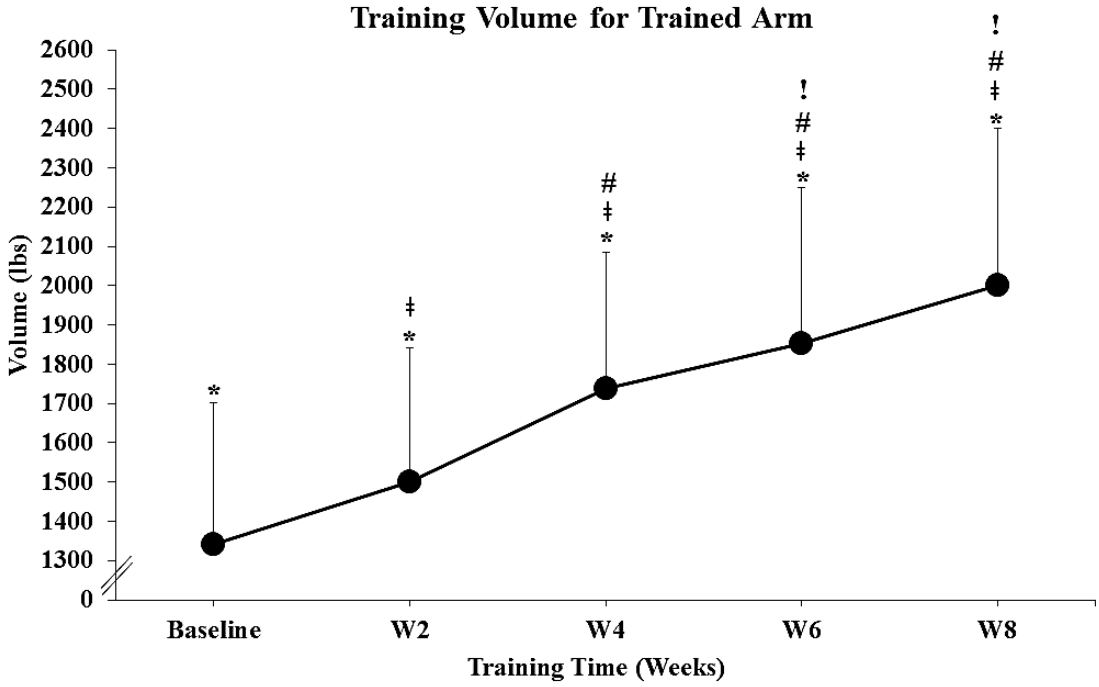


Figure 11. Changes in training volume from pre-measurements (W0 or baseline) to post-measurements (W8). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

4.3. Dynamic Strength

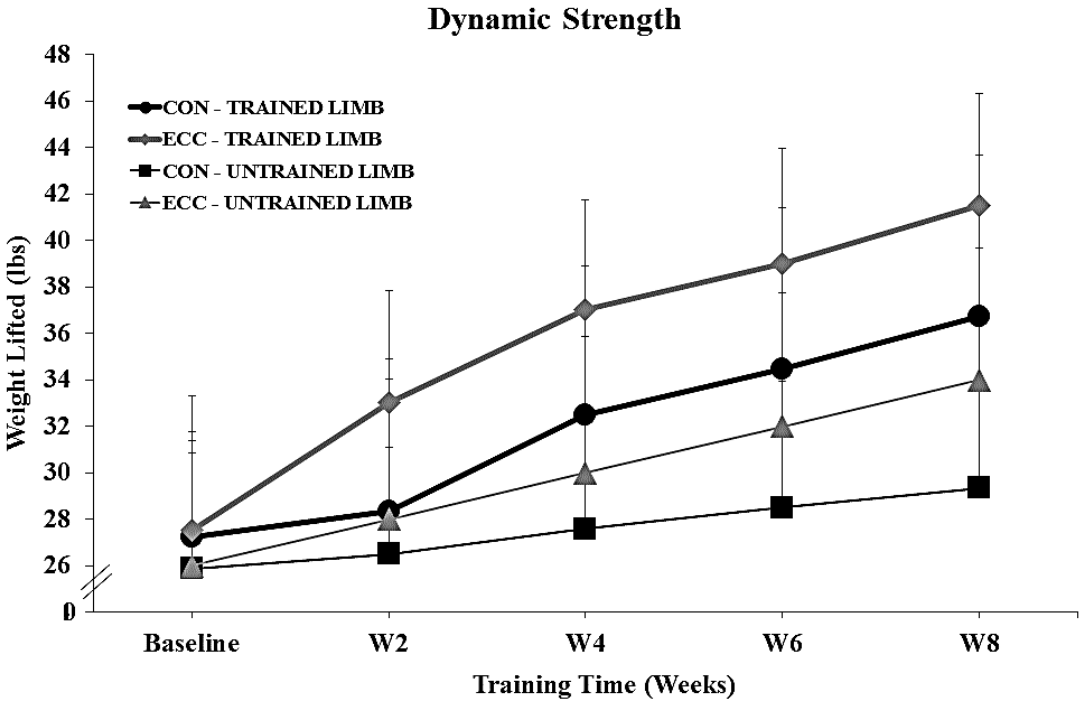


Figure 12. Changes in dynamic strength from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.

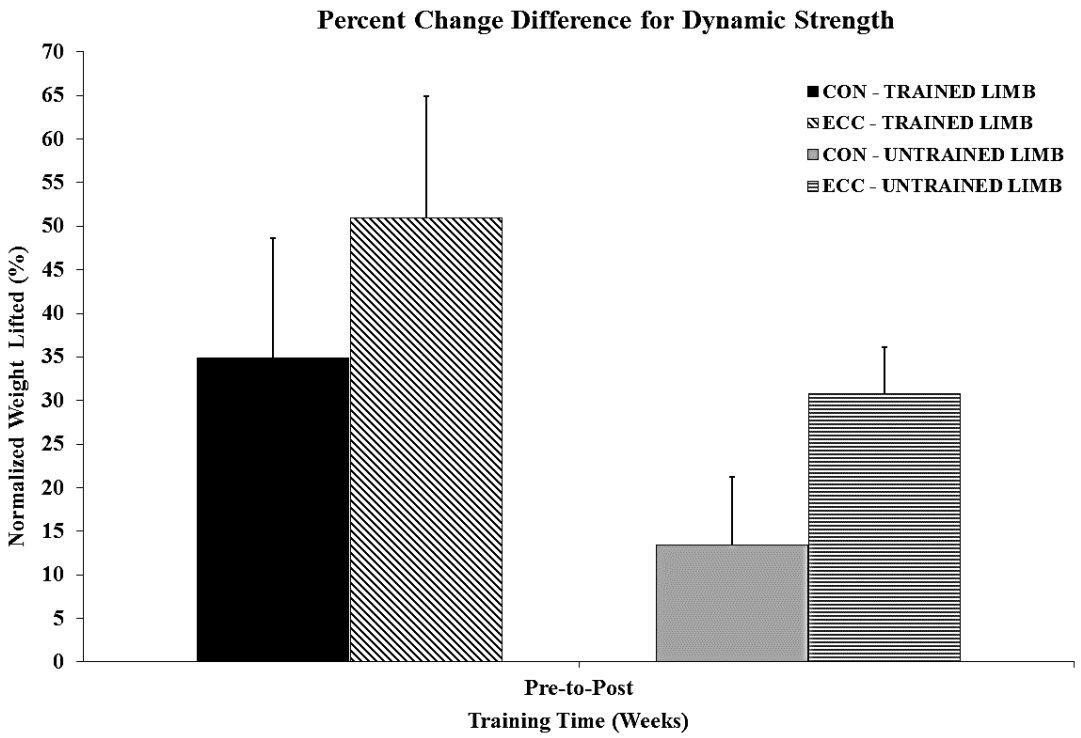


Figure 13. Percent change difference for normalized dynamic strength from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the three-way repeated measures ANOVA for dynamic strength indicated a statistically significant ($p < 0.050$) two-way interaction for group and time ($p = 0.025$ and $\eta^2 = 0.382$), and a main effect for time ($p = < 0.001$ and $\eta^2 = 0.951$). For the main effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.716$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following time points:

Table 3. Paired Samples T-Test for Time – Dynamic Strength

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.48
Baseline vs. Week 4	< 0.001	0.97
Baseline vs. Week 6	< 0.001	1.28
Baseline vs. Week 8	< 0.001	1.52
Week 2 vs. Week 4	< 0.001	0.51
Week 2 vs. Week 6	< 0.001	0.81
Week 2 vs. Week 8	< 0.001	1.08
Week 4 vs. Week 6	< 0.001	0.31
Week 4 vs. Week 8	< 0.001	0.58
Week 6 vs. Week 8	< 0.001	0.28

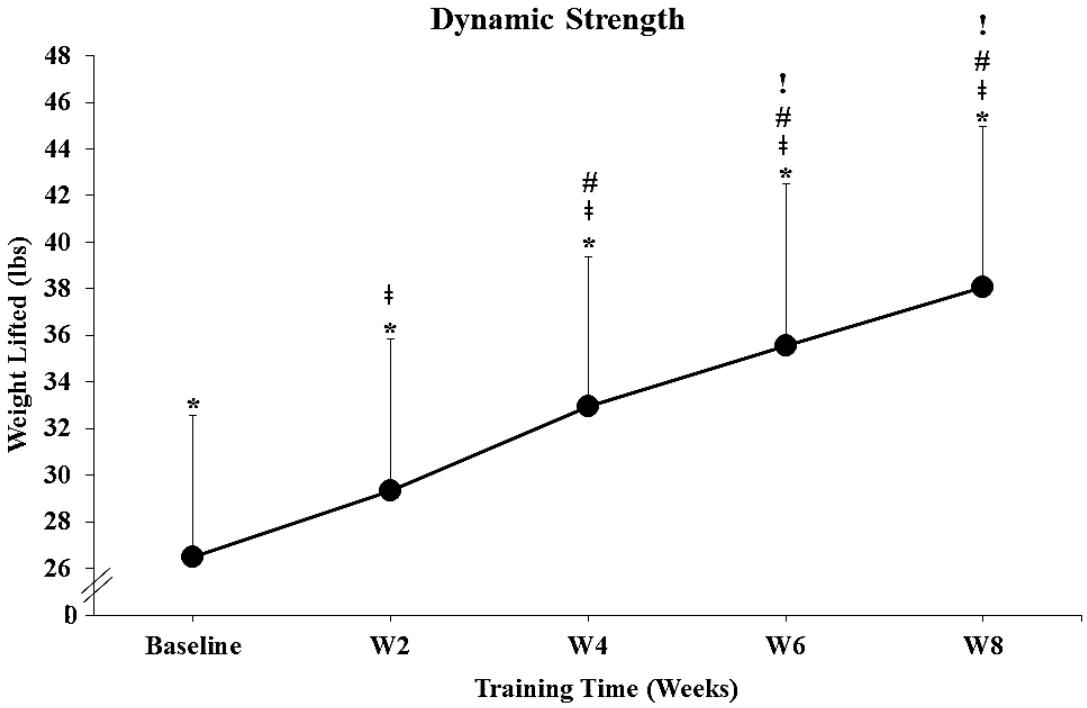


Figure 14. Changes in dynamic strength across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

As for the interaction between group and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant interaction for group and time ($p = 0.046$ and $\eta^2 =$

0.171). Two separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated a statistically significant mean difference across time for the CON ($p = < 0.001$ and $\eta^2 = 0.708$) and ECC ($p = < 0.001$ and $\eta^2 = 0.771$) groups, respectively. For the CON group, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 4. Paired Samples T-Test for Time – Group x Time Interaction – Dynamic Strength for Concentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.005	0.34
Baseline vs. Week 4	< 0.001	0.81
Baseline vs. Week 6	< 0.001	1.07
Baseline vs. Week 8	< 0.001	0.45
Week 2 vs. Week 4	< 0.001	0.72
Week 2 vs. Week 6	< 0.001	0.96
Week 2 vs. Week 8	< 0.001	0.29
Week 4 vs. Week 6	< 0.001	0.31
Week 4 vs. Week 8	< 0.001	0.51
Week 6 vs. Week 8	0.003	0.21

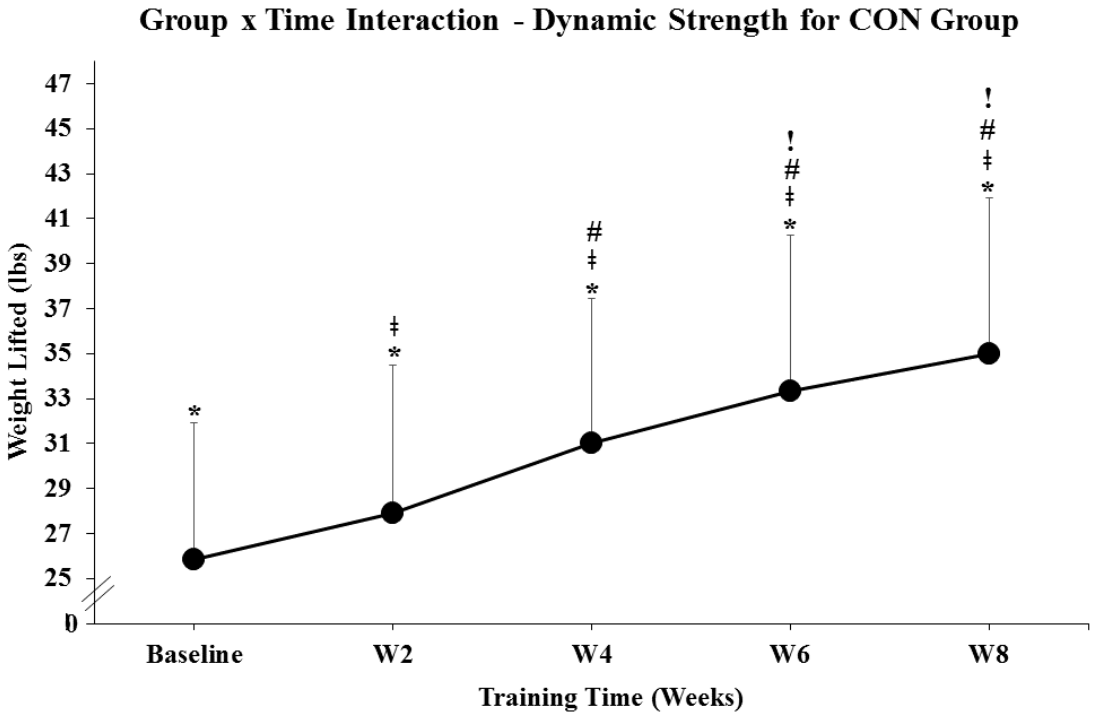


Figure 15. Changes in dynamic strength for concentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

For the ECC group, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 5. Paired Samples T-Test for Time – Group x Time Interaction – Dynamic Strength for Eccentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.68
Baseline vs. Week 4	< 0.001	1.21
Baseline vs. Week 6	< 0.001	1.61
Baseline vs. Week 8	< 0.001	1.87
Week 2 vs. Week 4	< 0.001	0.58
Week 2 vs. Week 6	< 0.001	0.98
Week 2 vs. Week 8	< 0.001	1.13
Week 4 vs. Week 6	< 0.001	0.36
Week 4 vs. Week 8	< 0.001	0.72
Week 6 vs. Week 8	< 0.001	0.38

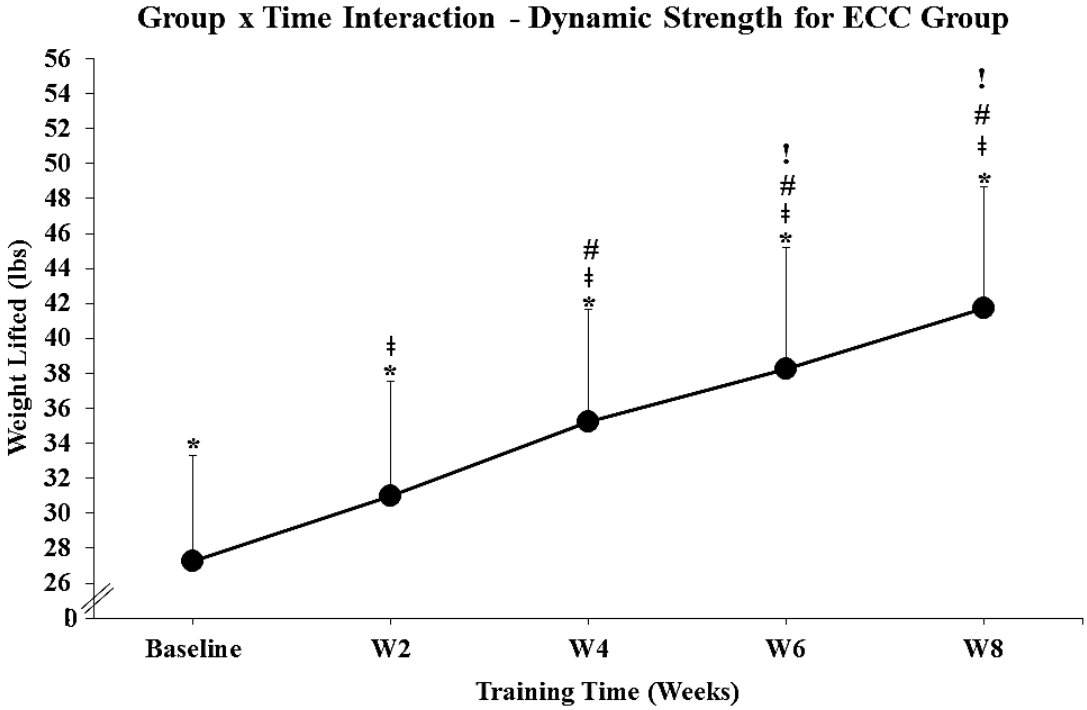


Figure 16. Changes in dynamic strength for eccentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

4.4. Isometric Strength

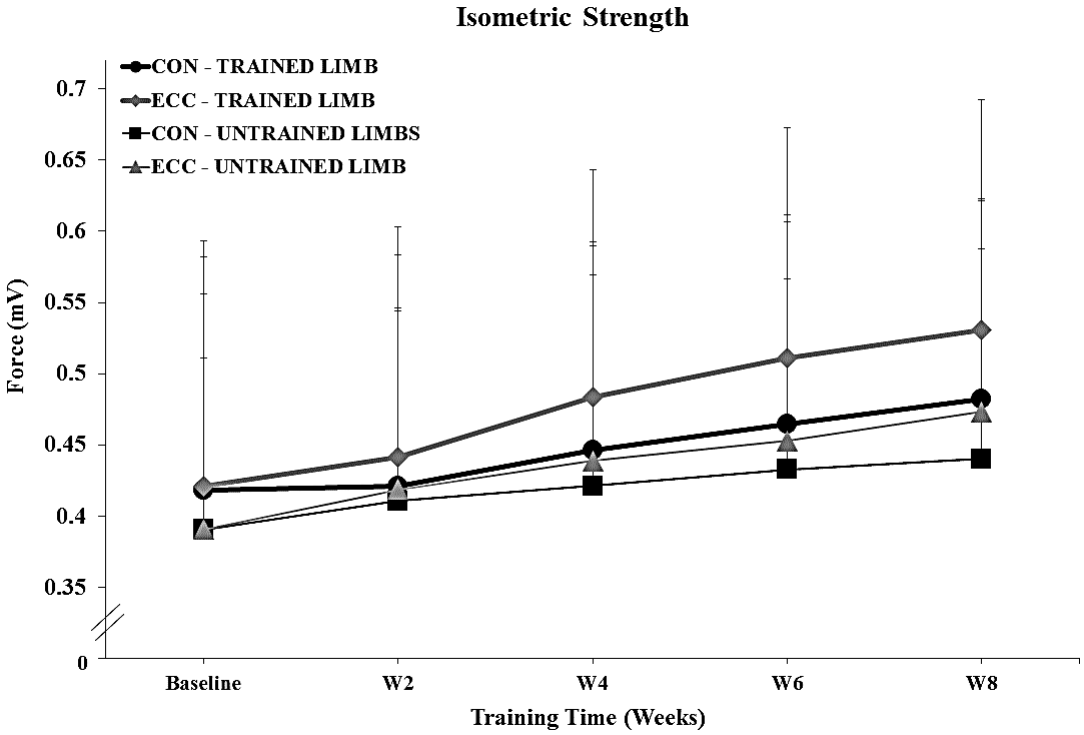


Figure 17. Changes in isometric strength from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.

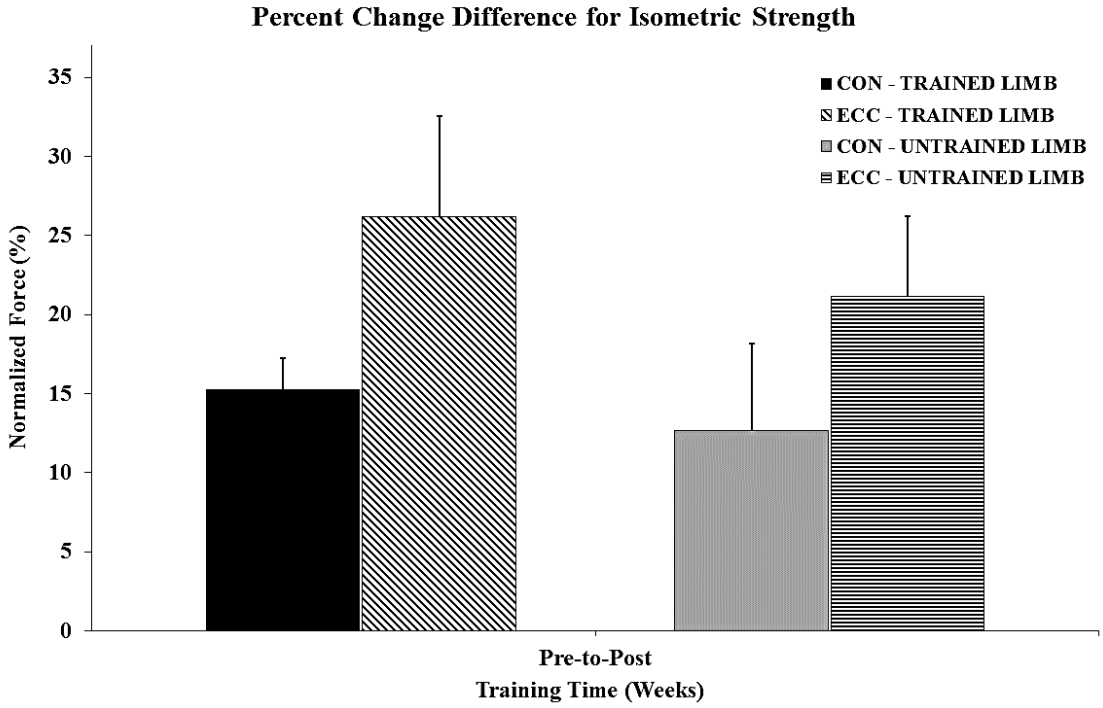


Figure 18. Percent change difference for normalized isometric strength from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the three-way repeated measures ANOVA for isometric strength indicated a statistically significant ($p < 0.050$) main effect for time ($p = 0.002$ and $\eta^2 = 0.598$). A one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.236$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following time points:

Table 6. Paired Samples T-Test for Time – Isometric Strength

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.022	0.27
Baseline vs. Week 4	0.009	0.33
Baseline vs. Week 6	< 0.001	0.48
Baseline vs. Week 8	< 0.001	0.52
Week 2 vs. Week 6	< 0.001	0.91
Week 2 vs. Week 8	< 0.001	0.23
Week 4 vs. Week 6	0.006	0.29
Week 4 vs. Week 8	0.002	0.51

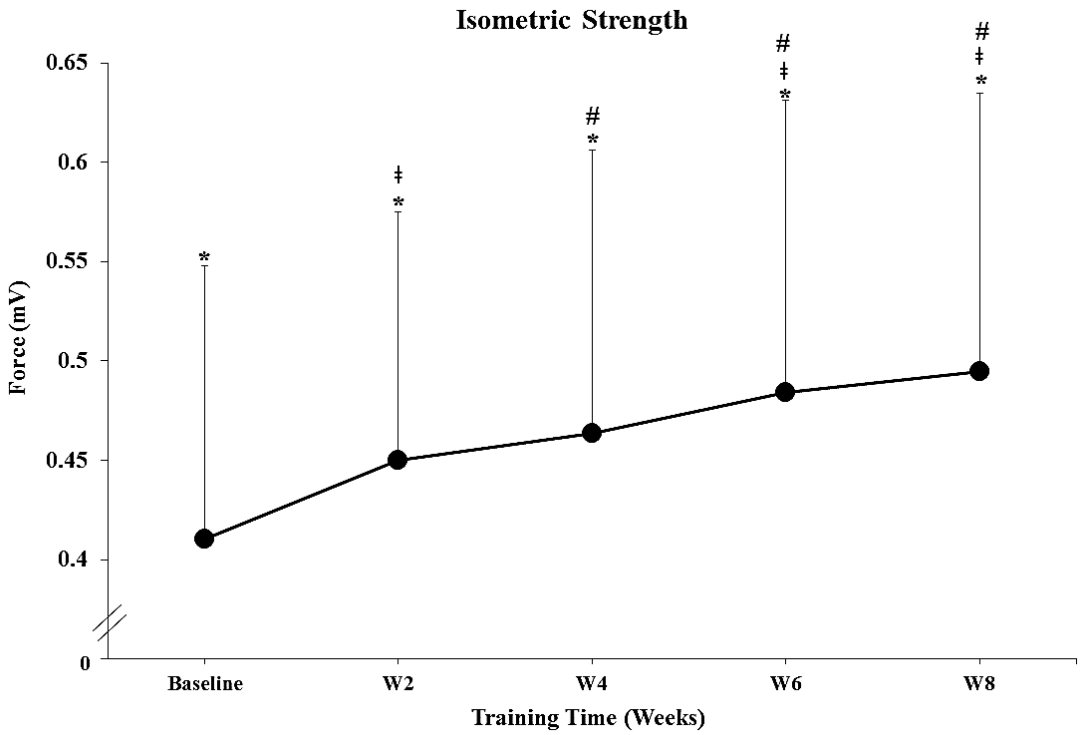


Figure 19. Changes in isometric strength across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

4.5. Specific Tension

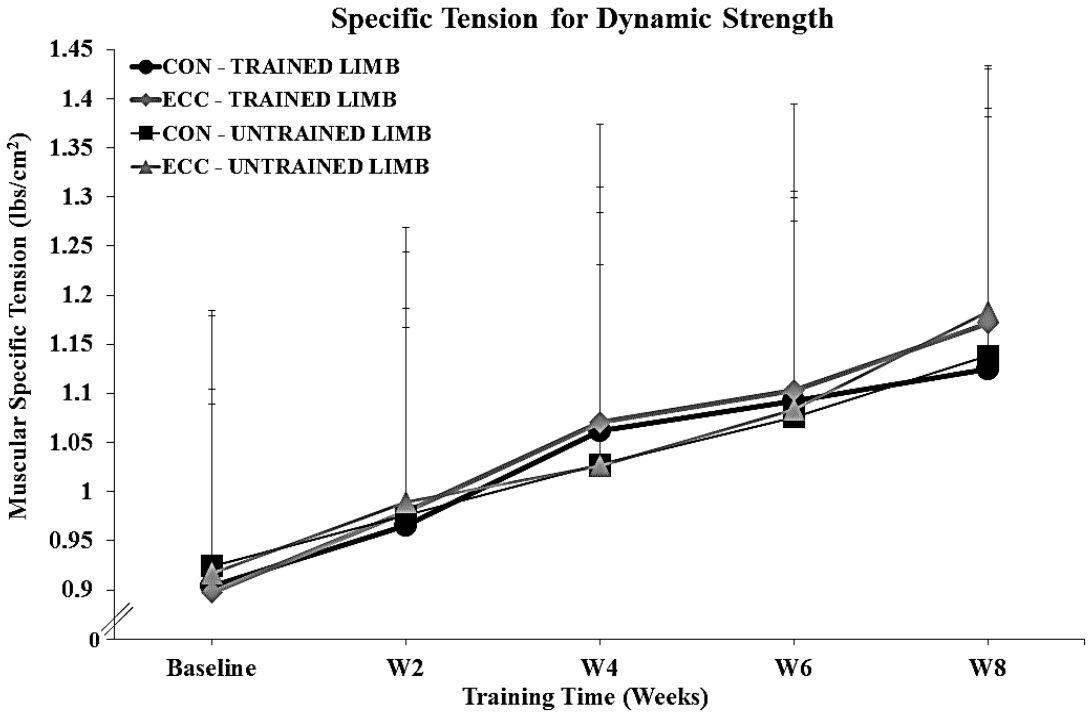


Figure 20. Changes in specific tension for dynamic strength from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.

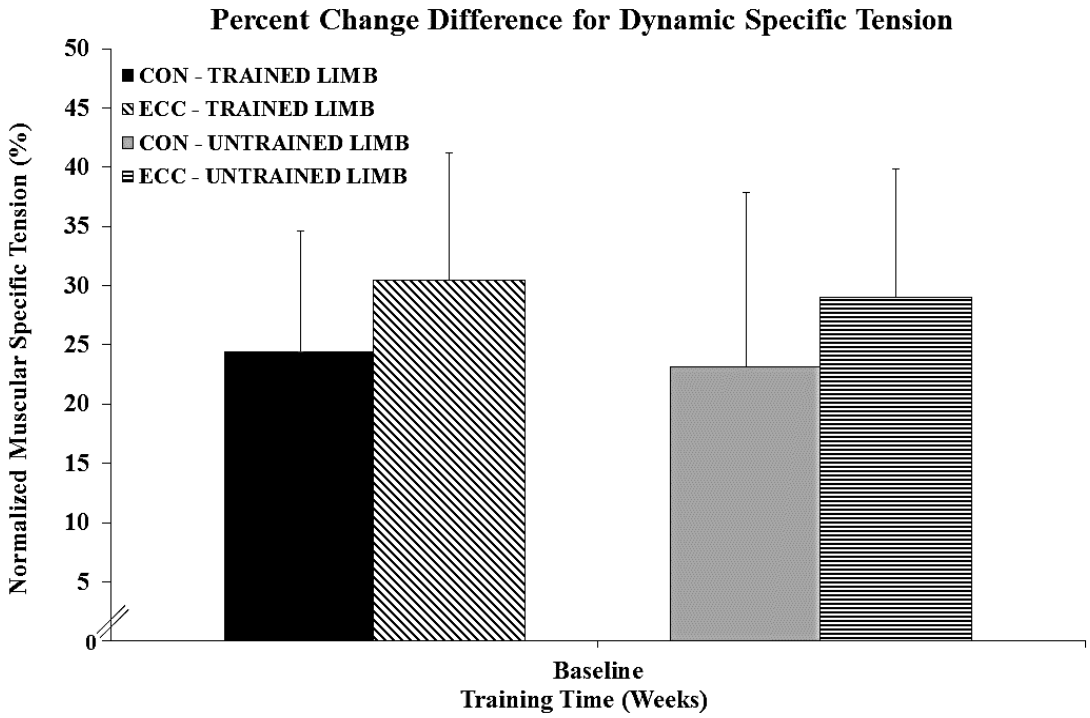


Figure 21. Percent change difference for normalized dynamic specific tension from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the three-way repeated measures ANOVA for dynamic specific tension indicated a statistically significant ($p < 0.050$) a main effect for time ($p = < 0.001$ and $\eta^2 = 0.860$). For the main effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.553$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following time points:

Table 7. Paired Samples T-Test for Time – Dynamic Specific Tension

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.19
Baseline vs. Week 4	< 0.001	0.41
Baseline vs. Week 6	< 0.001	0.57
Baseline vs. Week 8	< 0.001	0.68
Week 2 vs. Week 4	< 0.001	0.22
Week 2 vs. Week 6	< 0.001	0.37
Week 2 vs. Week 8	< 0.001	0.48
Week 4 vs. Week 6	< 0.001	0.16
Week 4 vs. Week 8	< 0.001	0.26
Week 6 vs. Week 8	< 0.001	0.19

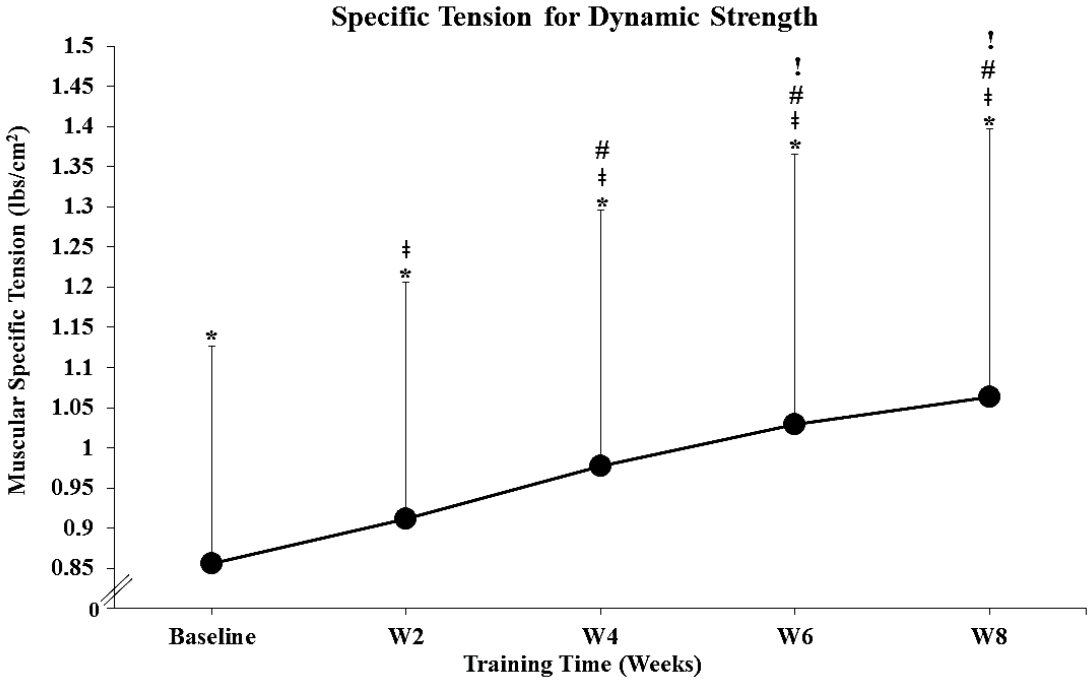


Figure 22. Changes in dynamic specific tension across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

4.6. Cross-Sectional Area

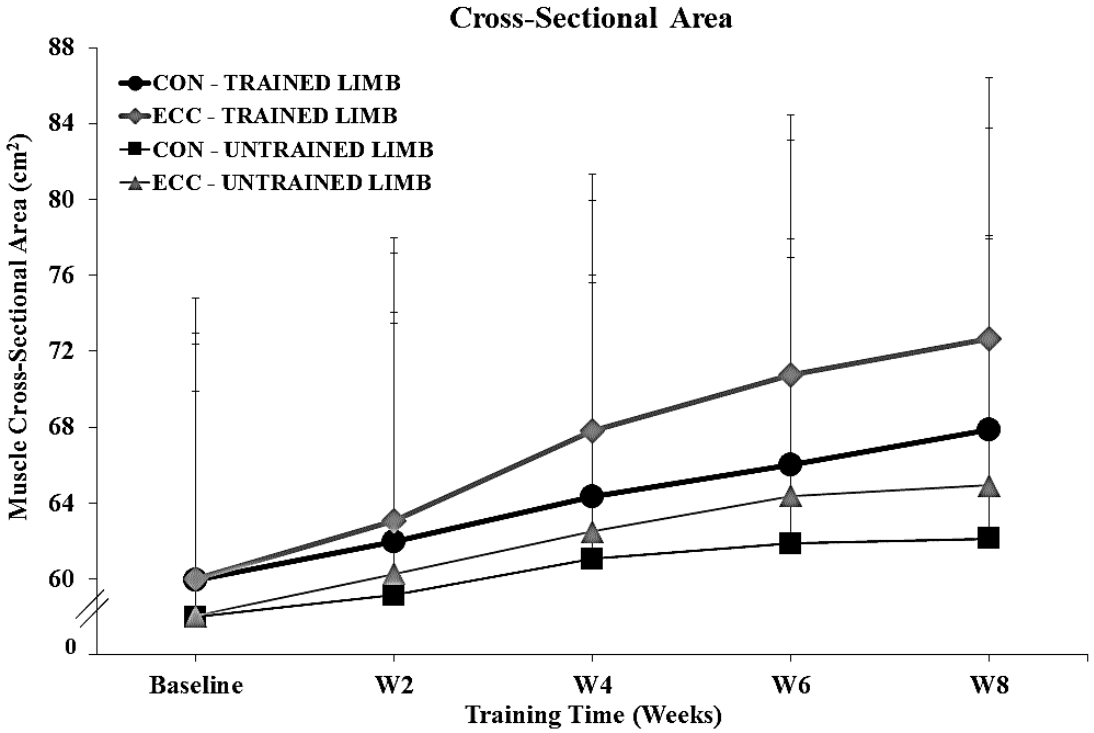


Figure 23. Changes in cross-sectional area from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.

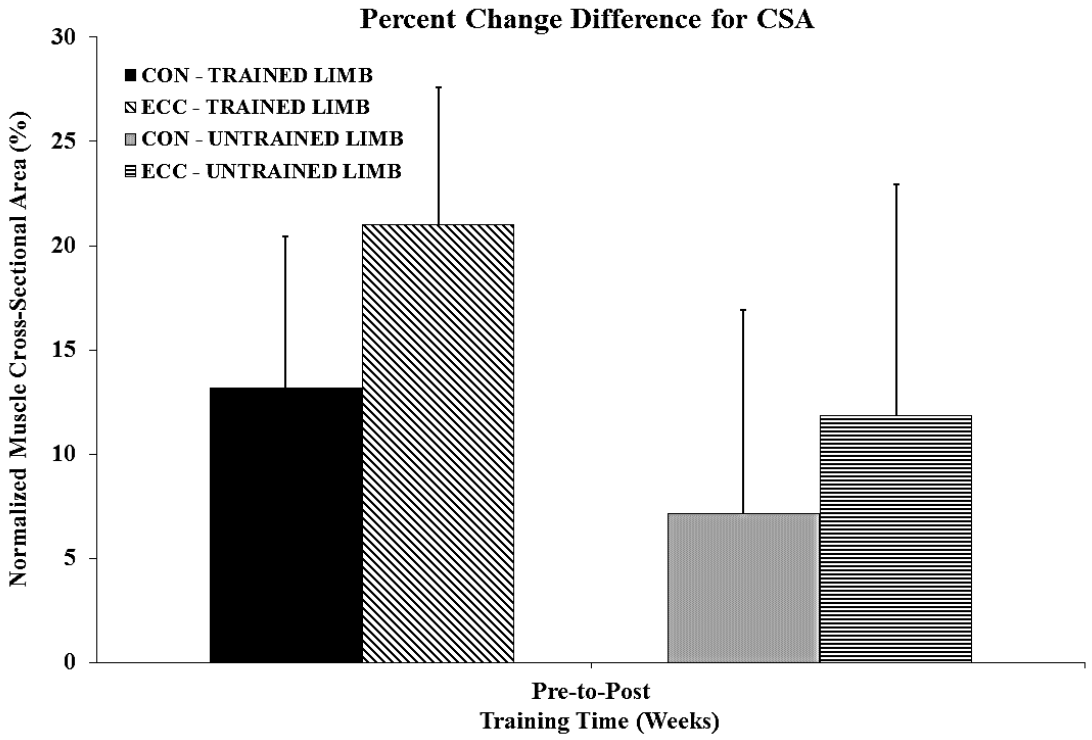


Figure 24. Percent change difference for normalized cross-sectional area from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the three-way repeated measures ANOVA for CSA indicated a statistically significant interaction for group and time ($p = < 0.001$ and $\eta^2 = 0.597$), and for arm and time ($p = 0.049$ and $\eta^2 = 0.329$). In addition, a main effect for arm ($p = 0.002$ and $\eta^2 = 0.666$) and for time ($p = < 0.001$ and $\eta^2 = 0.901$) was also found. For the main effect for arm, a follow-up paired samples t-test was considered appropriate to be performed, and the results indicated a statistically significant mean difference between arms ($p = < 0.001$ and $d = 0.17$). For the main effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a significant mean difference across time ($p = 0.003$ and $\eta^2 = 0.655$).

Follow-up paired samples t-tests were performed and the results indicated significant mean differences between the following time points:

Table 8. Paired Samples T-Test for Time – Cross-Sectional Area

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.12
Baseline vs. Week 4	< 0.001	0.25
Baseline vs. Week 6	< 0.001	0.34
Baseline vs. Week 8	< 0.001	0.42
Week 2 vs. Week 4	< 0.001	0.13
Week 2 vs. Week 6	< 0.001	0.22
Week 2 vs. Week 8	< 0.001	0.29
Week 4 vs. Week 6	< 0.001	0.81
Week 4 vs. Week 8	< 0.001	0.16
Week 6 vs. Week 8	< 0.001	0.71

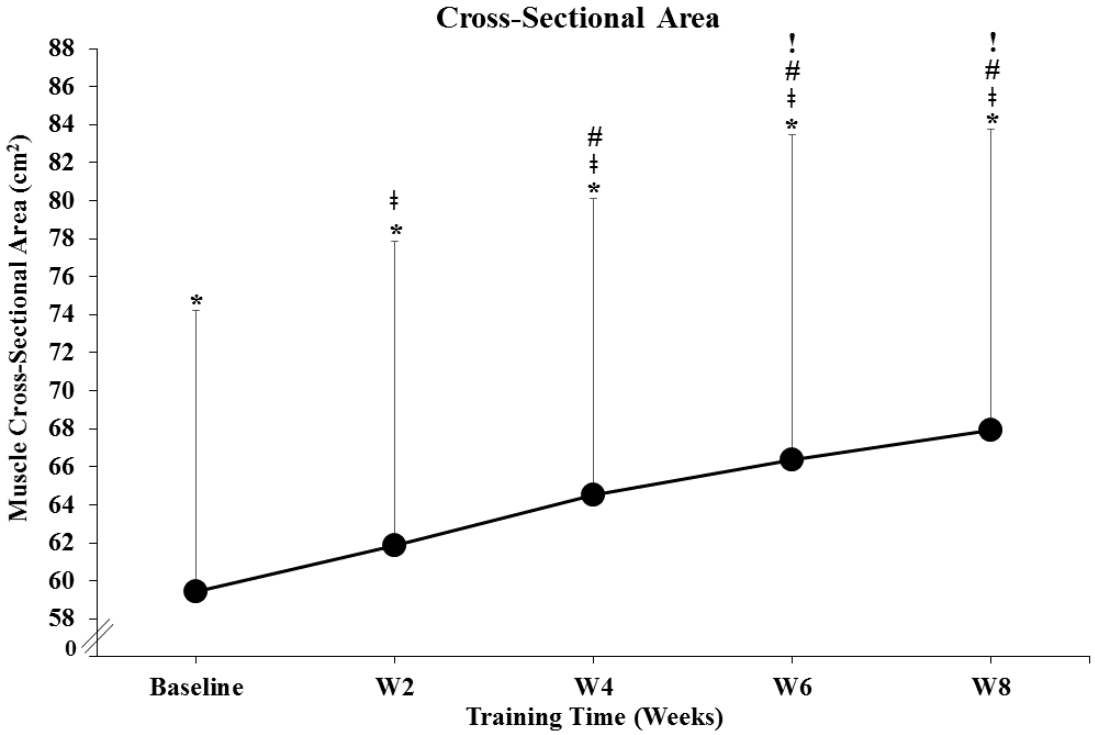


Figure 25. Changes in cross-sectional area across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

As for the interaction between group and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparison was performed and the results indicated a statistically significant interaction for group and time ($p = < 0.001$ and $\eta^2 = 0.089$). Two separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated a statistically significant mean difference across time for the CON ($p = < 0.001$ and $\eta^2 = 0.444$) and ECC ($p = < 0.001$ and $\eta^2 = 0.814$) groups, respectively. For the CON group, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 9. Paired Samples T-Test for Time – Group x Time Interaction – Cross-Sectional Area for Concentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.003	0.46
Baseline vs. Week 4	< 0.001	0.13
Baseline vs. Week 6	< 0.001	0.19
Baseline vs. Week 8	< 0.001	0.21
Week 2 vs. Week 4	< 0.001	0.61
Week 2 vs. Week 6	< 0.001	0.12
Week 2 vs. Week 8	< 0.001	0.15
Week 4 vs. Week 6	0.006	0.51
Week 4 vs. Week 8	0.001	0.81
Week 6 vs. Week 8	0.048	0.31

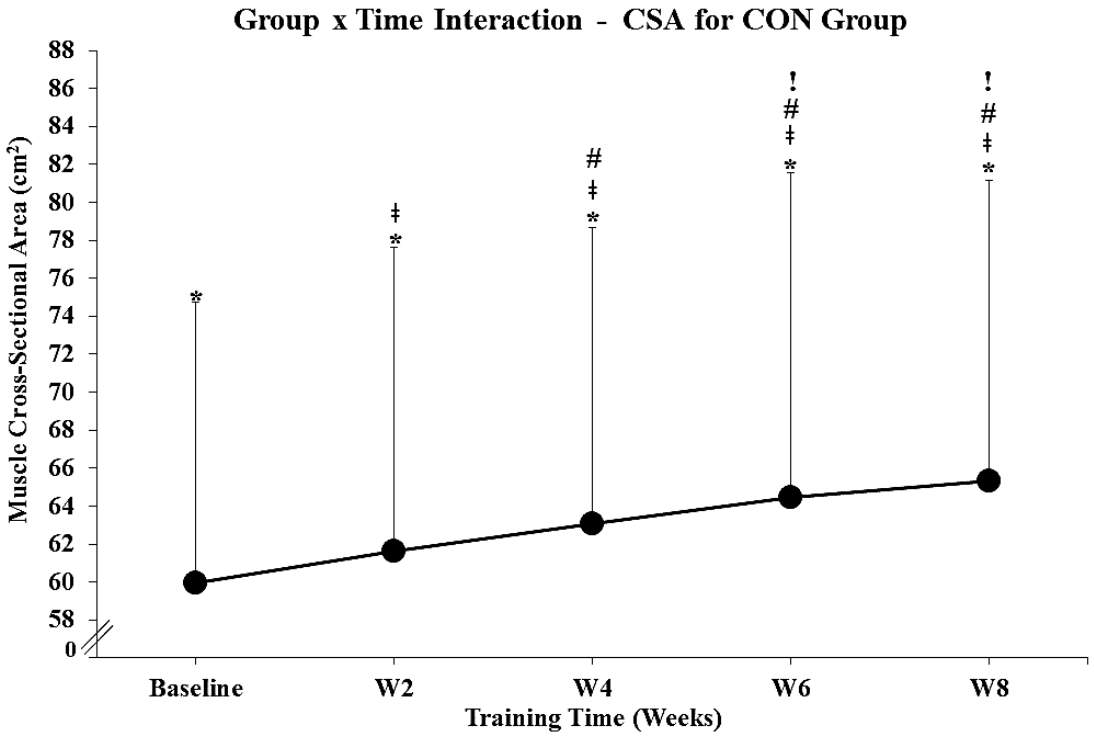


Figure 26. Changes in cross-sectional area for the concentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

For the ECC group, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 10. Paired Samples T-Test for Time – Group x Time Interaction – Cross-Sectional Area for Eccentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.001	0.27
Baseline vs. Week 4	< 0.001	0.57
Baseline vs. Week 6	< 0.001	0.73
Baseline vs. Week 8	< 0.001	0.96
Week 2 vs. Week 4	< 0.001	0.31
Week 2 vs. Week 6	< 0.001	0.47
Week 2 vs. Week 8	< 0.001	0.67
Week 4 vs. Week 6	< 0.001	0.17
Week 4 vs. Week 8	< 0.001	0.35
Week 6 vs. Week 8	< 0.001	0.17

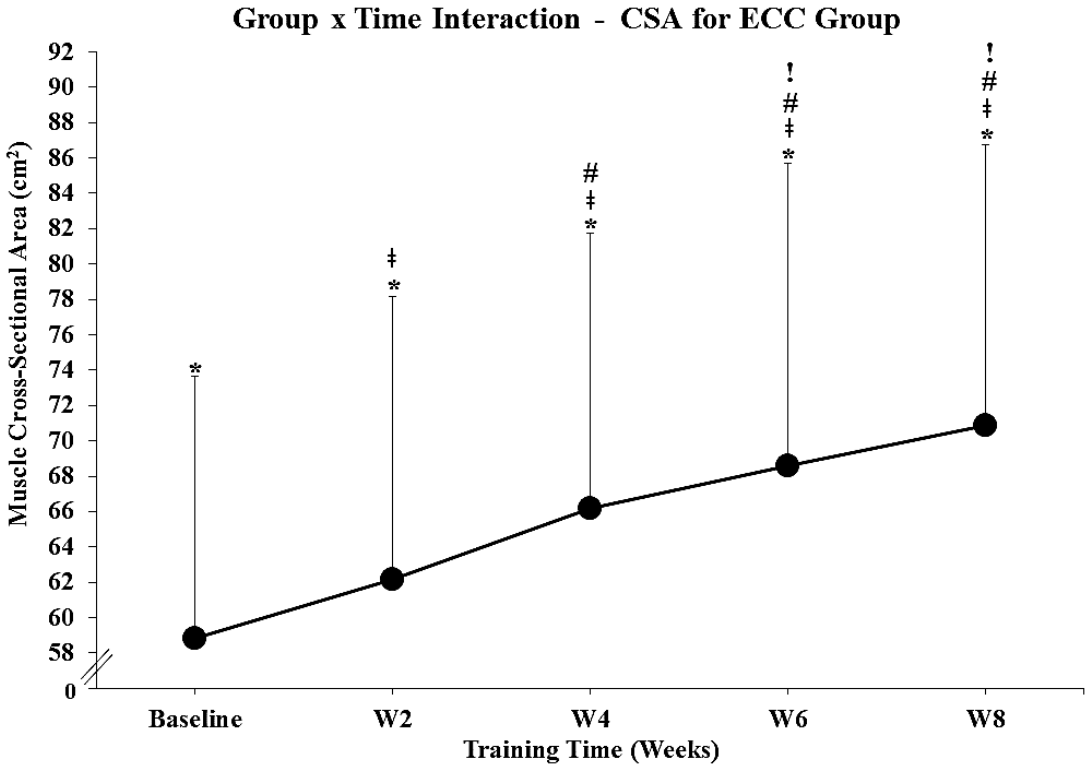


Figure 27. Changes in cross-sectional area for the eccentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

As for the interaction between arm and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant interaction for arm and time ($p = 0.001$ and $\eta^2 = 0.22$). Two separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated a statistically significant mean difference across time for the trained ($p = < 0.001$ and $\eta^2 = 0.75$) and untrained ($p = < 0.001$ and $\eta^2 = 0.566$) arms, respectively. For the trained arm, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 11. Paired Samples T-Test for Time – Arm x Time Interaction – Cross-Sectional Area for Trained Arm

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.13
Baseline vs. Week 4	< 0.001	0.31
Baseline vs. Week 6	< 0.001	0.41
Baseline vs. Week 8	< 0.001	0.48
Week 2 vs. Week 4	< 0.001	0.17
Week 2 vs. Week 6	< 0.001	0.27
Week 2 vs. Week 8	< 0.001	0.34
Week 4 vs. Week 6	0.001	0.15
Week 4 vs. Week 8	< 0.001	0.17
Week 6 vs. Week 8	0.008	0.62

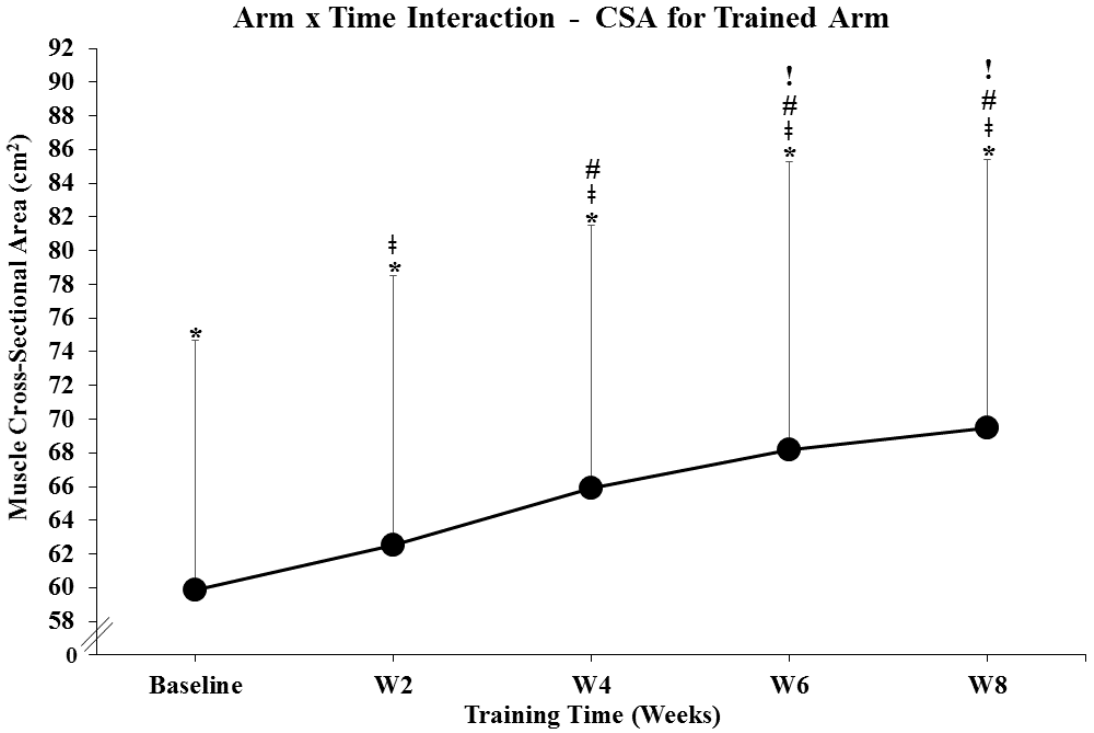


Figure 28. Changes in cross-sectional area for the trained arm across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

For the untrained arm, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 12. Paired Samples T-Test for Time – Arm x Time Interaction – Cross-Sectional Area for Untrained Arm

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.010	0.11
Baseline vs. Week 4	< 0.001	0.21
Baseline vs. Week 6	< 0.001	0.27
Baseline vs. Week 8	< 0.001	0.36
Week 2 vs. Week 4	0.010	0.99
Week 2 vs. Week 6	< 0.001	0.17
Week 2 vs. Week 8	< 0.001	0.25
Week 4 vs. Week 6	0.003	0.71
Week 4 vs. Week 8	< 0.001	0.15
Week 6 vs. Week 8	< 0.001	0.76

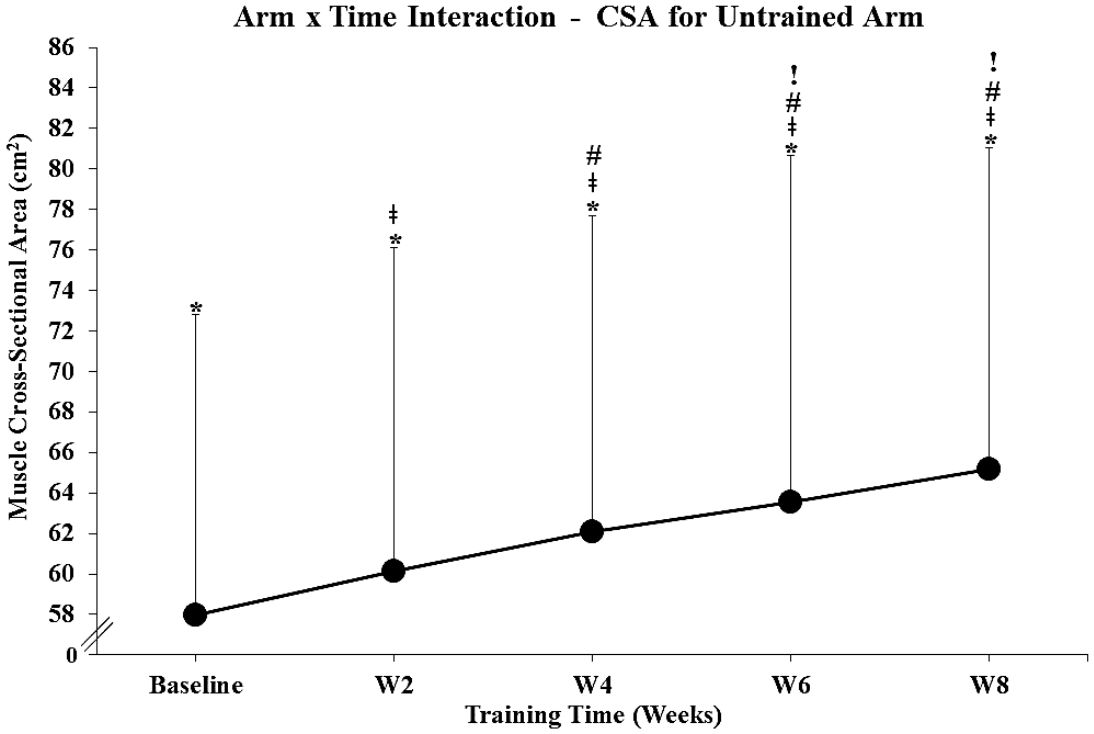
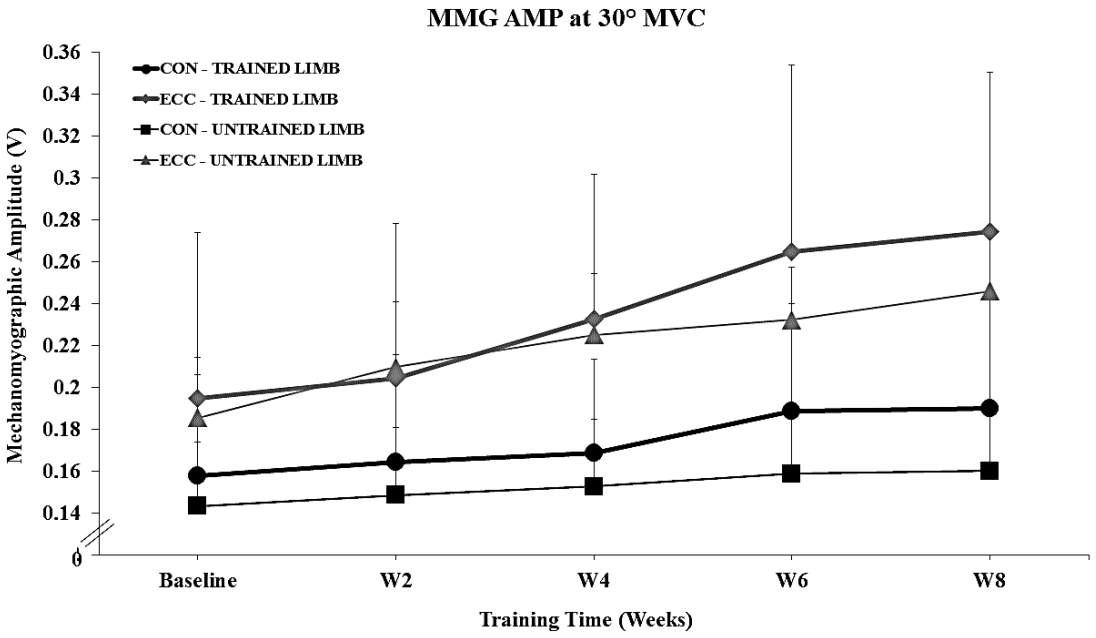
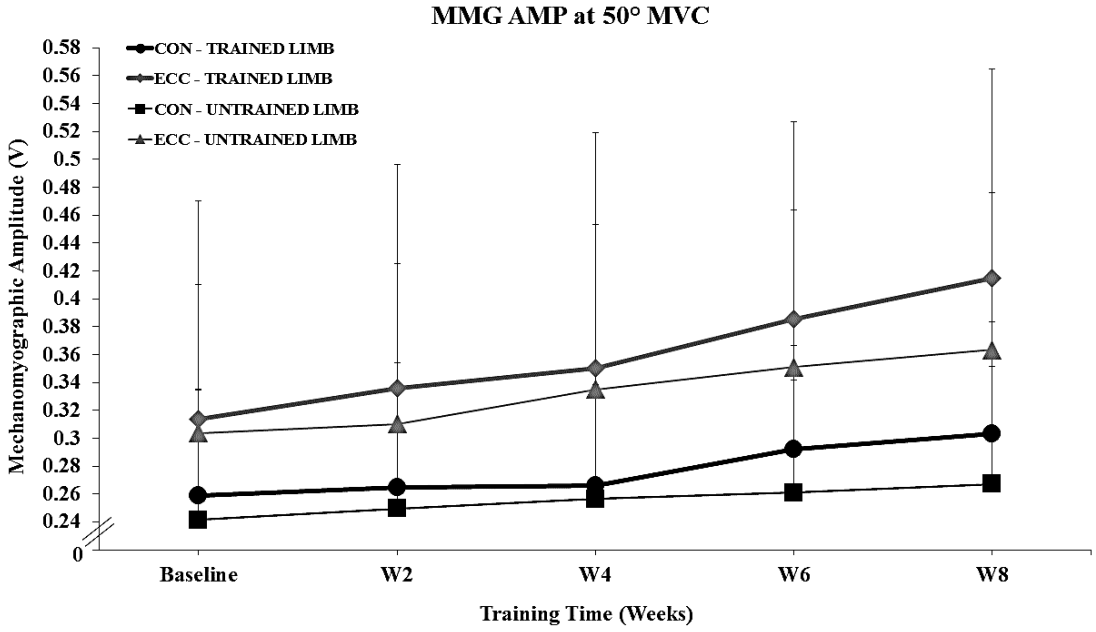


Figure 29. Changes in cross-sectional area for the untrained arm across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements; and an excamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

4.7. Mechanomyographic Amplitude





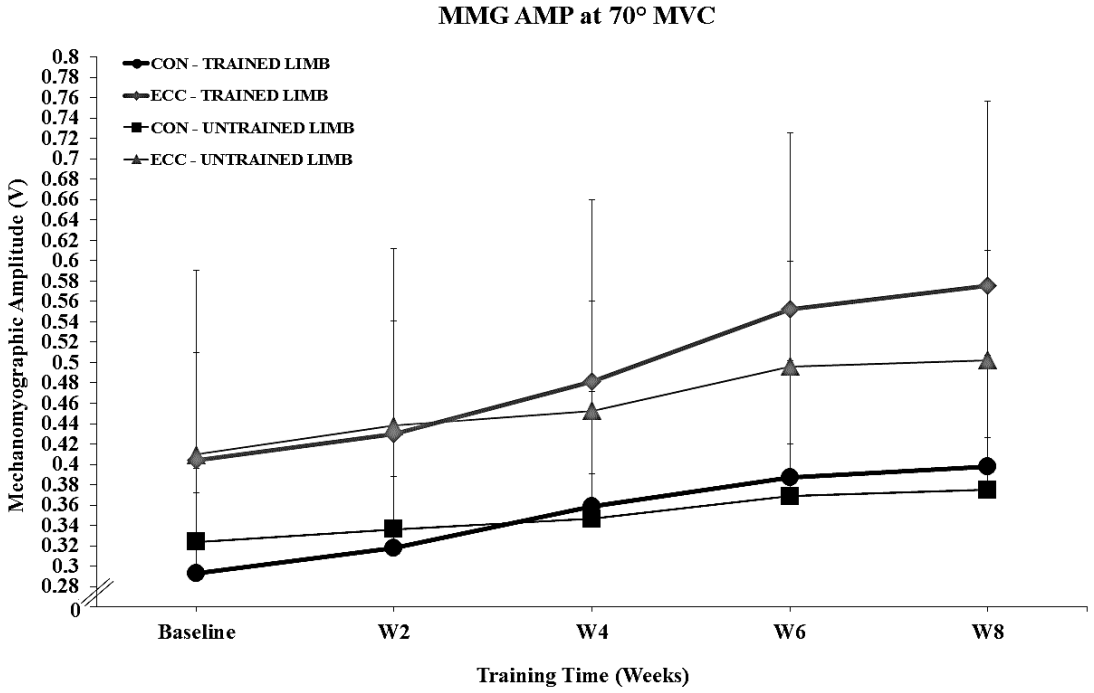
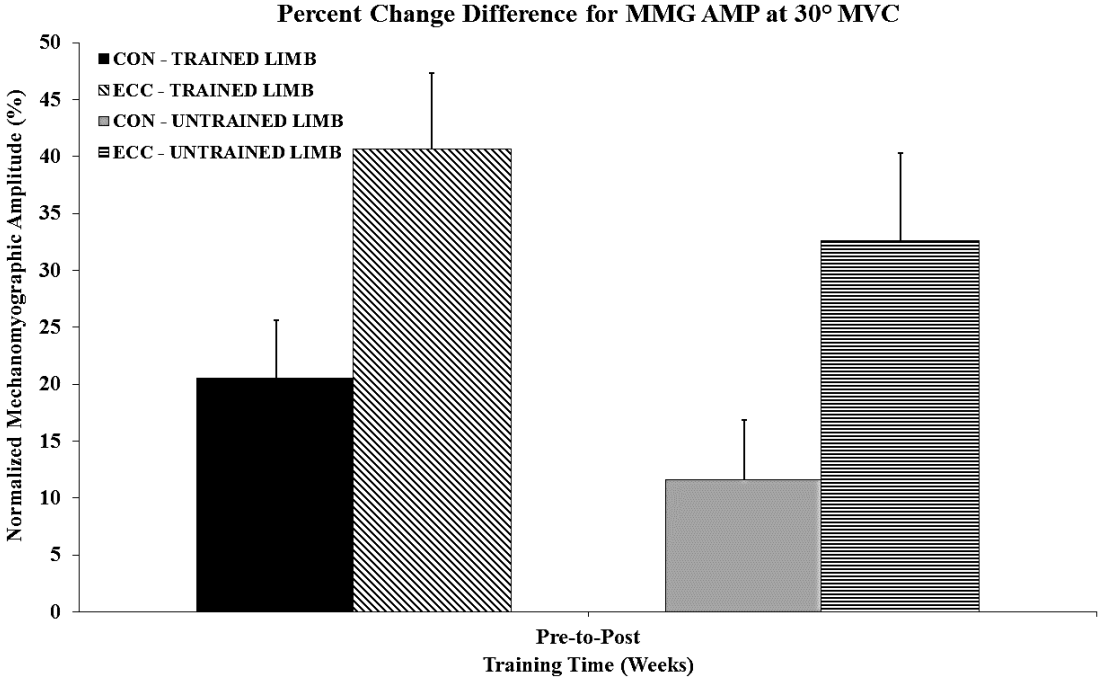
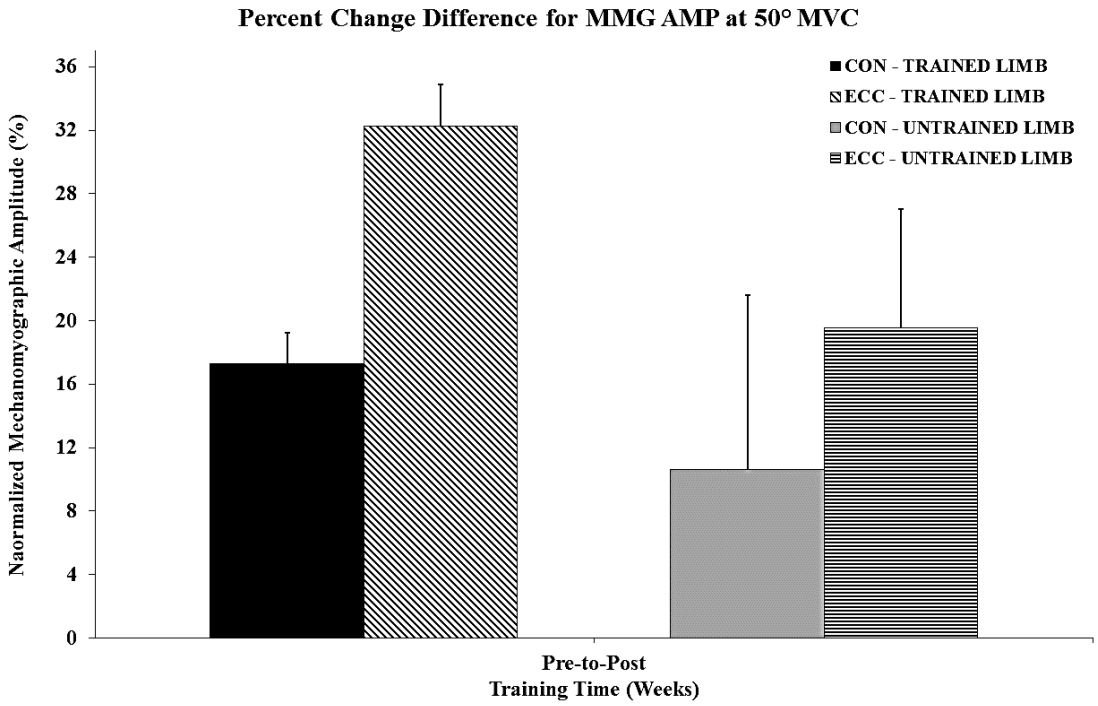


Figure 30. Changes in mechanomyographic amplitude at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.




Percent Change Difference for MMG AMP at 50° MVC
CON - TRAINED LIMB
ECC - TRAINED LIMB
CON - UNTRAINED LIMB
ECC - UNTRAINED LIMB
Naormalized Mechanomyographic Amplitude (%)
36
32
28
24
20
16
12
8
4
0
Pre-to-Post
Training Time (Weeks)

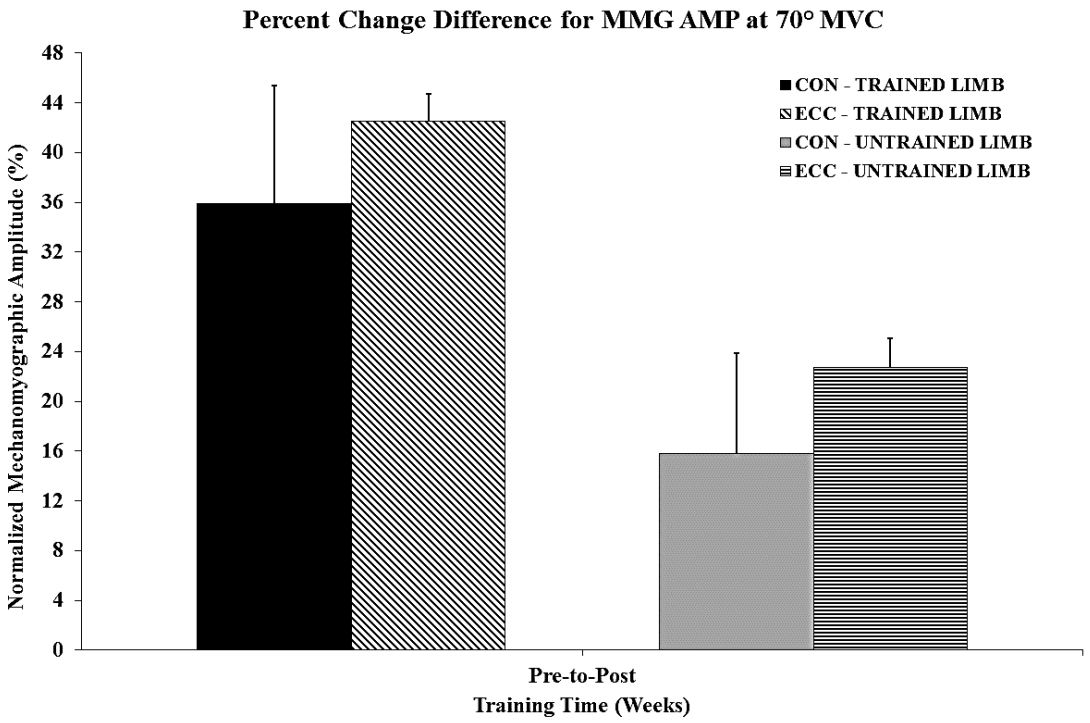


Figure 31. Percent change difference for normalized mechanomyographic amplitude at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the four-way repeated measures ANOVA for MMG AMP indicated a statistically significant two-way interaction for group and time ($p = 0.049$ and $\eta^2 = 0.333$), and a main effect for group ($p = 0.002$ and $\eta^2 = 0.683$) and intensity ($p = < 0.001$ and $\eta^2 = 0.938$), respectively. For the main effect for group, a follow-up paired samples t-test was considered appropriate to be performed and the results indicated a statistically significant mean difference between groups ($p = < 0.001$ and $d = 0.851$). For the main effect for intensity, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant difference across time ($p = < 0.001$ and $\eta^2 = 0.871$). Follow-up paired

samples t-tests were performed and the results indicated that there were significant mean differences between the following intensities:

Table 13. Paired Samples T-Test for Intensity – Mechanomyographic Amplitude

Intensity	P-value	Cohen's *d*
30% MVC vs. 50% MVC	< 0.001	1.48
30% MVC vs. 70% MVC	< 0.001	2.31
50% MVC vs. 70% MVC	< 0.001	1.07

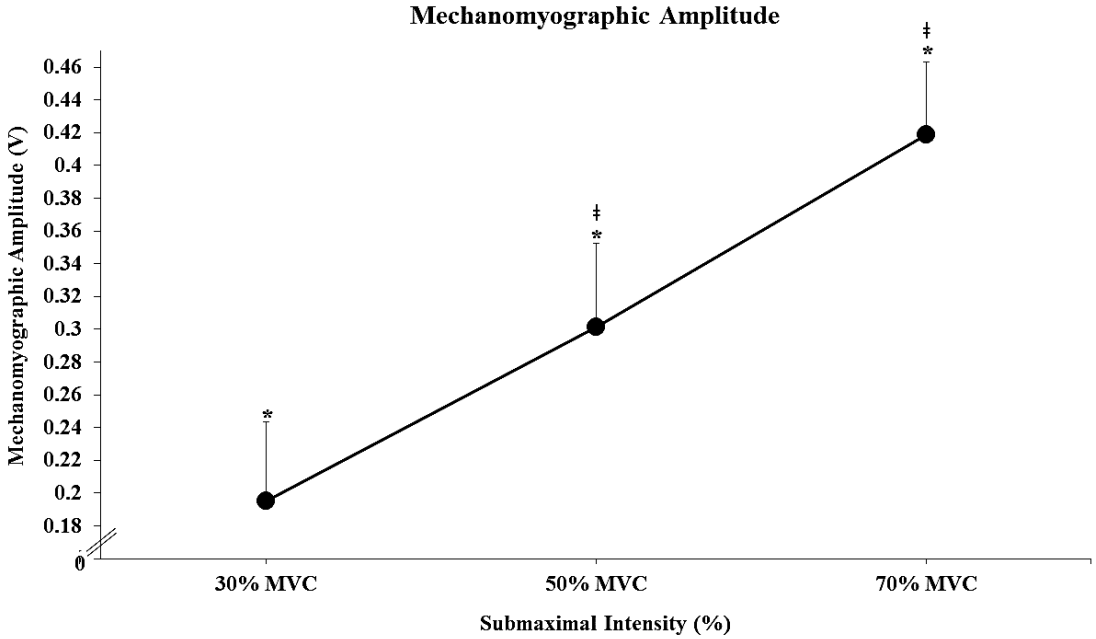


Figure 32. Changes in mechanomyographic amplitude across intensity (30% MVC to 70% MVC). An asterisk (*) signifys a significant difference between 30% MVC versus subsequent intensities; and a palatal click (ǂ) signifys a significant difference between 50% MVC versus subsequent intensities.

As for the interaction between group and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant interaction for group and time ($p = < 0.001$ and $\eta^2 = 0.089$), as well as a main effect for time ($p = < 0.001$ and $\eta^2 = 0.091$). For the main

effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = 0.003$ and $\eta^2 = 0.030$). Follow-up paired samples t-tests were performed and the results indicated significant mean differences between the following time points:

Table 14. Paired Samples T-Test for Time – Mechanomyographic Amplitude

Time	P-value	Cohen's *d*
Baseline vs. Week 6	0.030	0.17
Week 2 vs. Week 4	0.019	0.15
Week 2 vs. Week 6	0.001	0.23
Week 2 vs. Week 8	0.002	0.21

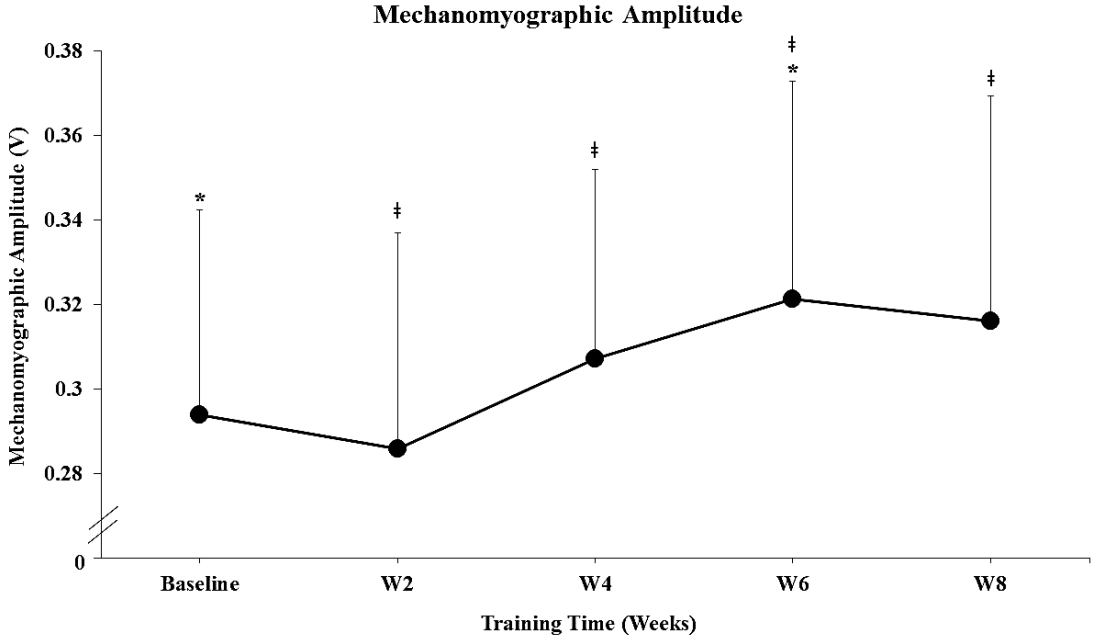


Figure 33. Changes in mechanomyographic amplitude across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

For the interaction between group and time, two separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the

results indicated a statistically significant mean difference across time for the ECC group only ($p = < 0.001$ and $\eta^2 = 0.142$). Follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 15. Paired Samples T-Test for Time – Group x Time Interaction – Mechanomyographic Amplitude for Eccentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 6	0.004	0.34
Baseline vs. Week 8	0.004	0.36
Week 2 vs. Week 4	0.002	0.31
Week 2 vs. Week 6	< 0.001	0.52
Week 2 vs. Week 8	< 0.001	0.53
Week 4 vs. Week 6	0.011	0.21
Week 4 vs. Week 8	0.014	0.22

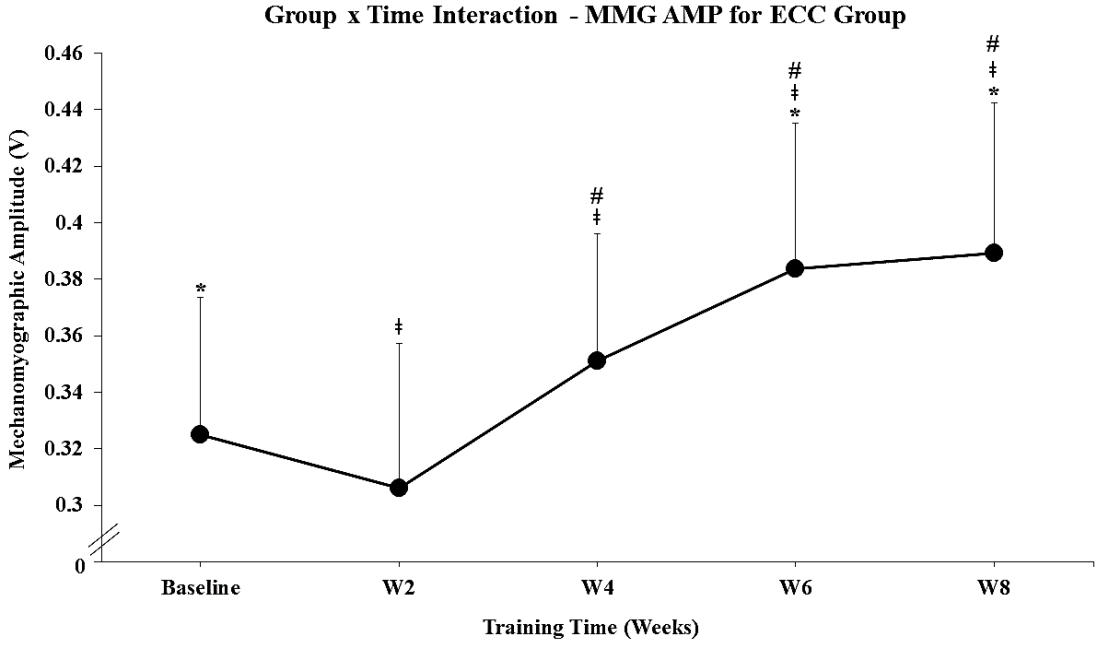
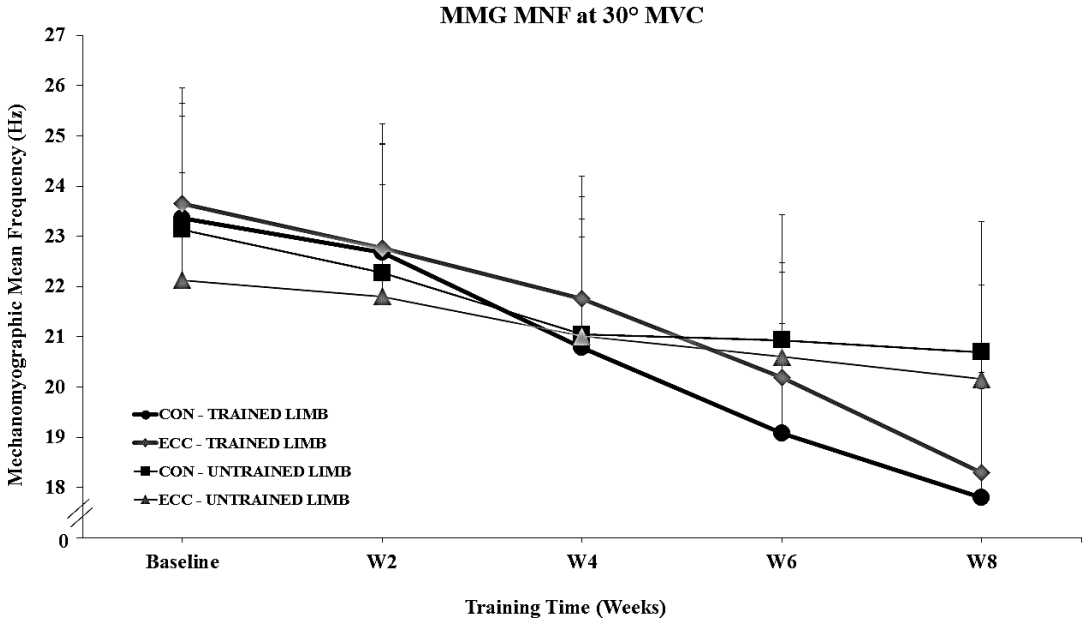
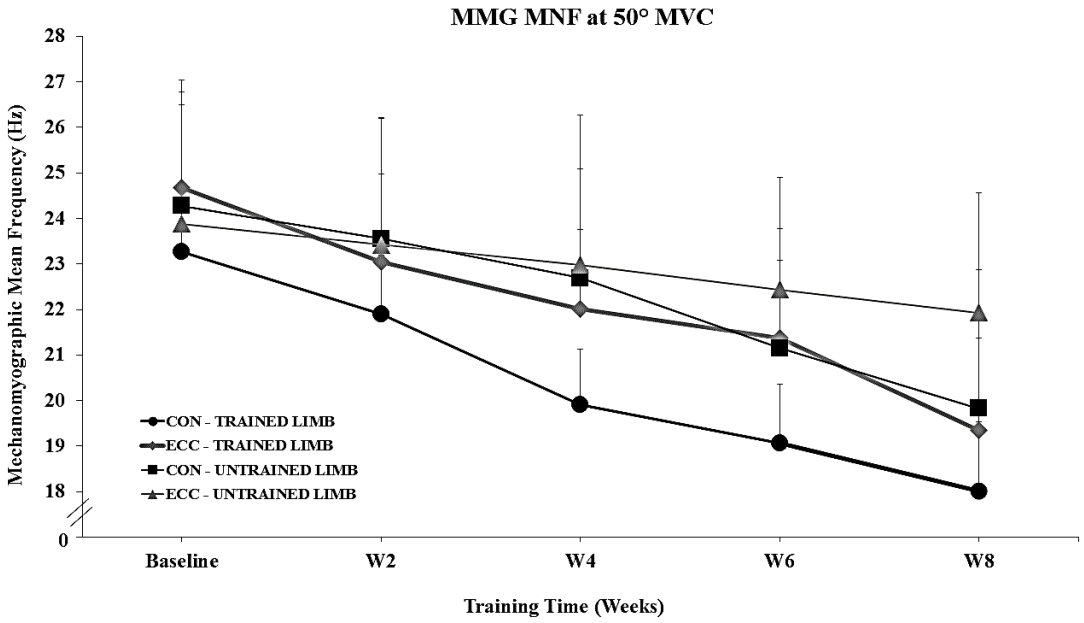


Figure 34. Changes in mechanomyographic amplitude for the eccentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

4.8. Mechanomyographic Mean Frequency





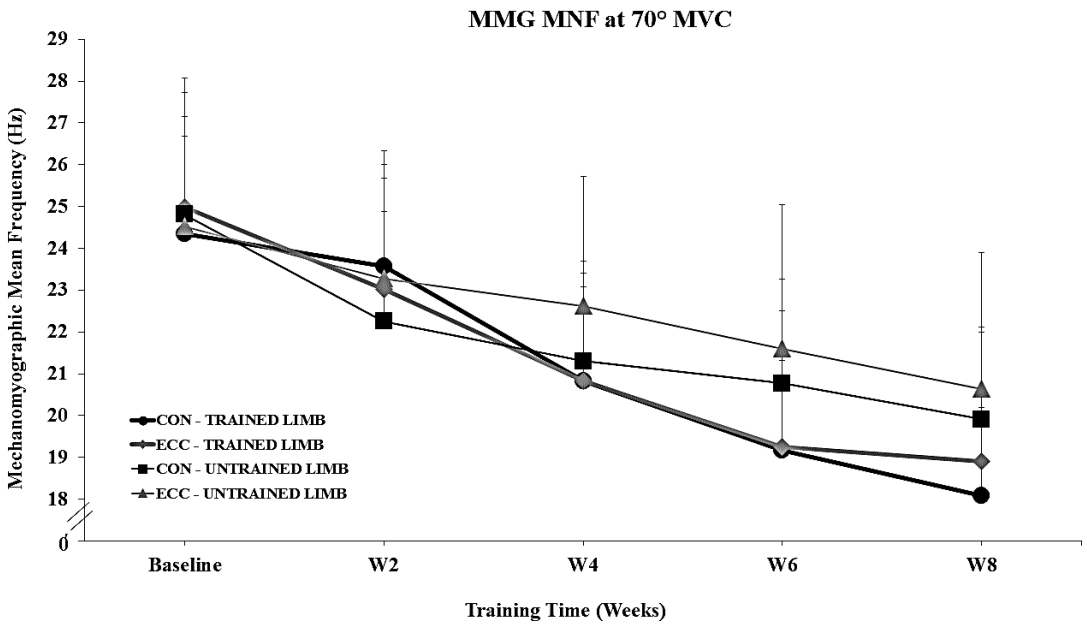
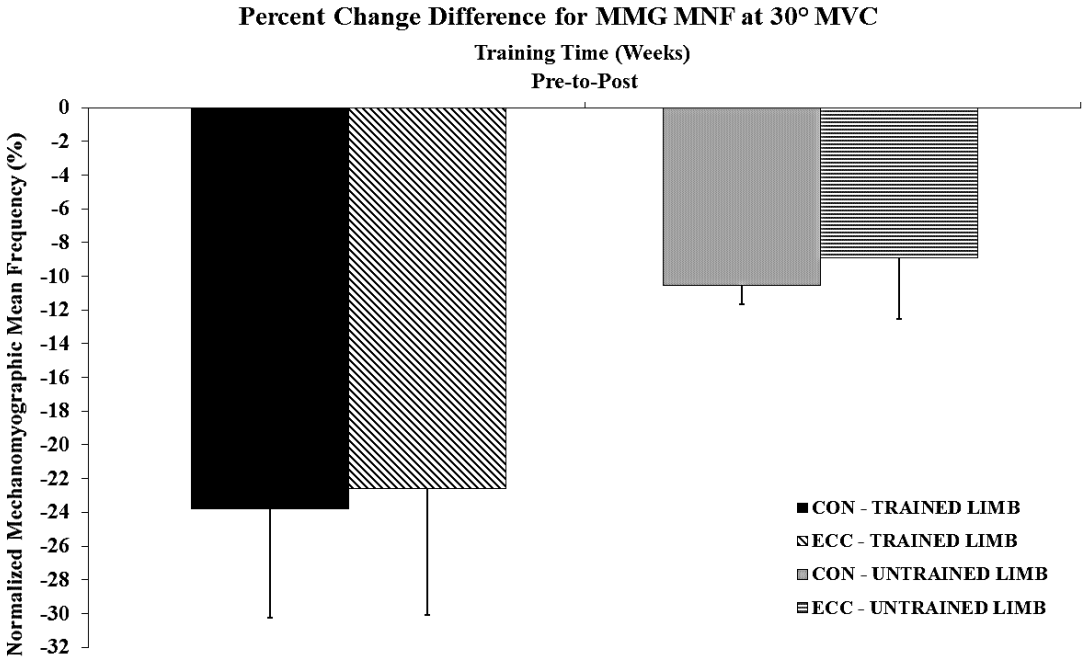


Figure 35. Changes in mechanomyographic mean frequency at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.



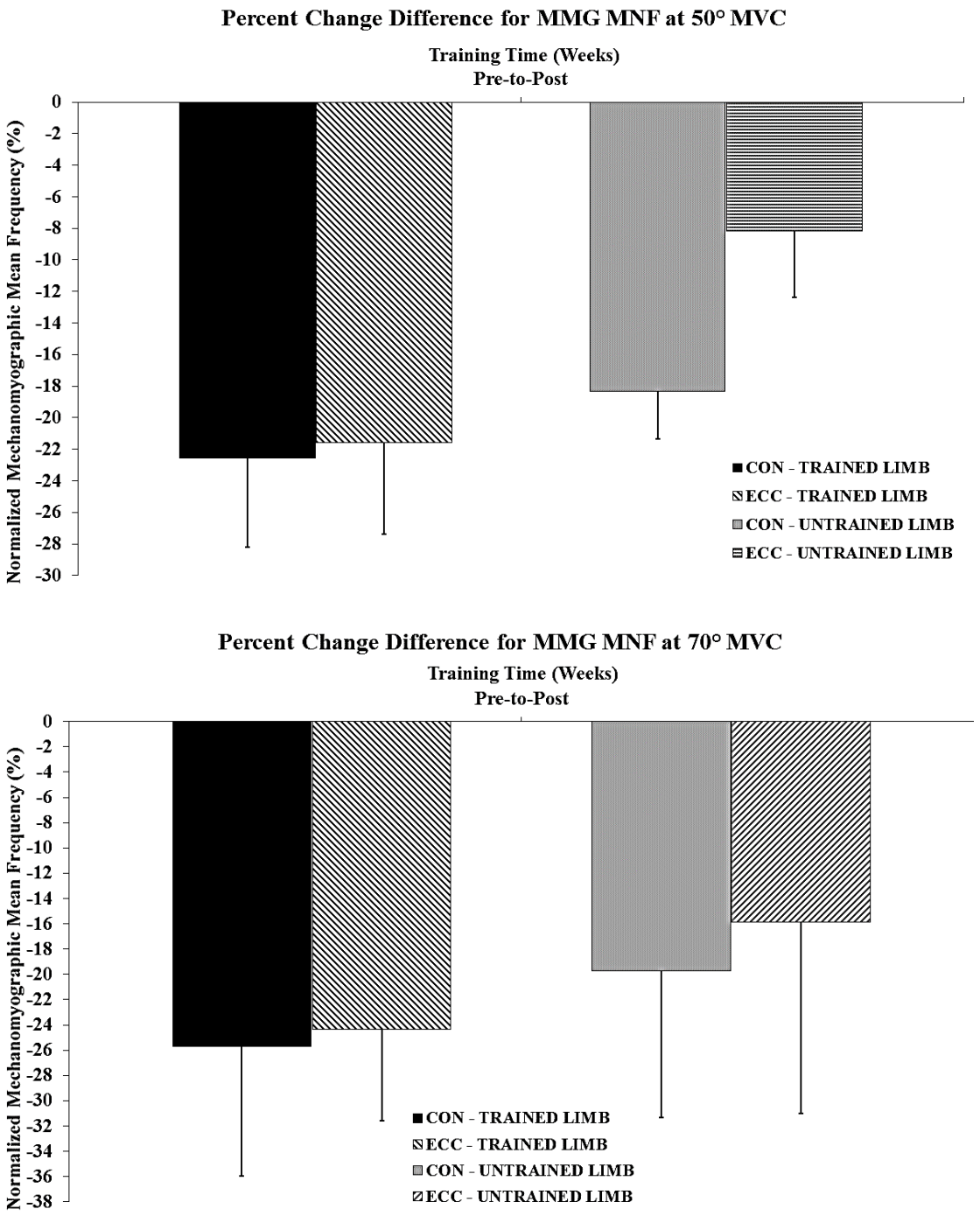


Figure 36. Percent change difference for normalized mechanomyographic mean frequency at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the four-way repeated measures ANOVA for MMG MNF indicated a statistically significant two-way interaction for intensity and time ($p = < 0.001$ and $\eta^2 = 0.397$), and a main effect for time ($p = < 0.001$ and $\eta^2 = 0.63$). For the main effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.202$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following time points:

Table 16. Paired Samples T-Test for Time – Mechanomyographic Mean Frequency

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.001	0.37
Baseline vs. Week 4	< 0.001	0.59
Baseline vs. Week 6	< 0.001	0.62
Baseline vs. Week 8	< 0.001	0.78
Week 2 vs. Week 4	< 0.001	0.82
Week 2 vs. Week 6	< 0.001	0.85
Week 2 vs. Week 8	< 0.001	1.02

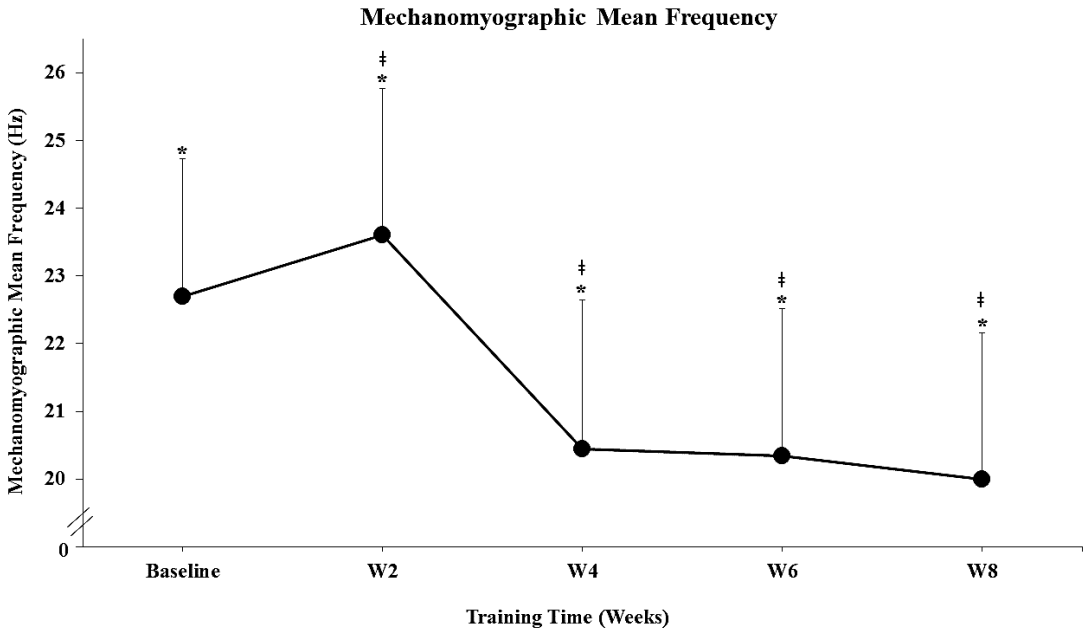


Figure 37. Changes in mechanomyographic mean frequency across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

As for the interaction between intensity and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant interaction for group and time ($p = < 0.001$ and $\eta^2 = 0.099$). Three separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated statistically significant mean differences across time for the following intensities: 30% MVC ($p = < 0.001$ and $\eta^2 = 0.148$), 50% MVC ($p = < 0.001$ and $\eta^2 = 0.186$), and 70% MVC ($p = < 0.001$ and $\eta^2 = 0.354$), respectively. For the follow-up analysis for 30% MVC, paired samples t-tests was performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 17. Paired Samples T-Test for Time – Intensity x Time Interaction – 30% MVC for Mechanomyographic Mean Frequency

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.029	0.47
Baseline vs. Week 6	0.002	0.64
Week 2 vs. Week 4	0.008	0.49
Week 2 vs. Week 6	< 0.001	0.93
Week 2 vs. Week 8	0.002	0.64
Week 4 vs. Week 6	0.027	0.42

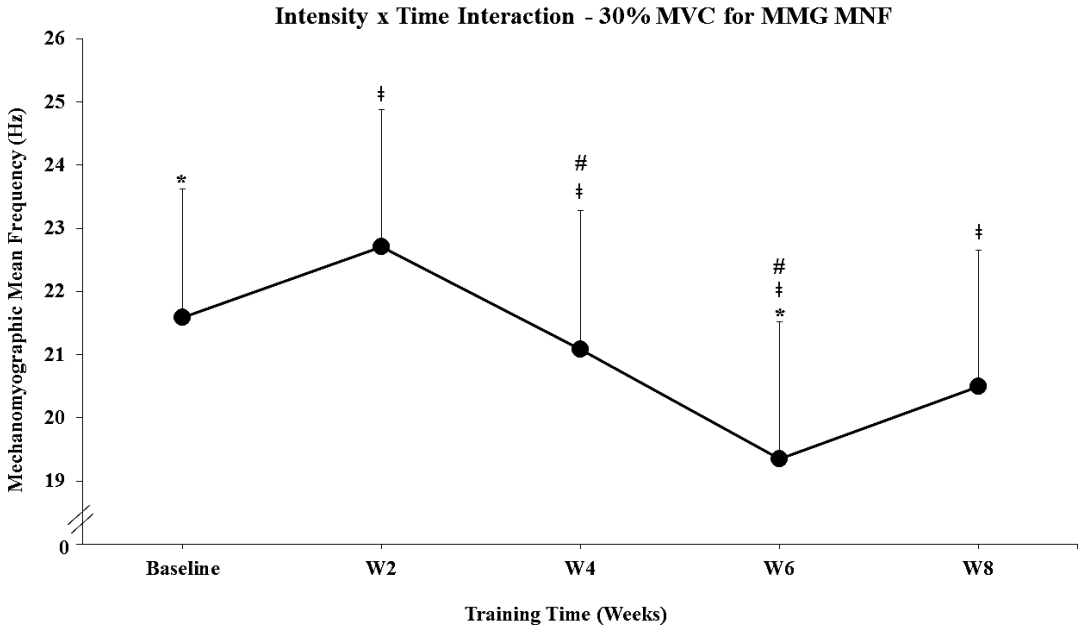


Figure 38. Changes in mechanomyographic mean frequency at 30% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

For the follow-up analysis for 50% MVC, paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 18. Paired Samples T-Test for Time – Intensity x Time Interaction – 50% MVC for Mechanomyographic Mean Frequency

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.027	0.41
Baseline vs. Week 4	0.031	0.42
Baseline vs. Week 6	0.039	0.36
Baseline vs. Week 8	< 0.001	0.79
Week 2 vs. Week 4	0.001	0.66
Week 2 vs. Week 6	0.001	0.62
Week 2 vs. Week 8	< 0.001	1.06
Week 6 vs. Week 8	0.032	0.31

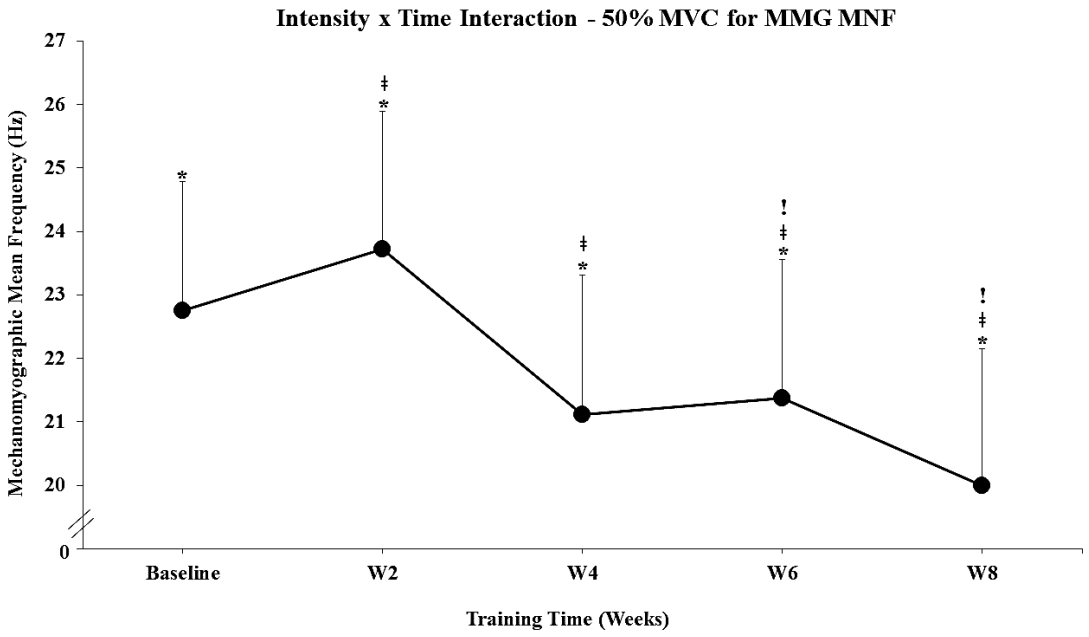


Figure 39. Changes in mechanomyographic mean frequency at 50% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and an exclamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

For the follow-up analysis for 70% MVC, paired samples t-tests was performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 19. Paired Samples T-Test for Time – Intensity x Time Interaction – 70% MVC for Mechanomyographic Mean Frequency

Time	P-value	Cohen's *d*
Baseline vs. Week 4	< 0.001	1.18
Baseline vs. Week 6	< 0.001	0.91
Baseline vs. Week 8	< 0.001	1.28
Week 2 vs. Week 4	< 0.001	1.30
Week 2 vs. Week 6	< 0.001	1.04
Week 2 vs. Week 8	< 0.001	1.41

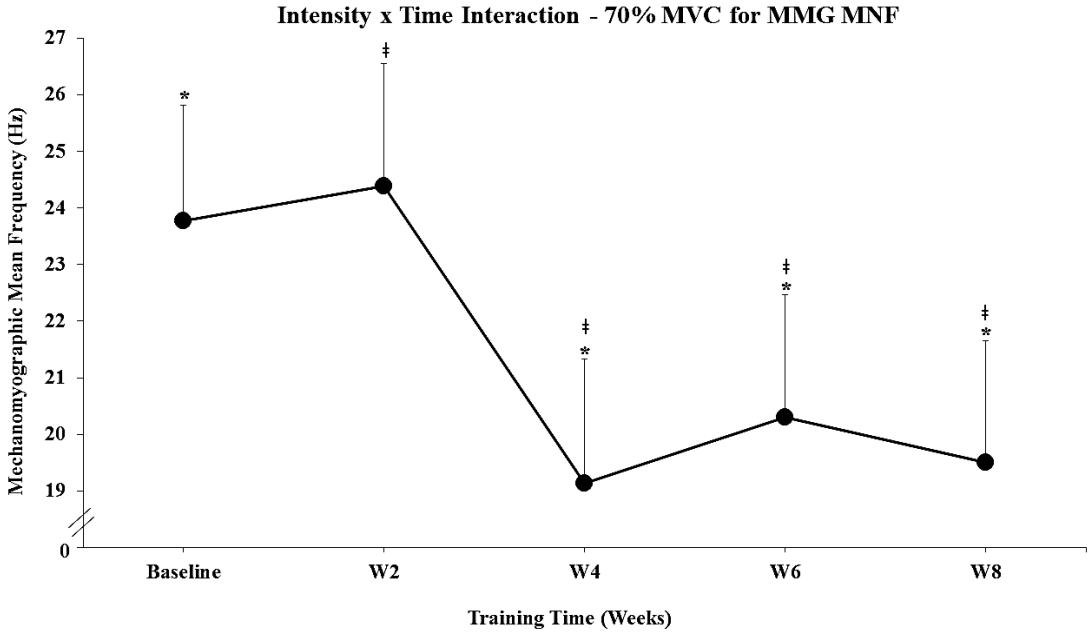
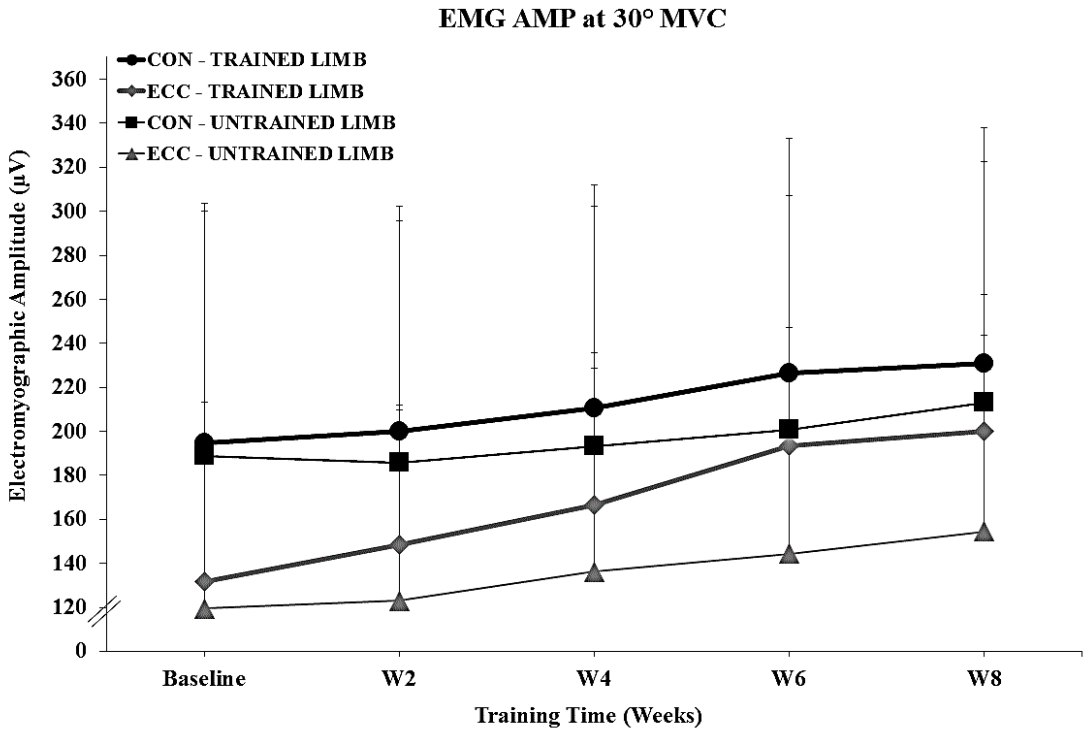
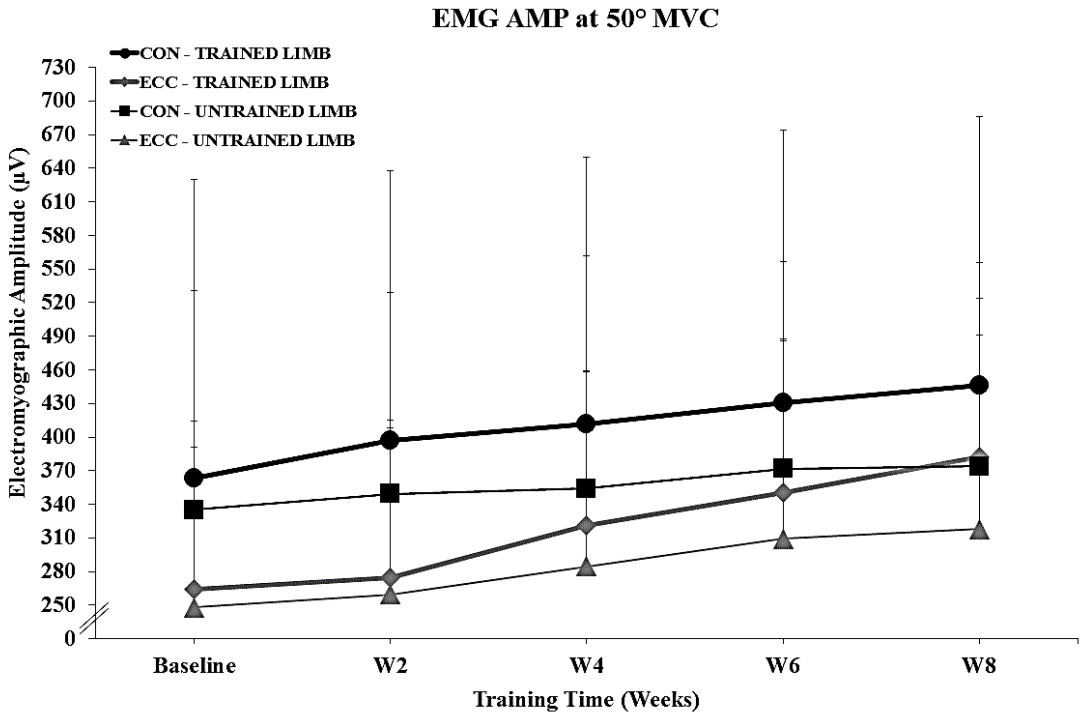


Figure 40. Changes in mechanomyographic mean frequency at 70% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

4.9. Electromyographic Amplitude





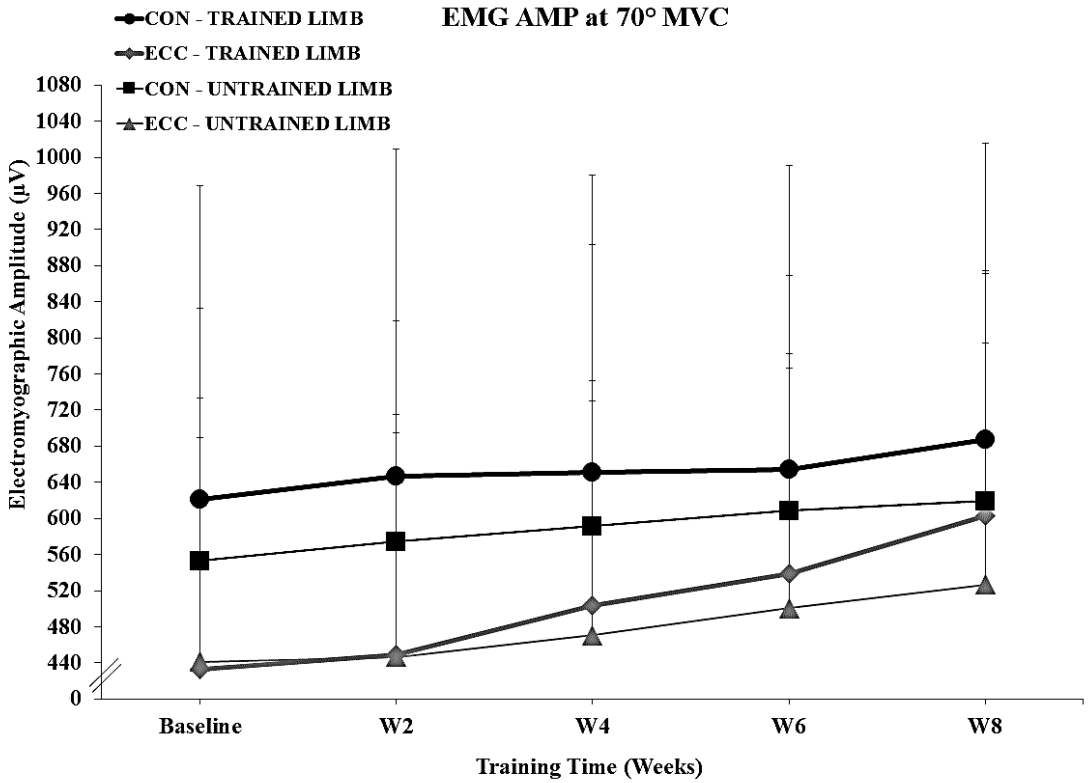
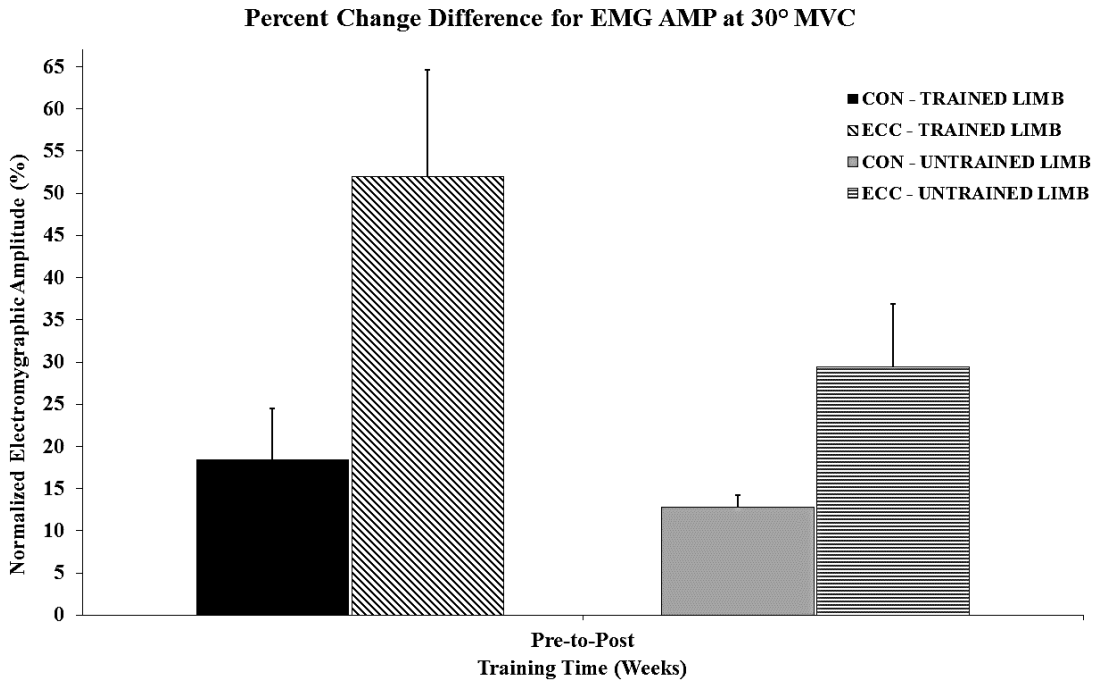
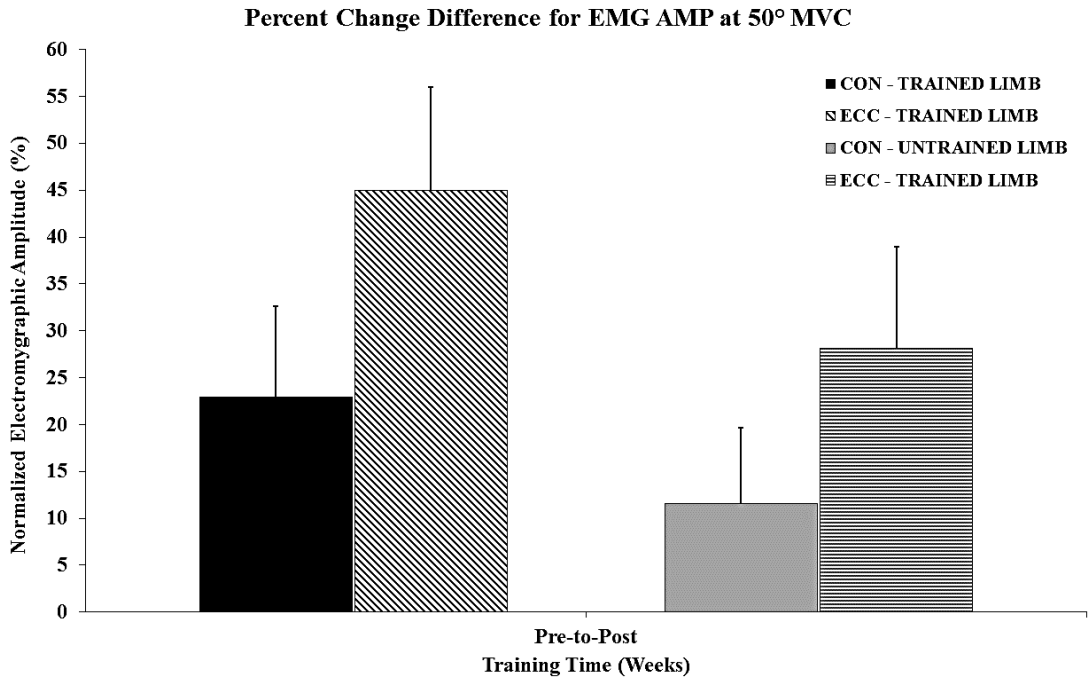


Figure 41. Changes in electromyographic amplitude at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.


Percent Change Difference for EMG AMP at 30° MVC
Normalized Electromygraphic Amplitude (%)
65
60
55
50
45
40
35
30
25
20
15
10
5
0
CON - TRAINED LIMB
ECC - TRAINED LIMB
CON - UNTRAINED LIMB
ECC - UNTRAINED LIMB
Pre-to-Post
Training Time (Weeks)


Percent Change Difference for EMG AMP at 50° MVC
Normalized Electromygraphic Amplitude (%)
60
55
50
45
40
35
30
25
20
15
10
5
0
CON - TRAINED LIMB
ECC - TRAINED LIMB
CON - UNTRAINED LIMB
ECC - TRAINED LIMB
Pre-to-Post
Training Time (Weeks)

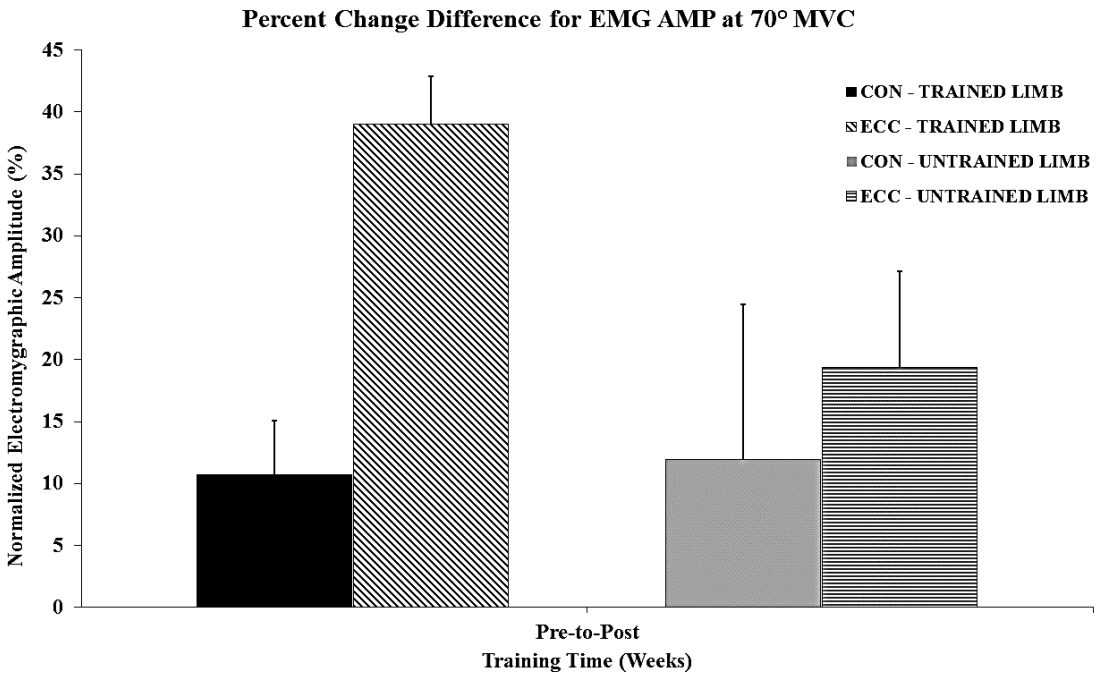


Figure 42. Percent change difference for normalized electromyographic amplitude at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the four-way repeated measures ANOVA for EMG AMP indicated a statistically significant two-way interaction for intensity and time ($p = 0.007$ and $\eta^2 = 0.244$), and a main effect for group ($p = 0.025$ and $\eta^2 = 0.446$), arm ($p = 0.028$ and $\eta^2 = 0.433$), intensity ($p = < 0.001$ and $\eta^2 = 0.858$), and time ($p = < 0.001$ and $\eta^2 = 0.397$), respectively. For the main effect for group, a paired samples t-test was considered appropriate to be performed and the results indicated a statistically significant mean difference between groups ($p = 0.038$ and $d = 0.39$). For the main effect for arm, a paired samples t-test was considered appropriate to be performed and the results indicated a statistically significant mean difference between arms ($p = 0.002$ and $d = 0.15$). For the main effect for intensity, a one-way repeated measures ANOVA

with Bonferroni post-hoc comparisons was performed and the results indicated a significant difference across time ($p = 0.001$ and $\eta^2 = 0.799$). Follow-up paired samples t-tests concluded that there were significant mean differences between the following intensities:

Table 20. Paired Samples T-Test for Intensity – Electromyographic Amplitude

Intensity	P-value	Cohen's *d*
30% MVC vs. 50% MVC	< 0.001	1.15
30% MVC vs. 70% MVC	< 0.001	1.83
50% MVC vs. 70% MVC	< 0.001	0.89

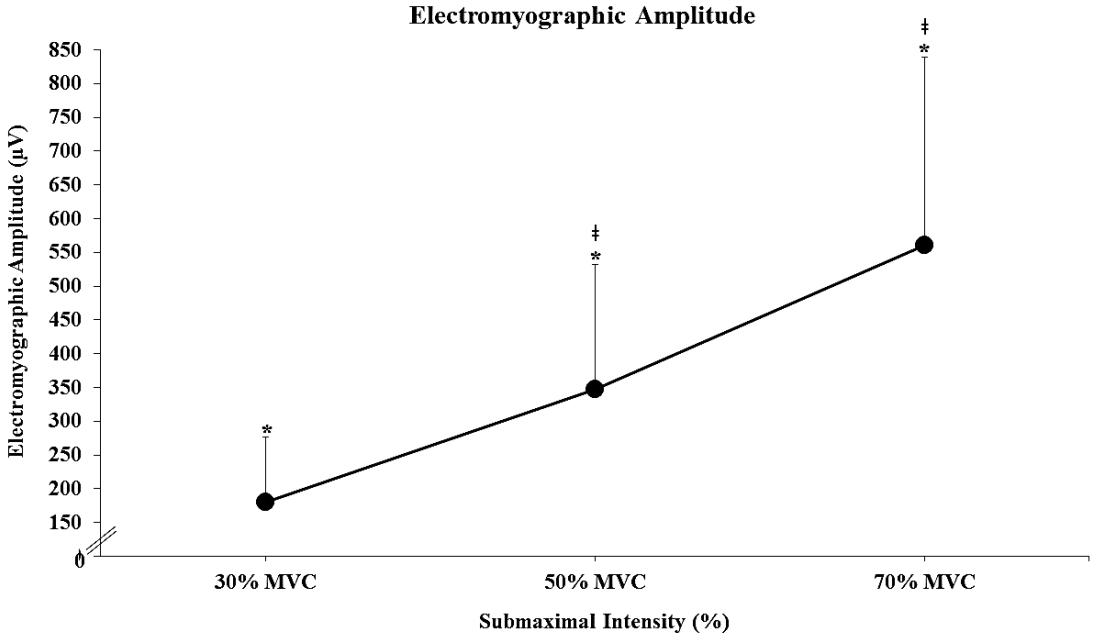


Figure 43. Changes in electromyographic amplitude across intensity (30% MVC to 70% MVC). An asterisk (*) signifys a significant difference between 30% MVC versus subsequent intensities; and a palatal click (ǂ) signifys a significant difference between 50% MVC versus subsequent intensities.

For the main effect for time, a one-way ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.1$). Follow-up paired samples t-tests

indicated that there were significant mean differences between the following time points:

Table 21. Paired Samples T-Test for Time – Electromyographic Amplitude

Time	P-value	Cohen's *d*
Baseline vs. Week 4	0.001	0.11
Baseline vs. Week 6	< 0.001	0.25
Baseline vs. Week 8	< 0.001	0.24
Week 2 vs. Week 6	< 0.001	0.21
Week 2 vs. Week 8	< 0.001	0.17
Week 4 vs. Week 6	0.008	0.19
Week 4 vs. Week 8	0.049	0.11

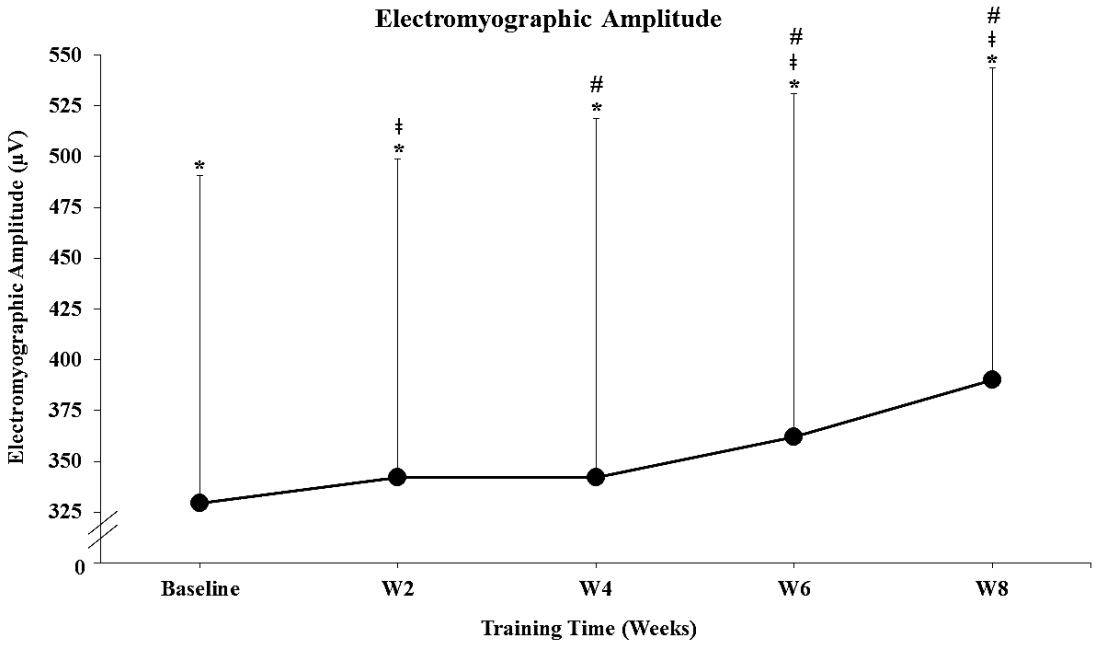


Figure 44. Changes in electromyographic amplitude across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

As for the interaction between intensity and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results

indicated a statistically significant interaction for group and time ($p = 0.032$ and $\eta^2 = 0.043$). Three separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated statistically significant mean differences across time for the following intensities: 30% MVC ($p = < 0.001$ and $\eta^2 = 0.115$), 50% MVC ($p = 0.001$ and $\eta^2 = 0.1$), and 70% MVC ($p = < 0.001$ and $\eta^2 = 0.094$), respectively. For the follow-up analysis for 30% MVC, paired samples t-tests was performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 22. Paired Samples T-Test for Time – Intensity x Time Interaction – 30% MVC for Electromyographic Amplitude

Time	P-value	Cohen's *d*
Baseline vs. Week 6	0.008	0.28
Baseline vs. Week 8	< 0.001	0.38
Week 2 vs. Week 6	0.009	0.22
Week 2 vs. Week 8	< 0.001	0.32
Week 4 vs. Week 6	0.037	0.21
Week 4 vs. Week 8	0.002	0.31

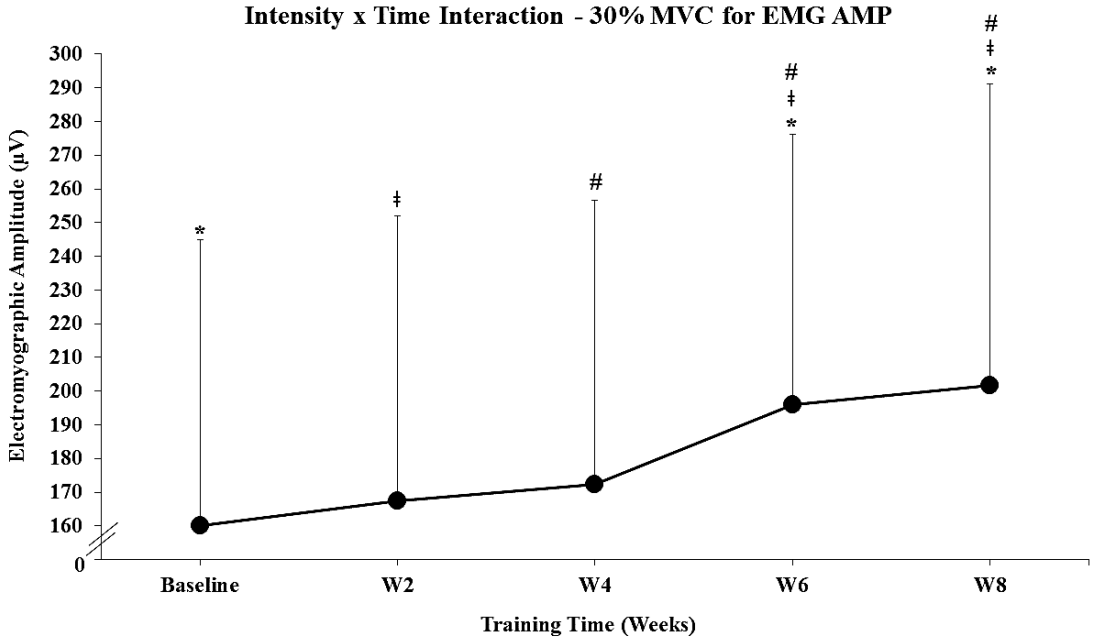


Figure 45. Changes in electromyographic amplitude at 30% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

For the follow-up analysis for 50% MVC, paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 23. Paired Samples T-Test for Time – Intensity x Time Interaction – 50% MVC for Electromyographic Amplitude

Time	P-value	Cohen's *d*
Baseline vs. Week 4	0.016	0.15
Baseline vs. Week 6	0.002	0.31
Baseline vs. Week 8	0.002	0.29
Week 2 vs. Week 6	0.001	0.26
Week 2 vs. Week 8	0.001	0.25

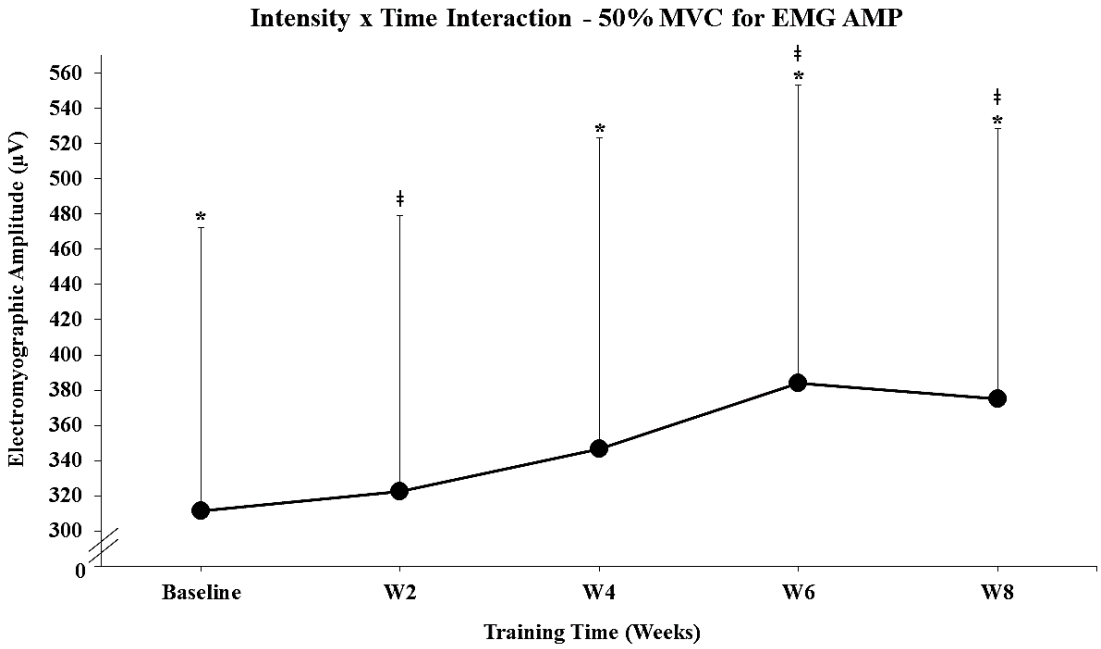


Figure 46. Changes in electromyographic amplitude at 50% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

For the follow-up analysis for 70% MVC, paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 24. Paired Samples T-Test for Time – Intensity x Time Interaction – 70% MVC for Electromyographic Amplitude

Time	P-value	Cohen's *d*
Baseline vs. Week 4	0.010	0.15
Baseline vs. Week 6	0.004	0.21
Baseline vs. Week 8	< 0.001	0.26
Week 2 vs. Week 6	0.011	0.15
Week 2 vs. Week 8	0.005	0.21

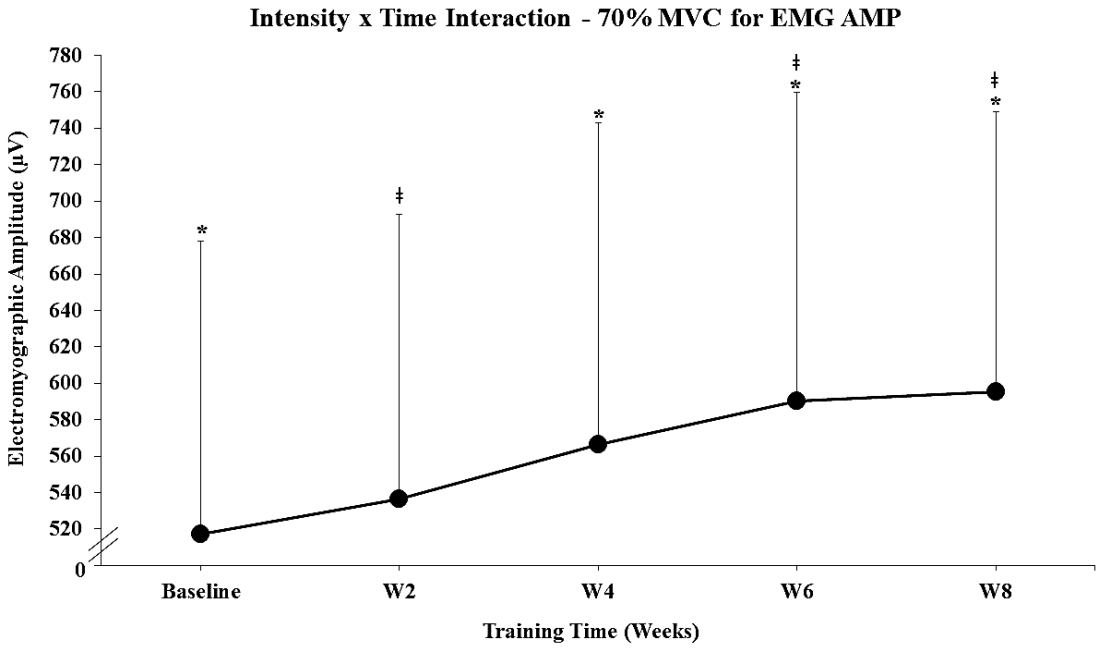
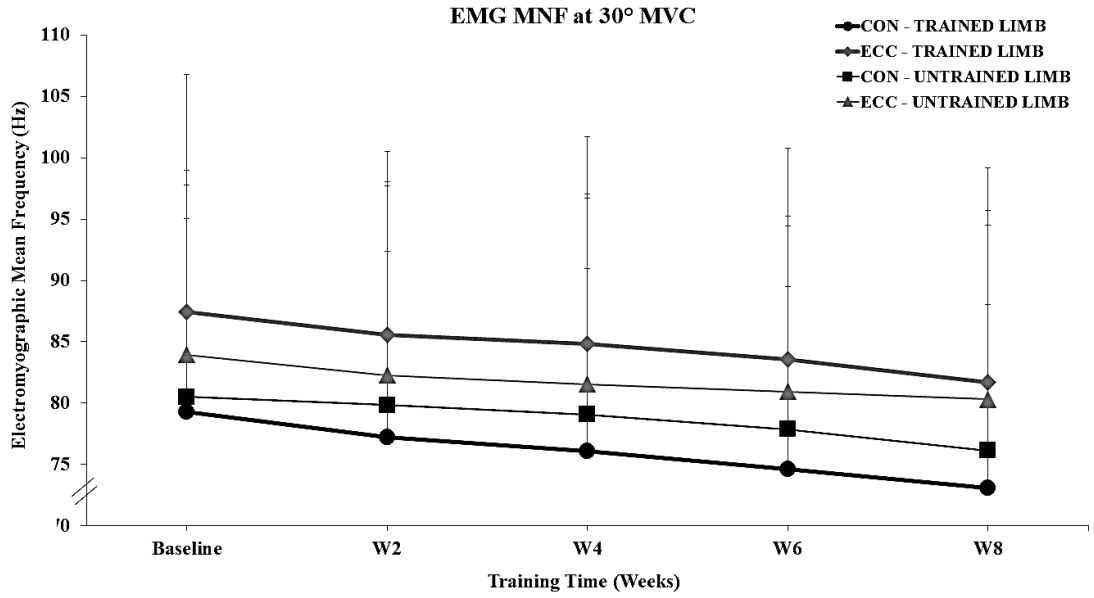


Figure 47. Changes in electromyographic amplitude at 70% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

4.10. Electromyographic Mean Frequency



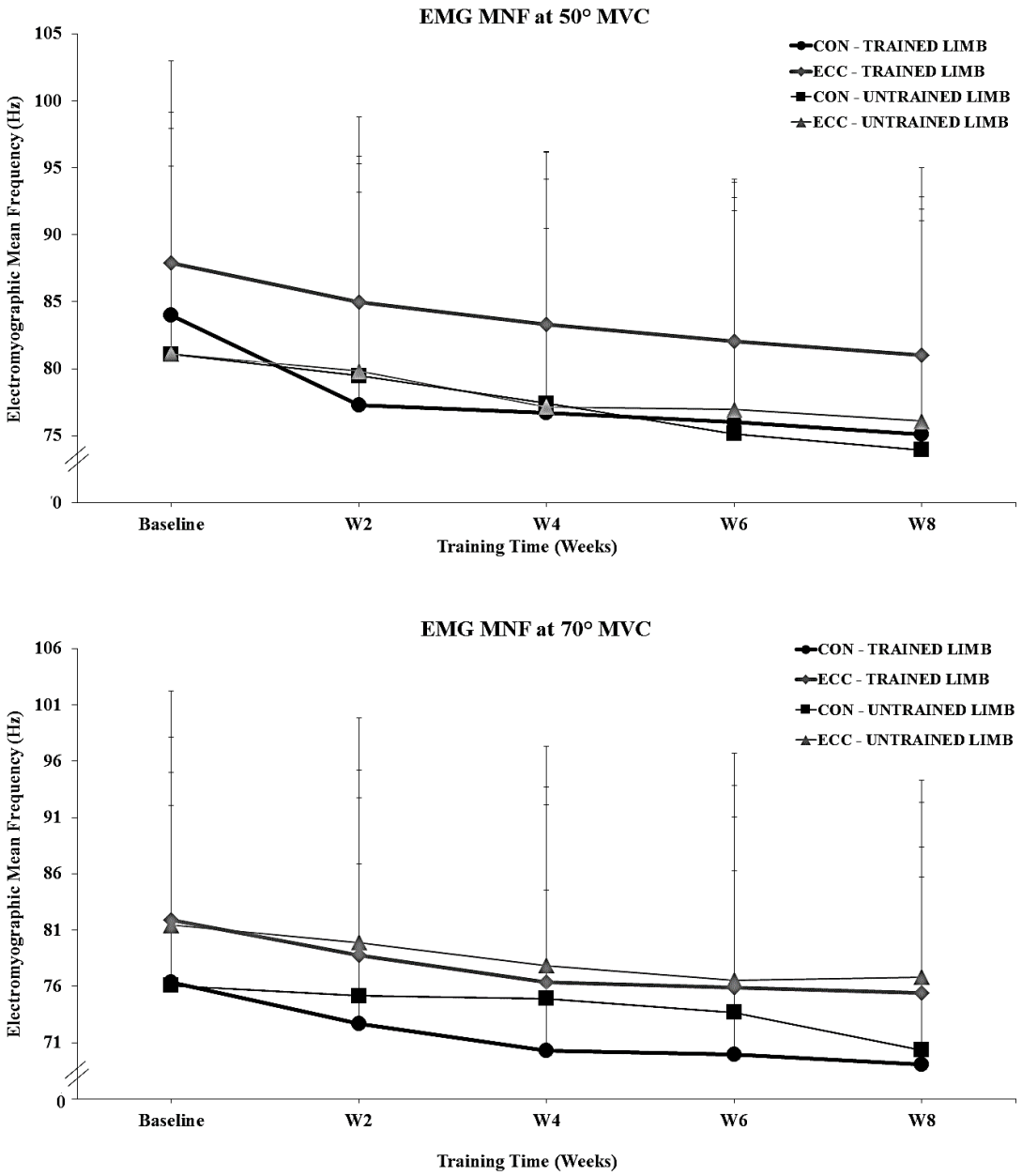
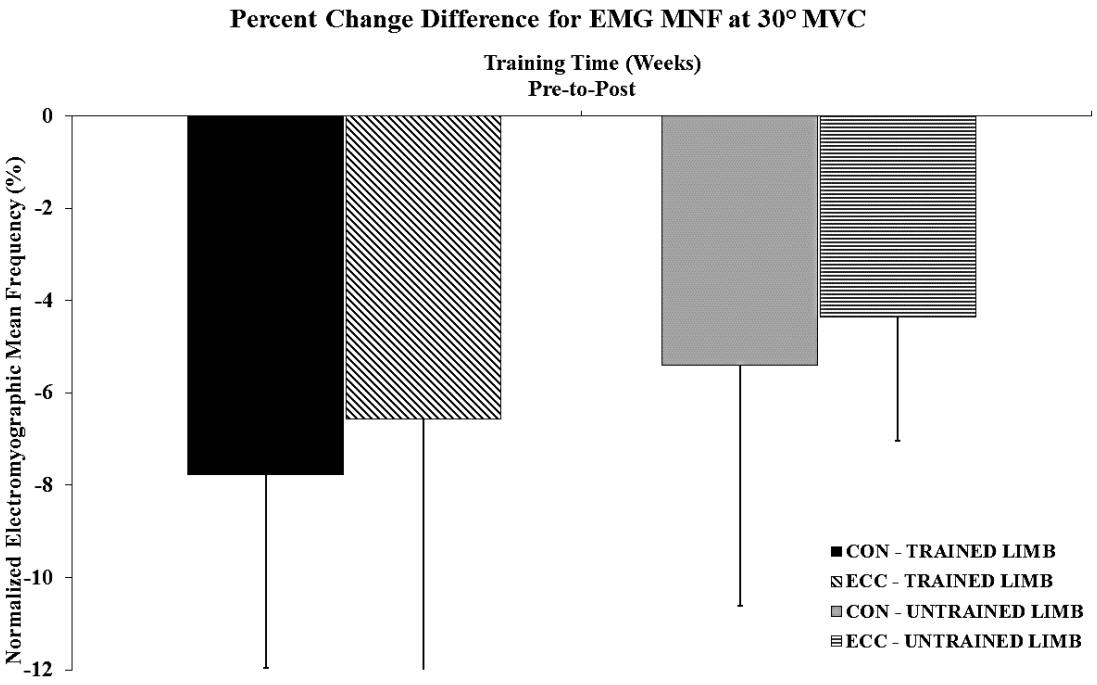
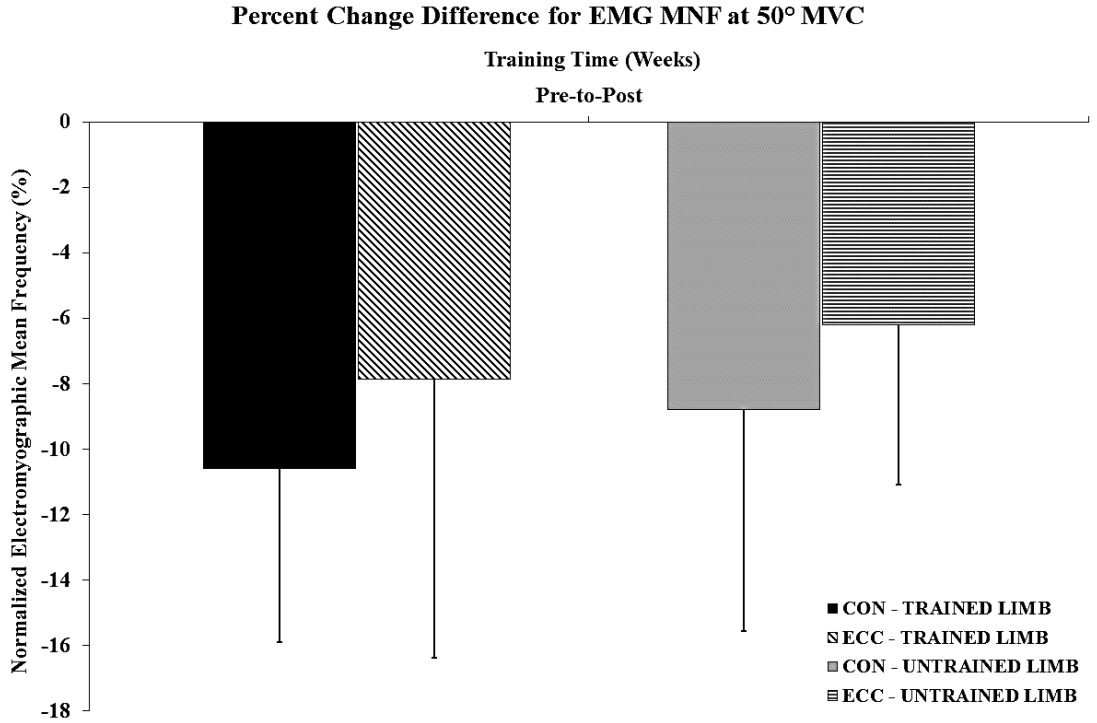


Figure 48. Changes in electromyographic mean frequency at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.


Percent Change Difference for EMG MNF at 30° MVC
Training Time (Weeks)
Pre-to-Post
Normalized Electromyographic Mean Frequency (%)
0
-2
-4
-6
-8
-10
-12
CON - TRAINED LIMB
ECC - TRAINED LIMB
CON - UNTRAINED LIMB
ECC - UNTRAINED LIMB


Percent Change Difference for EMG MNF at 50° MVC
Training Time (Weeks)
Pre-to-Post
Normalized Electromyographic Mean Frequency (%)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
CON - TRAINED LIMB
ECC - TRAINED LIMB
CON - UNTRAINED LIMB
ECC - UNTRAINED LIMB

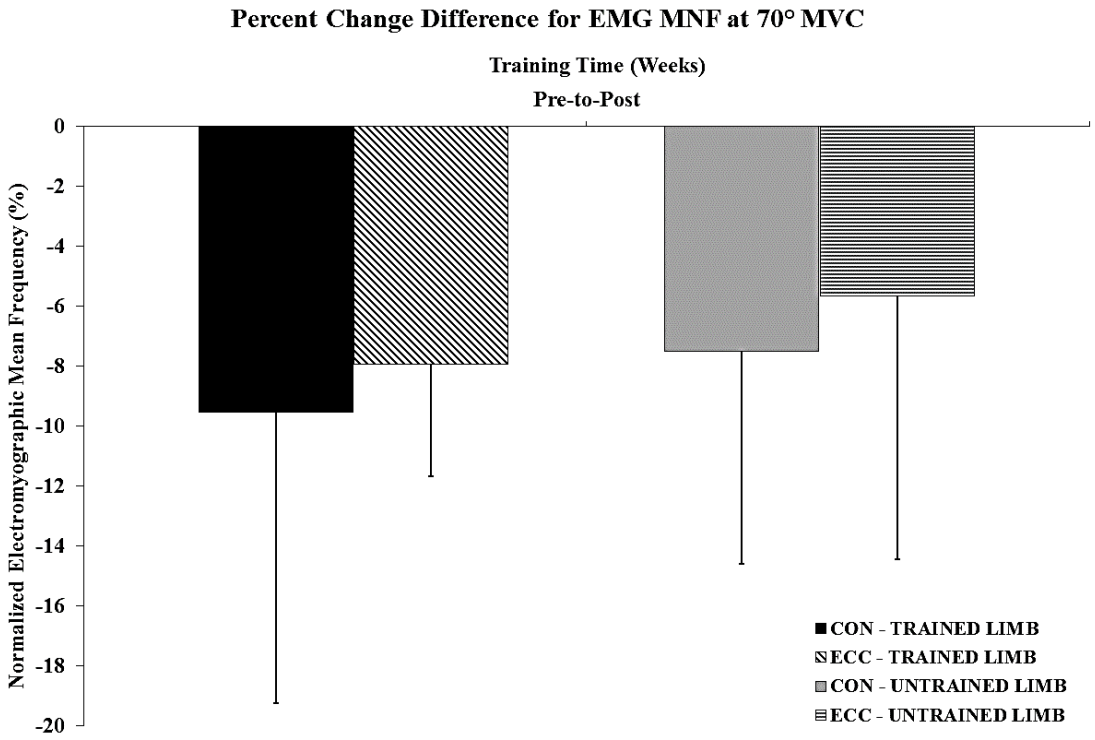


Figure 49. Percent change difference for normalized electromyographic mean frequency at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the four-way repeated measures ANOVA for EMG MNF indicated a statistically significant ($p < 0.050$) four-way interaction for group, arm, intensity and time ($p = 0.02$ and $\eta^2 = 0.216$), a two-way interaction for arm and time ($p = 0.013$ and $\eta^2 = 0.292$), and a main effect for intensity ($p = < 0.001$ and $\eta^2 = 0.893$). For the main effect for intensity, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.465$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following intensities:

Table 25. Paired Samples T-Test for Intensity – Electromyographic Mean Frequency

Intensity	P-value	Cohen's *d*
30% MVC vs. 50% MVC	0.031	0.60
30% MVC vs. 70% MVC	< 0.001	0.32
50% MVC vs. 70% MVC	< 0.001	0.26

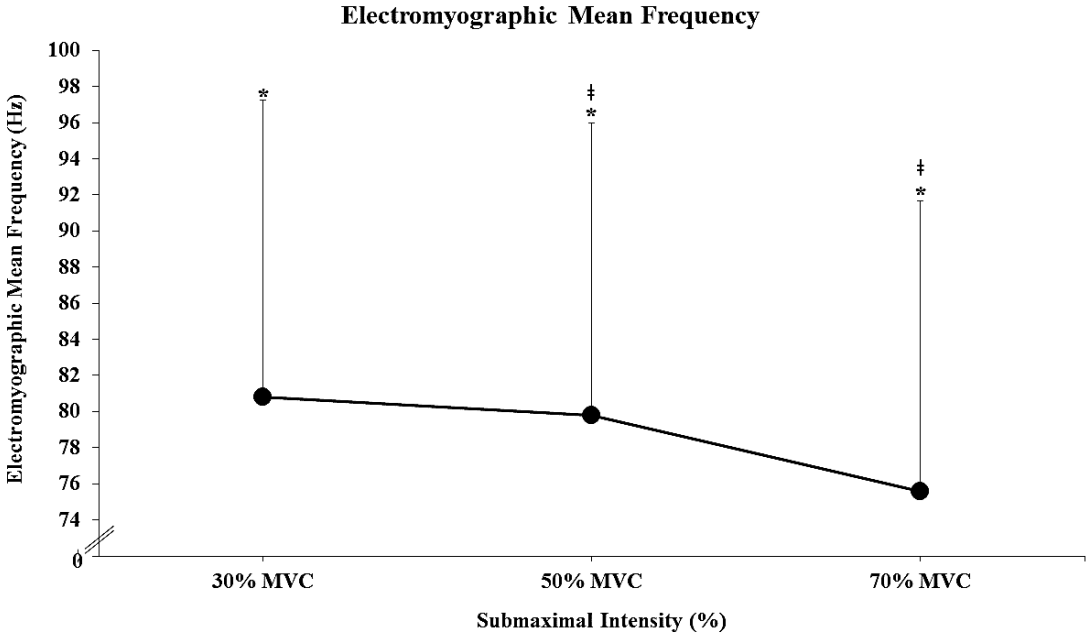


Figure 50. Changes in electromyographic mean frequency across intensity (30% MVC to 70% MVC). An asterisk (*) signifys a significant difference between 30% MVC versus subsequent intensities; and a palatal click (ǂ) signifys a significant difference between 50% MVC versus subsequent intensities.

As for the interaction between arm and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant interaction for arm and time ($p = < 0.001$ and $\eta^2 = 0.098$). Two separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated statistically significant mean differences across time for the CON ($p = 0.025$ and $\eta^2 = 0.045$) and ECC ($p = 0.002$ and $\eta^2 = 0.07$) groups, respectively. For the follow-up analysis for the trained arm,

paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 26. Paired Samples T-Test for Time – Arm x Time Interaction – Electromyographic Mean Frequency for the Trained Arm

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.002	0.16
Baseline vs. Week 4	0.001	0.21
Baseline vs. Week 8	0.045	0.18

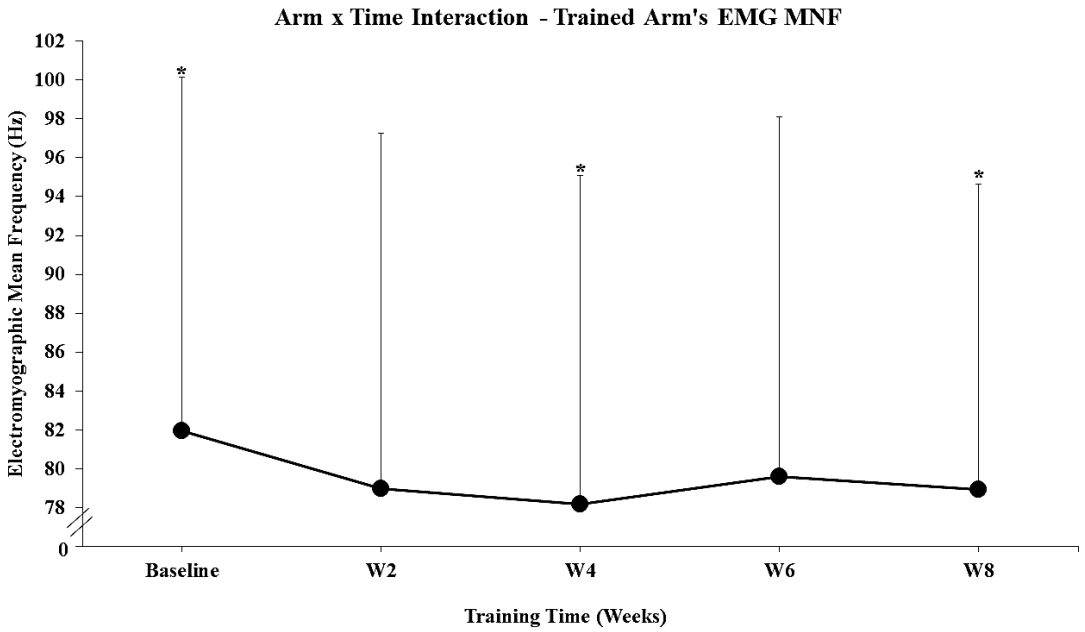


Figure 51. Changes in electromyographic mean frequency for the trained arm across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements.

For the follow-up analysis for the untrained arm, paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 27. Paired Samples T-Test for Time – Arm x Time Interaction – Electromyographic Mean Frequency for the Untrained Arm

Time	P-value	Cohen's *d*
Baseline vs. Week 4	0.004	0.22
Week 2 vs. Week 4	0.002	0.25
Week 4 vs. Week 6	0.001	0.24

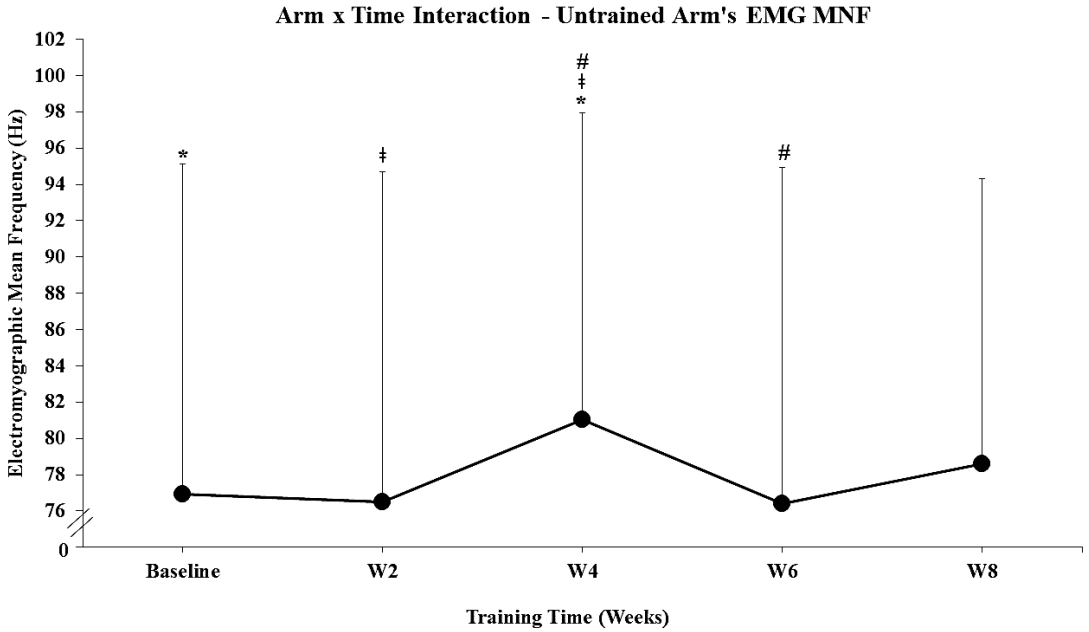


Figure 52. Changes in electromyographic mean frequency for the untrained arm across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

As for the interaction between group, arm, intensity, and time, twelve separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated a statistically significant interaction for the CON groups untrained arm at 70% MVC across time only ($p = 0.038$ and $\eta^2 = 0.202$). Follow-up paired samples t-tests was performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 28. Paired Samples T-Test for Time – Group x Arm x Intensity x Time Interaction – Electromyographic Mean Frequency for Concentric Group's Trained Arm at 70% MVC across Time

Time	P-value	Cohen's *d*
Baseline vs. Week 4	0.017	0.34
Week 4 vs. Week 6	0.042	0.42

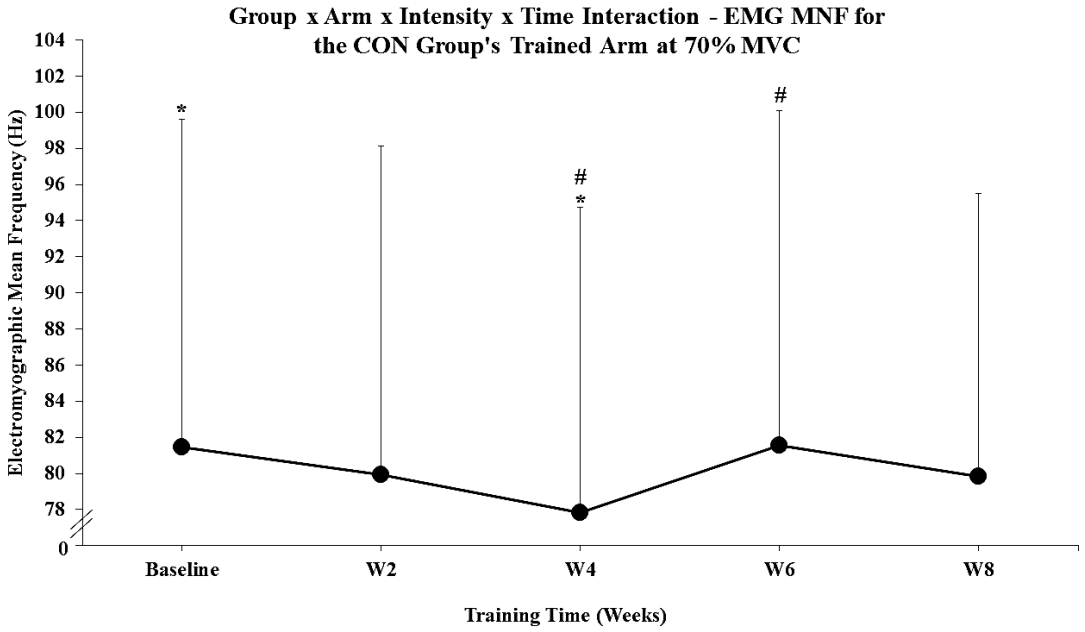


Figure 53. Changes in electromyographic mean frequency for the concentric group's trained arm at 70% MVC across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a numeric symbol (#) signifys a significant difference between week 4 measurements versus subsequent post-exercise measurements.

4.11. Correlation of MMG and EMG AMP and MNF

Table 29. Correlation between the Concentric Group's MMG and EMG AMP at 30% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.403	0.075	0.162	0.065
	Significance	0.000	0.194	0.817	0.615	0.842
EMG AMP W4	Pearson Correlation	0.000	0.343	0.227	0.539	0.413
	Significance	0.000	0.275	0.478	0.071	0.182
EMG AMP W6	Pearson Correlation	0.000	0.535	0.381	0.580	0.563
	Significance	0.000	0.073	0.221	0.051	0.056
EMG AMP W8	Pearson Correlation	0.000	0.514	0.288	0.395	0.384
	Significance	0.000	0.087	0.365	0.204	0.217

Table 30. Correlation between the Concentric Group's MMG and EMG AMP at 50% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.496	0.362	0.356	0.204
	Significance	0.000	0.101	0.250	0.257	0.526
EMG AMP W4	Pearson Correlation	0.000	0.092	0.132	0.112	0.211
	Significance	0.000	0.776	0.683	0.705	0.511
EMG AMP W6	Pearson Correlation	0.000	0.200	0.138	0.003	0.034
	Significance	0.000	0.532	0.669	0.992	0.916
EMG AMP W8	Pearson Correlation	0.000	0.235	0.111	0.054	0.299
	Significance	0.000	0.461	0.731	0.867	0.346

Table 31. Correlation between the Concentric Group's MMG and EMG AMP at 70% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.257	0.145	0.542	0.013
	Significance	0.000	0.419	0.654	0.069	0.968
EMG AMP W4	Pearson Correlation	0.000	0.341	0.297	0.039	0.034
	Significance	0.000	0.278	0.349	0.903	0.917
EMG AMP W6	Pearson Correlation	0.000	0.053	0.020	0.378	0.233
	Significance	0.000	0.870	0.950	0.225	0.467
EMG AMP W8	Pearson Correlation	0.000	0.218	0.152	0.253	0.238
	Significance	0.000	0.496	0.638	0.428	0.456

Table 32. Correlation between the Concentric Group's MMG and EMG AMP at 30% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.127	0.013	0.214	0.206
	Significance	0.000	0.694	0.968	0.504	0.521
EMG AMP W4	Pearson Correlation	0.000	0.066	0.205	0.149	0.370
	Significance	0.000	0.838	0.523	0.644	0.237
EMG AMP W6	Pearson Correlation	0.000	0.334	0.254	0.217	0.031
	Significance	0.000	0.289	0.426	0.499	0.924
EMG AMP W8	Pearson Correlation	0.000	0.345	0.277	0.537	0.135
	Significance	0.000	0.272	0.384	0.059	0.676

Table 33. Correlation between the Concentric Group's MMG and EMG AMP at 50% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.202	0.215	0.166	0.255
	Significance	0.000	0.528	0.502	0.607	0.423
EMG AMP W4	Pearson Correlation	0.000	0.209	0.247	0.221	0.220
	Significance	0.000	0.514	0.439	0.491	0.491
EMG AMP W6	Pearson Correlation	0.000	0.142	0.115	0.176	0.109
	Significance	0.000	0.660	0.721	0.585	0.736
EMG AMP W8	Pearson Correlation	0.000	0.012	0.040	0.025	0.056
	Significance	0.000	0.971	0.901	0.938	0.863

Table 34. Correlation between the Concentric Group's MMG and EMG AMP at 70% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.060	0.108	0.476	0.074
	Significance	0.000	0.854	0.738	0.118	0.820
EMG AMP W4	Pearson Correlation	0.000	0.043	0.108	0.514	0.350
	Significance	0.000	0.894	0.738	0.064	0.265
EMG AMP W6	Pearson Correlation	0.000	0.025	0.280	0.255	0.001
	Significance	0.000	0.938	0.379	0.425	0.999
EMG AMP W8	Pearson Correlation	0.000	0.057	0.015	0.451	0.017
	Significance	0.000	0.861	0.964	0.141	0.957

Table 35. Correlation between the Eccentric Group's MMG and EMG AMP at 30% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.383	0.370	0.127	0.391
	Significance	0.000	0.257	0.293	0.727	0.264
EMG AMP W4	Pearson Correlation	0.000	0.569	0.186	0.064	0.259
	Significance	0.000	0.086	0.607	0.861	0.470
EMG AMP W6	Pearson Correlation	0.000	0.076	0.261	0.186	0.262
	Significance	0.000	0.836	0.466	0.608	0.465
EMG AMP W8	Pearson Correlation	0.000	0.056	0.121	0.081	0.248
	Significance	0.000	0.877	0.739	0.825	0.490

Table 36. Correlation between the Eccentric Group's MMG and EMG AMP at 50% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.027	0.020	0.035	0.032
	Significance	0.000	0.941	0.957	0.924	0.930
EMG AMP W4	Pearson Correlation	0.000	0.215	0.231	0.211	0.221
	Significance	0.000	0.552	0.520	0.558	0.540
EMG AMP W6	Pearson Correlation	0.000	0.154	0.196	0.175	0.182
	Significance	0.000	0.672	0.587	0.630	0.615
EMG AMP W8	Pearson Correlation	0.000	0.162	0.191	0.188	0.189
	Significance	0.000	0.654	0.598	0.602	0.600

Table 37. Correlation between the Eccentric Group's MMG and EMG AMP at 70% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.030	0.279	0.052	0.060
	Significance	0.000	0.934	0.1435	0.886	0.869
EMG AMP W4	Pearson Correlation	0.000	0.286	0.053	0.102	0.115
	Significance	0.000	0.424	0.884	0.779	0.752
EMG AMP W6	Pearson Correlation	0.000	0.026	0.126	0.054	0.026
	Significance	0.000	0.943	0.728	0.883	0.943
EMG AMP W8	Pearson Correlation	0.000	0.165	0.185	0.059	0.089
	Significance	0.000	0.650	0.609	0.871	0.808

Table 38. Correlation between the Eccentric Group's MMG and EMG AMP at 30% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.451	0.593	0.555	0.250
	Significance	0.000	0.191	0.071	0.096	0.485
EMG AMP W4	Pearson Correlation	0.000	0.347	0.263	0.320	0.500
	Significance	0.000	0.326	0.464	0.367	0.141
EMG AMP W6	Pearson Correlation	0.000	0.474	0.450	0.508	0.562
	Significance	0.000	0.166	0.192	0.134	0.091
EMG AMP W8	Pearson Correlation	0.000	0.266	0.264	0.353	0.052
	Significance	0.000	0.457	0.461	0.317	0.887

Table 39. Correlation between the Eccentric Group's MMG and EMG AMP at 50% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.528	0.407	0.588	0.501
	Significance	0.000	0.116	0.243	0.051	0.140
EMG AMP W4	Pearson Correlation	0.000	0.088	0.168	0.130	0.278
	Significance	0.000	0.808	0.643	0.721	0.437
EMG AMP W6	Pearson Correlation	0.000	0.373	0.035	0.441	0.193
	Significance	0.000	0.288	0.923	0.202	0.594
EMG AMP W8	Pearson Correlation	0.000	0.359	0.216	0.445	0.474
	Significance	0.000	0.308	0.549	0.198	0.167

Table 40. Correlation between the Eccentric Group's MMG and EMG AMP at 70% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.431	0.049	0.118	0.156
	Significance	0.000	0.214	0.893	0.745	0.666
EMG AMP W4	Pearson Correlation	0.000	0.381	0.269	0.304	0.541
	Significance	0.000	0.277	0.453	0.392	0.056
EMG AMP W6	Pearson Correlation	0.000	0.325	0.604	0.616	0.625
	Significance	0.000	0.359	0.059	0.058	0.054
EMG AMP W8	Pearson Correlation	0.000	0.114	0.209	0.469	0.097
	Significance	0.000	0.753	0.563	0.172	0.789

Table 41. Correlation between the Concentric Group's MMG and EMG MNF at 30% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.094	0.055	0.114	0.386
	Significance	0.000	0.770	0.864	0.724	0.215
EMG AMP W4	Pearson Correlation	0.000	0.040	0.011	0.203	0.177
	Significance	0.000	0.770	0.973	0.527	0.583
EMG AMP W6	Pearson Correlation	0.000	0.117	0.345	0.194	0.207
	Significance	0.000	0.717	0.272	0.546	0.518
EMG AMP W8	Pearson Correlation	0.000	0.533	0.432	0.157	0.340
	Significance	0.000	0.075	0.161	0.625	0.279

Table 42. Correlation between the Concentric Group's MMG and EMG MNF at 50% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.561	0.286	0.371	0.558
	Significance	0.000	0.052	0.367	0.235	0.059
EMG AMP W4	Pearson Correlation	0.000	0.334	0.038	0.108	0.075
	Significance	0.000	0.289	0.908	0.739	0.823
EMG AMP W6	Pearson Correlation	0.000	0.365	0.122	0.146	0.157
	Significance	0.000	0.244	0.706	0.651	0.626
EMG AMP W8	Pearson Correlation	0.000	0.129	0.024	0.083	0.031
	Significance	0.000	0.690	0.940	0.796	0.924

Table 43. Correlation between the Concentric Group's MMG and EMG MNF at 70% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.038	0.111	0.208	0.050
	Significance	0.000	0.907	0.731	0.517	0.878
EMG AMP W4	Pearson Correlation	0.000	0.184	0.443	0.194	0.004
	Significance	0.000	0.566	0.149	0.545	0.989
EMG AMP W6	Pearson Correlation	0.000	0.172	0.263	0.222	0.093
	Significance	0.000	0.594	0.409	0.488	0.773
EMG AMP W8	Pearson Correlation	0.000	0.190	0.038	0.253	0.309
	Significance	0.000	0.555	0.906	0.428	0.329

Table 44. Correlation between the Concentric Group's MMG and EMG MNF at 30% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.068	0.327	0.260	0.073
	Significance	0.000	0.834	0.299	0.414	0.822
EMG AMP W4	Pearson Correlation	0.000	0.417	0.302	0.118	0.531
	Significance	0.000	0.177	0.340	0.715	0.076
EMG AMP W6	Pearson Correlation	0.000	0.517	0.407	0.390	0.252
	Significance	0.000	0.063	0.189	0.210	0.429
EMG AMP W8	Pearson Correlation	0.000	0.275	0.420	0.071	0.027
	Significance	0.000	0.387	0.175	0.826	0.934

Table 45. Correlation between the Concentric Group's MMG and EMG MNF at 50% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.316	0.193	0.349	0.099
	Significance	0.000	0.317	0.547	0.267	0.759
EMG AMP W4	Pearson Correlation	0.000	0.487	0.280	0.242	0.573
	Significance	0.000	0.108	0.379	0.449	0.052
EMG AMP W6	Pearson Correlation	0.000	0.393	0.115	0.139	0.234
	Significance	0.000	0.207	0.722	0.666	0.463
EMG AMP W8	Pearson Correlation	0.000	0.193	0.239	0.130	0.126
	Significance	0.000	0.548	0.455	0.688	0.695

Table 46. Correlation between the Concentric Group's MMG and EMG MNF at 70% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.232	0.135	0.229	0.203
	Significance	0.000	0.468	0.675	0.474	0.526
EMG AMP W4	Pearson Correlation	0.000	0.565	0.111	0.342	0.096
	Significance	0.000	0.056	0.732	0.277	0.767
EMG AMP W6	Pearson Correlation	0.000	0.333	0.028	0.193	0.020
	Significance	0.000	0.290	0.930	0.548	0.950
EMG AMP W8	Pearson Correlation	0.000	0.060	0.274	0.144	0.044
	Significance	0.000	0.854	0.388	0.656	0.892

Table 47. Correlation between the Eccentric Group's MMG and EMG MNF at 30% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.535	0.318	0.621	0.088
	Significance	0.000	0.056	0.371	0.054	0.808
EMG AMP W4	Pearson Correlation	0.000	0.629	0.492	0.609	0.544
	Significance	0.000	0.051	0.149	0.062	0.104
EMG AMP W6	Pearson Correlation	0.000	0.631	0.316	0.367	0.208
	Significance	0.000	0.051	0.373	0.297	0.564
EMG AMP W8	Pearson Correlation	0.000	0.215	0.253	0.187	0.156
	Significance	0.000	0.552	0.481	0.605	0.668

Table 48. Correlation between the Eccentric Group's MMG and EMG MNF at 50% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.314	0.145	0.413	0.228
	Significance	0.000	0.376	0.689	0.236	0.526
EMG AMP W4	Pearson Correlation	0.000	0.058	0.445	0.350	0.626
	Significance	0.000	0.873	0.198	0.322	0.056
EMG AMP W6	Pearson Correlation	0.000	0.120	0.573	0.059	0.617
	Significance	0.000	0.741	0.084	0.871	0.053
EMG AMP W8	Pearson Correlation	0.000	0.203	0.535	0.067	0.561
	Significance	0.000	0.574	0.111	0.854	0.092

Table 49. Correlation between the Eccentric Group's MMG and EMG MNF at 70% MVC for the Trained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.160	0.390	0.632	0.331
	Significance	0.000	0.659	0.265	0.052	0.350
EMG AMP W4	Pearson Correlation	0.000	0.456	0.096	0.525	0.261
	Significance	0.000	0.185	0.792	0.119	0.467
EMG AMP W6	Pearson Correlation	0.000	0.220	0.395	0.529	0.387
	Significance	0.000	0.541	0.258	0.116	0.269
EMG AMP W8	Pearson Correlation	0.000	0.605	0.089	0.614	0.370
	Significance	0.000	0.064	0.808	0.059	0.292

Table 50. Correlation between the Eccentric Group's MMG and EMG MNF at 30% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.048	0.265	0.034	0.245
	Significance	0.000	0.895	0.460	0.925	0.495
EMG AMP W4	Pearson Correlation	0.000	0.253	0.477	0.049	0.629
	Significance	0.000	0.480	0.164	0.893	0.051
EMG AMP W6	Pearson Correlation	0.000	0.355	0.183	0.477	0.349
	Significance	0.000	0.315	0.612	0.164	0.322
EMG AMP W8	Pearson Correlation	0.000	0.060	0.283	0.072	0.512
	Significance	0.000	0.870	0.429	0.843	0.130

Table 51. Correlation between the Eccentric Group's MMG and EMG MNF at 50% MVC for the Untrained Arm

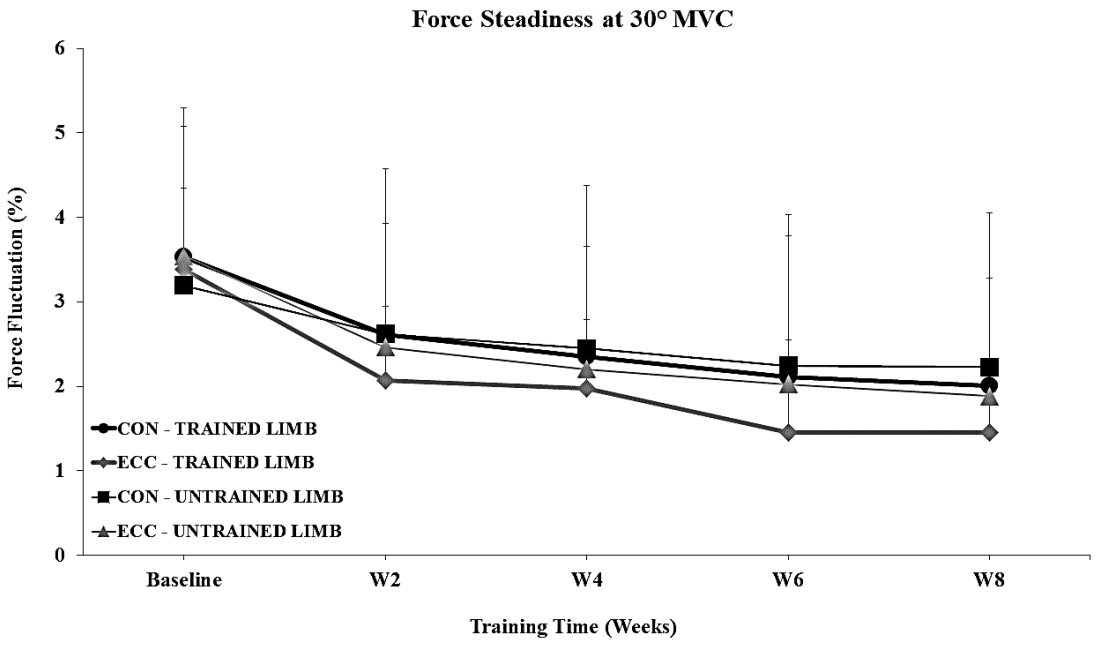
		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.519	0.324	0.064	0.462
	Significance	0.000	0.124	0.360	0.860	0.179
EMG AMP W4	Pearson Correlation	0.000	0.386	0.500	0.362	0.269
	Significance	0.000	0.271	0.141	0.304	0.452
EMG AMP W6	Pearson Correlation	0.000	0.498	0.526	0.319	0.312
	Significance	0.000	0.143	0.118	0.368	0.381
EMG AMP W8	Pearson Correlation	0.000	0.261	0.327	0.063	0.058
	Significance	0.000	0.467	0.357	0.862	0.873

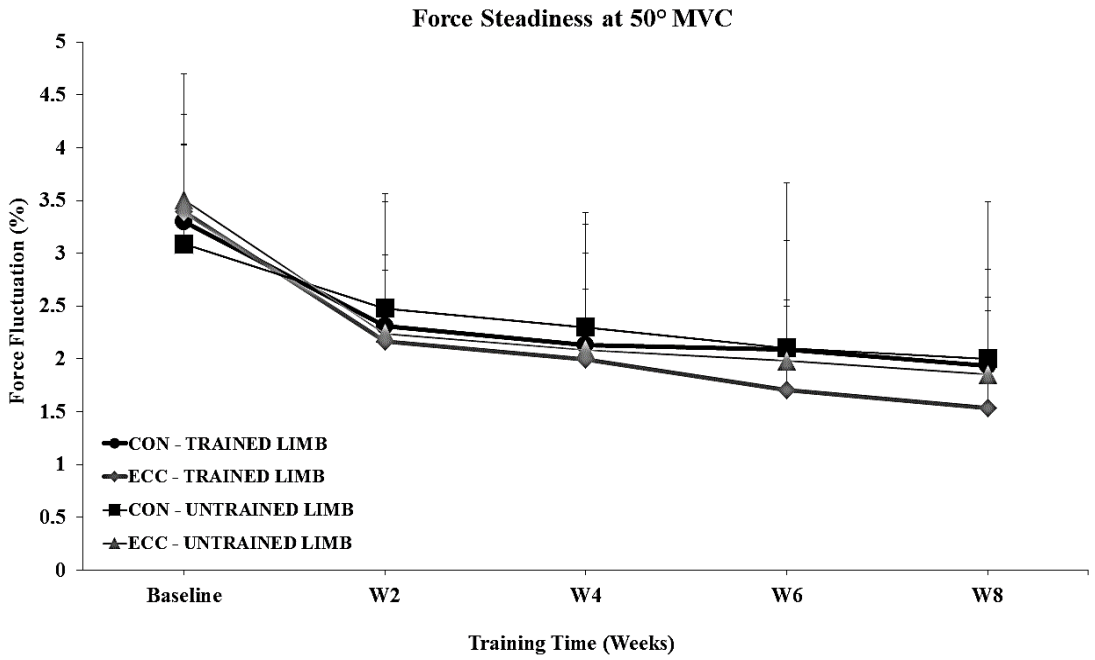
Table 52. Correlation between the Eccentric Group's MMG and EMG MNF at 70% MVC for the Untrained Arm

		MMG AMP Baseline	MMG AMP W2	MMG AMP W4	MMG AMP W6	MMG AMP W8
EMG AMP Baseline	Pearson Correlation	0.000	0.000	0.000	0.000	0.000
	Significance	0.000	0.000	0.000	0.000	0.000
EMG AMP W2	Pearson Correlation	0.000	0.209	0.265	0.463	0.623
	Significance	0.000	0.563	0.459	0.178	0.052
EMG AMP W4	Pearson Correlation	0.000	0.276	0.134	0.625	0.397
	Significance	0.000	0.440	0.711	0.051	0.256
EMG AMP W6	Pearson Correlation	0.000	0.374	0.319	0.066	0.028
	Significance	0.000	0.287	0.369	0.857	0.939
EMG AMP W8	Pearson Correlation	0.000	0.200	0.542	0.175	0.059
	Significance	0.000	0.579	0.105	0.629	0.872

The results from the bivariate correlation analysis of MMG and EMG AMP and MNF indicated that there were no statistically significant correlations between the AMP or MNF components from either measurement for either training group.

4.12. Force Steadiness





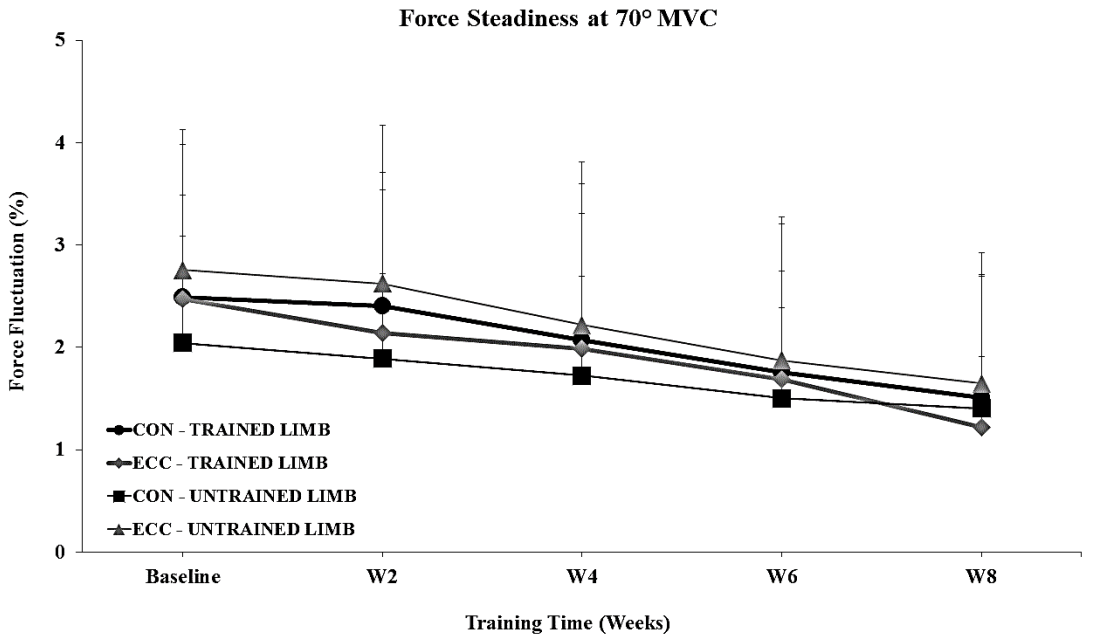
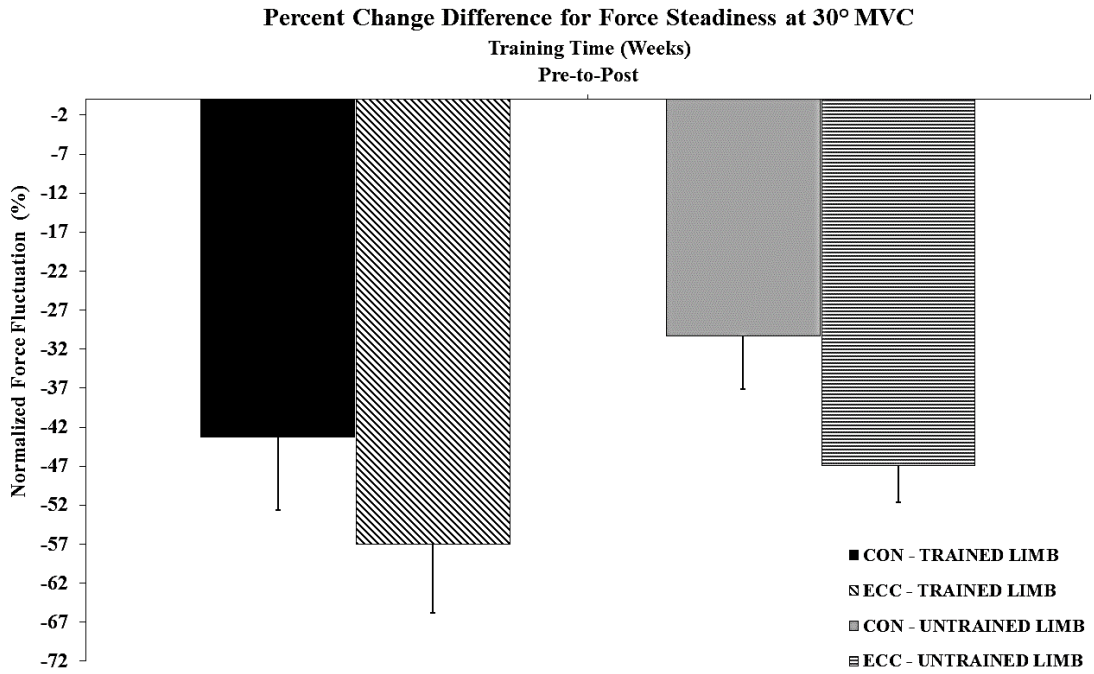
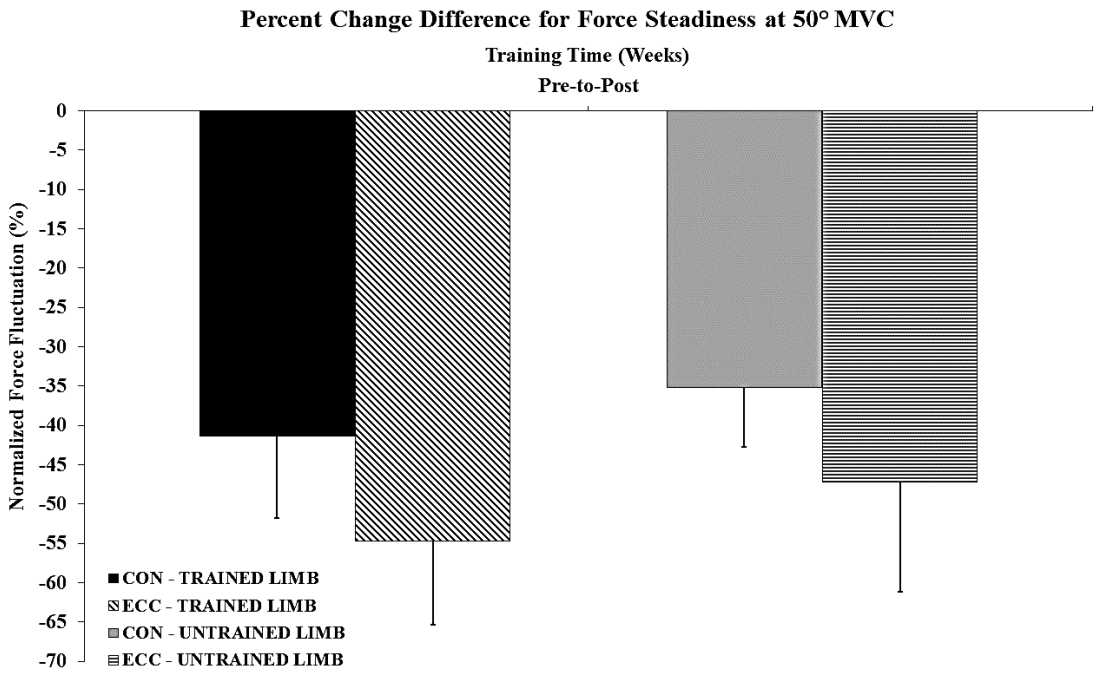


Figure 54. Changes in force steadiness at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (W0 or baseline) to post-measurements (W8). Trained arm for the CON group is depicted by the thick black line with black circles at each time point, while the trained arm for the ECC group is depicted by the thick grey line with grey diamonds at each time point. Furthermore, the untrained arm for the CON group is depicted by the thin black line with black squares at each time point, while the untrained arm for the ECC group is depicted by the thin grey line with grey triangles at each time point.




Percent Change Difference for Force Steadiness at 50° MVC
Training Time (Weeks)
Pre-to-Post
Normalized Force Fluctuation (%)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
-70
CON - TRAINED LIMB
ECC - TRAINED LIMB
CON - UNTRAINED LIMB
ECC - UNTRAINED LIMB

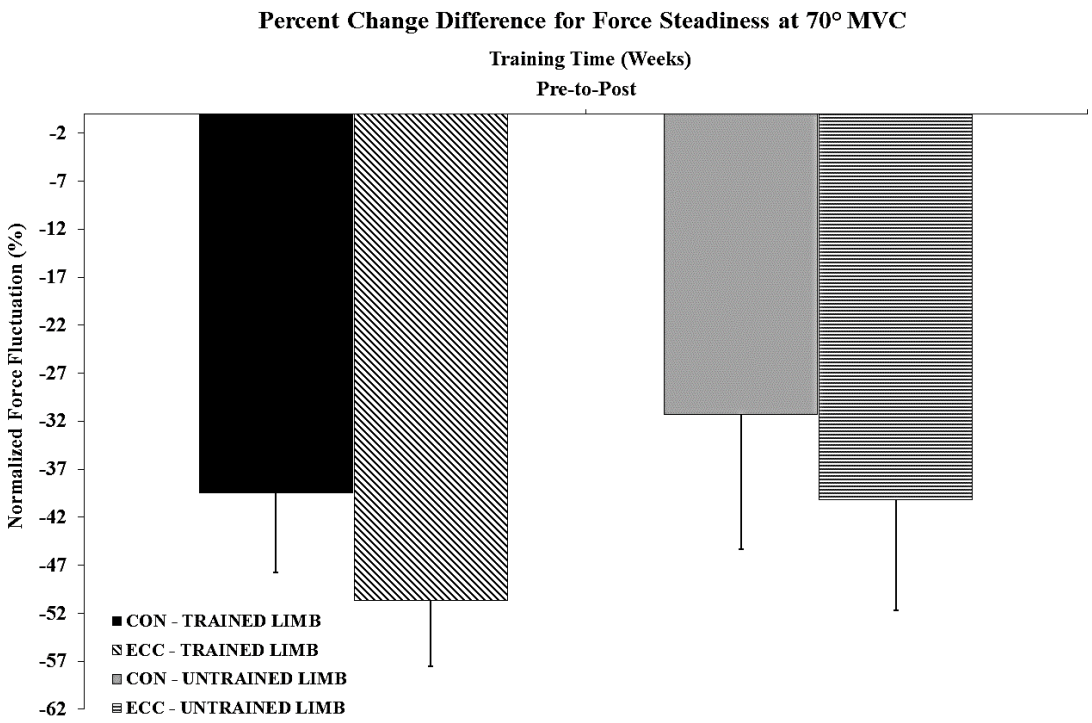


Figure 55. Percent change difference for normalized force fluctuation at 30% MVC (top), 50% MVC (middle), and 70% (bottom) MVC from pre-measurements (week 0 or baseline) to post-measurements (week 8). Pre-measurements are related to 0%, while post-measurements are shown on the graph. Trained arm for the CON group is depicted by a black rectangle (far left), while the trained arm for the ECC group is depicted by the angular black and white stripe rectangle (middle left). Furthermore, the untrained arm for the CON group is depicted by a grey rectangle (middle right), while the untrained arm for the ECC group is depicted by the horizontal black and white strip rectangle (far right).

The results from the four-way repeated measures ANOVA for force steadiness indicated a statistically significant two-way interaction for group and time ($p = 0.004$ and $\eta^2 = 0.337$), and a main effect for intensity ($p = 0.046$ and $\eta^2 = 0.348$) and time ($p = < 0.001$ and $\eta^2 = 0.089$), respectively. For the main effect for intensity, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a significant mean difference across time ($p = 0.001$ and $\eta^2 = 0.18$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following intensities:

Table 53. Paired Samples T-Test for Intensity – Force Steadiness

Intensity	P-value	Cohen's *d*
30% MVC vs. 50% MVC	0.007	0.32
30% MVC vs. 70% MVC	0.001	0.51
50% MVC vs. 70% MVC	0.042	0.21

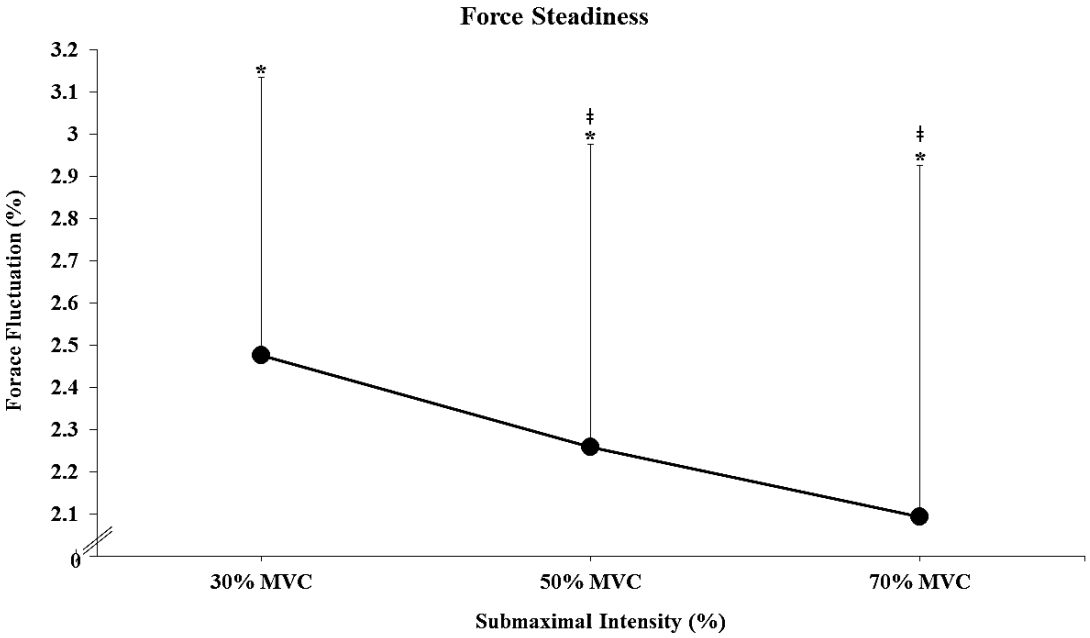


Figure 56. Changes in force steadiness across intensity (30% MVC to 70% MVC). An asterisk (*) signifys a significant difference between 30% MVC versus subsequent intensities; and a palatal click (ǂ) signifys a significant difference between 50% MVC versus subsequent intensities.

For the main effect for time, a one-way repeated measures ANOVA with Bonferroni post-hoc comparisons was performed and the results indicated a statistically significant mean difference across time ($p = < 0.001$ and $\eta^2 = 0.212$). Follow-up paired samples t-tests were performed and the results indicated that there were significant mean differences between the following time points:

Table 54. Paired Samples T-Test for Time – Force Steadiness

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.66
Baseline vs. Week 4	< 0.001	0.78
Baseline vs. Week 6	< 0.001	0.83
Baseline vs. Week 8	< 0.001	0.81
Week 2 vs. Week 4	0.040	0.16
Week 2 vs. Week 6	0.008	0.24
Week 2 vs. Week 8	0.006	0.21

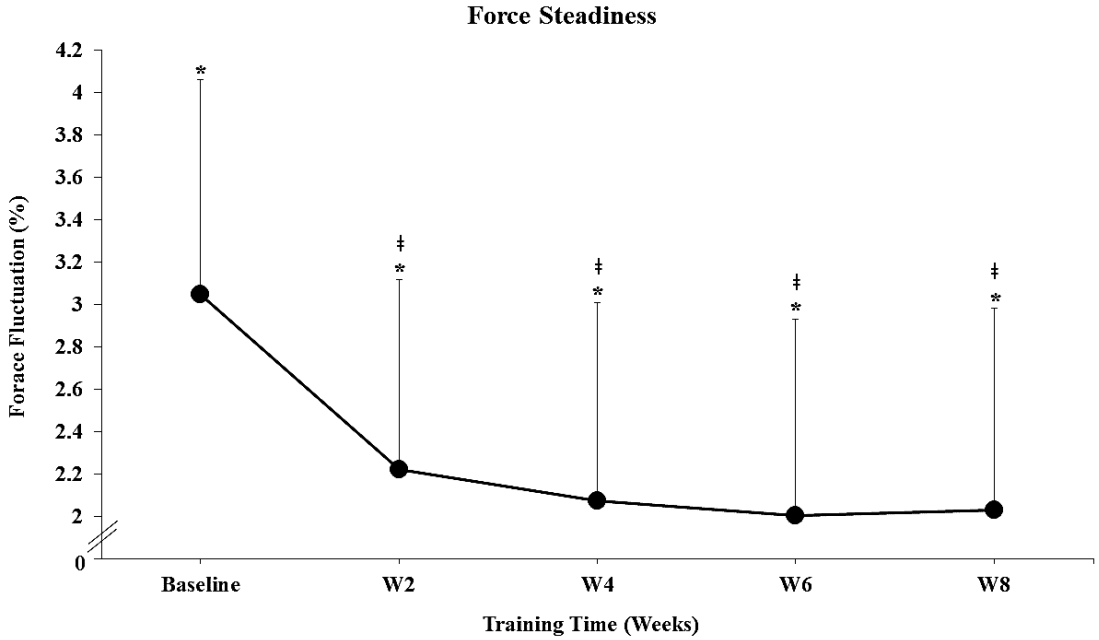


Figure 57. Changes in force steadiness across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

As for the interaction between group and time, a two-way repeated measures ANOVA with Bonferroni post-hoc comparison was performed and the results indicated a statistically significant interaction for group and time ($p = < 0.001$ and $\eta^2 = 0.138$), and a main effect for group ($p = 0.002$ and $\eta^2 = 0.147$). For the main effect for group, a paired samples t-test was considered appropriate to be performed and the results

indicated a statistically significant mean difference between groups ($p = 0.002$ and $d = 0.52$). For the interaction between group and time, two separate, one-way repeated measures ANOVAs with Bonferroni post-hoc comparisons were performed and the results indicated a statistically significant mean difference across time for the CON ($p = < 0.001$ and $\eta^2 = 0.322$) and ECC ($p = < 0.001$ and $\eta^2 = 0.113$) groups, respectively. For the CON group, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 55. Paired Samples T-Test for Time – Group x Time Interaction – Force Steadiness for Concentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 2	< 0.001	0.87
Baseline vs. Week 4	< 0.001	1.02
Baseline vs. Week 6	0.002	0.96
Baseline vs. Week 8	< 0.001	1.15
Week 2 vs. Week 4	< 0.001	0.23
Week 2 vs. Week 8	< 0.001	0.41

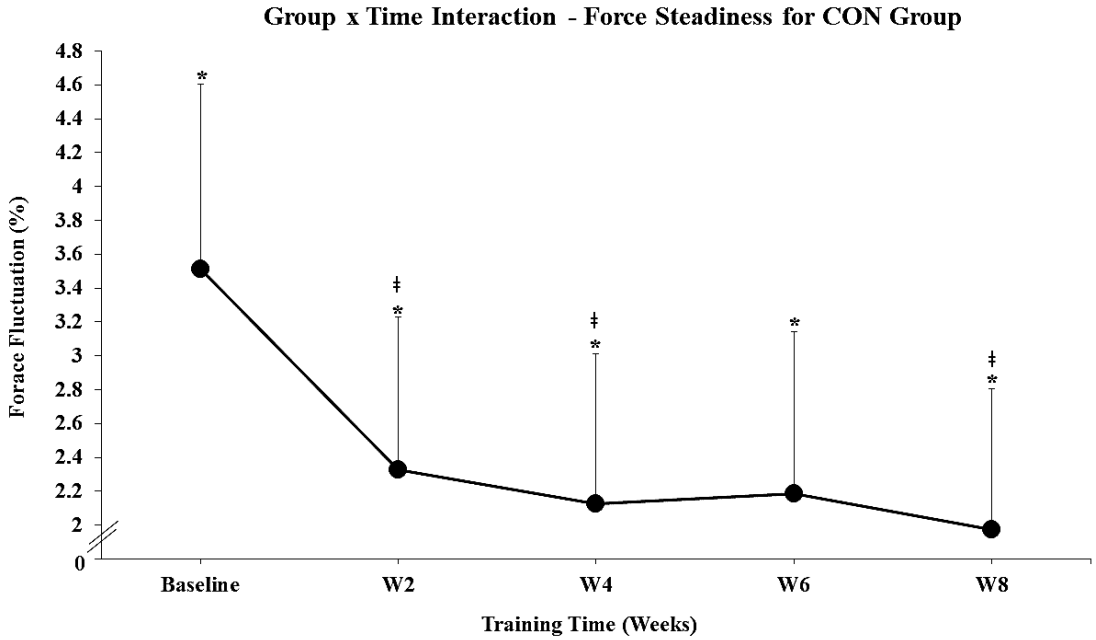


Figure 58. Changes in force steadiness for the concentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements.

For the ECC group, follow-up paired samples t-tests were performed and the results indicated that there were statistically significant mean differences between the following time points:

Table 56. Paired Samples T-Test for Time – Group x Time Interaction – Force Steadiness for Eccentric Group

Time	P-value	Cohen's *d*
Baseline vs. Week 2	0.011	0.41
Baseline vs. Week 4	0.003	0.47
Baseline vs. Week 6	< 0.001	0.75
Baseline vs. Week 8	0.032	0.38
Week 2 vs. Week 6	0.003	0.36
Week 6 vs. Week 8	0.002	0.32

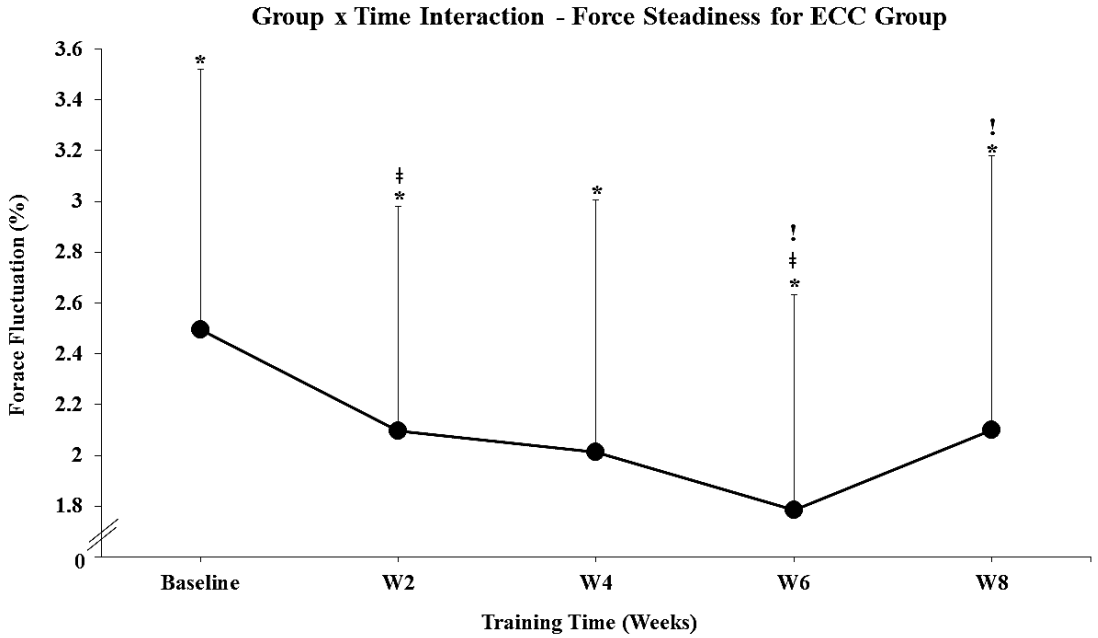


Figure 59. Changes in force steadiness for the eccentric group across time (pre-measurements [W0 or baseline] to post-measurements [W8]). An asterisk (*) signifys a significant difference between pre-exercise versus post-exercise measurements; and a palatal click (ǂ) signifys a significant difference between week 2 measurements versus subsequent post-exercise measurements; and an exclamation point (!) signifys a significant difference between week 6 measurements versus subsequent post-exercise measurements.

4.12. Discussion

The primary focus of this investigation was to compare the training adaptations elicited from CON versus ECC exercise programs. The secondary focus was to evaluate which training adaptation provides a greater contralateral cross-educational adaptation between homologous muscles. Based off our results it would appear that when ECC and CON exercises are performed in isolation, ECC training causes a greater stimulus for promoting physiological adaptations (e.g., greater increase in CSA, maximal dynamic and isometric strength, and a greater decrease in force fluctuations [e.g., force steadiness improves]) across time. Furthermore, these physiological adaptations are not only greater in the trained arm, but it also appears that they are greater in the untrained arm through inter-lateral transfer of sensorimotor adaptations. However, we need to

also mention that even though we observed an increase in the CSA for the untrained limb (which may suggest a hypertrophic effect due to a statistically significant increase in arm circumference), we still believe that this increase in volume is not due to a true hypertrophic effect, but may be potentially attributed to fluid shifts in the intracellular/extracellular matrix, or simply a measurement error by the tester.

4.12.1. Cross-Sectional Area

In our investigation, we found a positive percent change difference of 13.19 ± 4.33% and 7.14 ± 5.75%, and 21.03± 6.58% and 15.82 ± 11.12% for the trained and untrained BB muscles from the CON and ECC trained groups, respectively. Thus, the ECC trained group increased ~8% and ~8.5% more than the CON trained group in their trained and untrained arms from pre-to-post exercise, respectively. These results are consistent to those results found in the investigations of Hortobagyi *et al*., (2000), and Farthing & Chilibeck, (2003), both of which had their subjects perform isokinetic CON and ECC training. Specifically, in the Hortobagyi *et al*., (2000) article, these authors found that after 12 weeks of isolated CON or ECC leg extensions/curls the CSA of the quadriceps muscles, and of the Type IIA and IIX fibers, were greatest after ECC training (when compared to CON training). Furthermore, in the Farthing & Chilibeck (2003) article, these authors found that after 8 weeks of isolated CON or ECC bicep curls the CSA of the elbow flexors for the fast ECC training increased ~8% more than the fast CON training, while both slow ECC and CON training were similar and less than the results found with the fast training modality. Both sets of authors concluded

that adaptations to training with ECC exercise are associated with greater increases in neural drive and muscle hypertrophy (when compared to CON exercise).

4.12.2. Dynamic Strength

In our investigation, we found a positive percent change difference of 34.86 ± 13.75% and 13.45 ± 7.82%, and 50.91 ± 14.05% and 30.78 ± 5.32% for the trained and untrained BB muscles from the CON and ECC trained groups, respectively. Thus, the ECC trained group increased ~16% and ~17% more than the CON trained group in their trained and untrained BB muscles from pre-to-post exercise, respectively. These results are consistent to those found in the investigations of Seger *et al.*, (1998), and Vikne *et al*., (2006), both of which had their subjects perform isokinetic CON or ECC training. Specifically, in the Seger *et al*., (1998) article, these authors found that after 10 weeks of isolated CON or ECC leg extensions, the ECC trained group increased their VL muscle strength 20% more than the CON trained group. Furthermore, in the Vikne *et al.*, (2006) article, these authors found that after 12 weeks of isolated CON or ECC bicep curl, the ECC trained group increased their forearm flexor strength ~8% more than the CON trained group. Both authors reasoned that ECC training is superior to CON training due to changes in neural drive, recruitment pattern efficiency, and inhibition of protective mechanisms.

4.12.3. Isometric Strength

In our investigation, we found a positive percent change difference of 15.22 ± 2.01% and 12.67 ± 5.48%, and 26.17 ± 6.41% and 21.18 ± 5.04% for the trained and

untrained BB muscles from the CON and ECC trained groups, respectively. Thus, the ECC trained group increased ~11% and ~8.5% more than the CON trained group in their trained and untrained BB muscle from pre-to-post exercise, respectively. These results are consistent to those found in the investigations of Lastayo *et al*., (1999) and Mjølsnes *et al*., (2004), both of which had their subjects perform dynamic CON and ECC training. Specifically, in the Lastayo *et al*., (1999) article, these authors found that after 6 weeks of CON or ECC leg extensions the ECC trained group increased their isometric knee extensor strength ~15% more than the CON trained group. Furthermore, in the Mjølsnes *et al*., (2004) article, these authors found that after 10 weeks of CON or ECC hamstring curls (traditional and Nordic) the ECC trained group increased their isometric hamstring strength ~7% more than the CON trained group. Both sets of authors believed that submaximal ECC training causes greater adaptations through the mediation of multiple mechanical and neural factors cyclically contributing to strength increases across time.

4.12.4. Mechanomyographic Amplitude

In our investigation, we found a positive percent change difference of 20.5 ± 9.45% and 11.63 ± 7.38%, and 40.69 ± 3.64% and 32.61 ± 8.97%; 17.27 ± 5.23% and 10.64 ± 10.03%, and 32.27 ± 4.25% and 19.54 ± 6.1%; and 35.85 ± 5.76% and 15.81 ± 7.71%, and 42.52 ± 2.91% and 22.69 ± 6.92% for the trained and untrained BB muscles from the CON and ECC trained groups at 30% MVC, 50% MVC, and 70% MVC, respectively. Thus, the ECC trained group increased ~20% and ~21%, ~15% and ~9%, and ~7% and ~7% more than the CON trained group in their trained and untrained BB

muscles at 30% MVC, 50% MVC, and 70% MVC from pre-to-post exercise, respectively. These results are not consistent to those found in the investigations of Dalton & Stokes, (1991), and Smith *et al*., (1998), both of which had their subjects perform isokinetic CON and ECC exercise. Specifically, in the Dalton & Stokes, (1991) article, these authors found that during fatiguing bicep curls the MMG AMP values related to CON training were consistently greater than those for the ECC training for the forearm flexors. Furthermore, in the Smith *et al*., (1998) article, these authors found that during maximal bicep curls at 30°, 90°, and 150° s^{-1} the MMG AMP of the forearm flexors increased linearly and were statistically insignificant between CON and ECC training. Both sets of authors reasoned that differences/similarities between training modalities were due to muscular stiffness, velocity-related dissociations, specificity of cross-bridge dynamics, turbulence of cellular mediums, or a neural inhibitory mechanism to maintain muscle tension during ECC training to protect the muscle from injury.

4.12.5. Mechanomyographic Mean Frequency

In our investigation, we found a negative percent change difference of 23.78 ± 5.98% and 10.55 ± 3.12%, and 22.61 ± 13.5% and 8.92 ± 12.17%; 22.57 ± 11.24% and 18.3 ± 10.66%, and 21.6 ± 11.41% and 8.18 ± 9.09%; and 25.71 ± 10.21% and 19.74 ± 10.96%, and 24.33 ± 4.01% and 15.84 ± 1.79% for the trained and untrained BB muscles from CON and ECC groups at 30% MVC, 50% MVC, and 70% MVC, respectively. Thus, the CON trained group decreased ~1% and ~1.5%, ~1% and ~10%, and ~1.5% and ~4% more than the ECC trained group in their trained and untrained

arms at 30% MVC, 50% MVC, and 70% MVC from pre-to-post exercise, respectively. These results are not consistent to those found in the investigations of Madeleine *et al*., (2001), and Jaskolska *et al*., (2007), both of which had their subjects perform isometric CON and ECC contractions. Specifically, in Madeleine *et al*., (2001) article, these authors found that during abduction of the index finger of 0%, 25%, 50%, 75% and 100% MVC the MMG MNF of the FDI muscle remained similar between CON training than ECC training throughout all contractions. Furthermore, in the Jaskolska *et al*., (2007) article, these authors found that during isometric bicep curls of 10%, 30%, 50% and 70% MVC the MMG MNF of the BB muscle remained similar between CON training and ECC training throughout all contractions. These authors reasoned that the similarities were due to modified firing rate modulation patterns from less active motor units during ECC training. Both sets of authors reasoned that muscle stiffness was not a contributing factor between CON and ECC exercise.

4.12.6. Electromyographic Amplitude

In our investigation, we found a positive percent change difference of 18.41 ± 8.73% and 12.85 ± 7.4%, and 51.94 ± 10.3% and 29.43± 4.97%; 22.91 ± 10.19% and 11.6 ± 6.95%, and 44.96 ± 11.77% and 28.1 ± 3.95%; and 10.72 ± 5.57% and 11.97 ± 8.6%, and 39.02 ± 5.01% and 19.38 ± 8.27% for the trained and untrained BB muscles from CON and ECC groups at 30% MVC, 50% MVC, and 70% MVC, respectively. Thus, the ECC trained group increased ~33.5% and ~16.5%, ~22% and ~16.5%, and ~28% and ~7.5% more than the CON trained group in their trained and untrained arms at 30% MVC, 50% MVC, and 70% MVC, respectively. These results are consistent to

those found in the investigations of Hortobagyi *et al*., (1996) and Carvalho *et al*., (2014), with the former having their subjects perform isokinetic training, while the latter had their subjects perform dynamic training. Specifically, in Hortobagyi *et al*., (1996) article, these authors found that after 6 weeks of CON or ECC training that the ECC training group increased their EMG AMP of the quadriceps muscles by 74% more than the CON training group. Furthermore, in the Carvalho *et al*., (2014) article, these authors found that after 8 weeks of CON or ECC training, the ECC training group was able to increase their EMG AMP significantly more than the CON training group for all quadriceps muscles. Both sets of authors have determined that neural adaptations contribute more during ECC training than during CON training.

4.12.7. Electromyographic Mean Frequency

In our investigation, we found a negative percent change difference of 7.77 ± 5.41% and 5.4 ± 6.13, and 6.57 ± 5.84% and 4.35 ± 2.7%; 10.59 ± 5.03% and 8.05 ± 4.23 %, and 7.85 ± 8.54% and 6.19 ± 6.66%; and 9.54 ± 5.98% and 7.51 ± 4.69 %, and 7.92 ± 7.1% and 5.68 ± 7.31% for the trained and untrained BB muscles from CON and ECC groups at 30% MVC, 50% MVC, and 70% MVC, respectively. Thus, the CON trained group decreased ~1% and ~1%, ~3% and ~2%, and ~1.5% and ~2% more than the ECC trained group in their trained and untrained arms at 30% MVC, 50% MVC, and 70% MVC, respectively. These results are consistent to those found in the investigations of Tesch *et al*., (1990), and Linnamo *et al*., (2000), both of which had their subjects perform dynamic maximum CON and ECC exercise. Specifically, in the Tesch *et al*., (1990) article, these authors found that during fatiguing unilateral ECC

and CON leg extensions EMG MNF decreased more with CON training than ECC training for the quadriceps muscles. Furthermore, in the Linnamo *et al*., (2000) article, these authors found that during fatiguing unilateral ECC and CON bicep curl EMG MNF decreased more with CON training than ECC training for the forearm flexors. Both authors reasoned that the differences were due to modified recruitment and/or firing rate modulation patterns from higher threshold motor units during ECC training associated with muscle damage and not fatigue.

4.12.8. Force Steadiness

In our investigation, we found a positive percent change difference of 43.22 ± 13.52% and 30.31 ± 13.25%, and 57.05 ± 10.47% and 46.92 ± 8.75%; 41.36 ± 11.22% and 35.18 ± 9.68%, and 54.73 ± 13.95% and 47.17 ± 14.29%; and 39.25 ± 13.04% and 31.3 ± 10.46%, and 50.7 ± 12.72% and 40.16 ± 13.56% for the trained and untrained BB muscles from CON and ECC groups at 30% MVC, 50% MVC, and 70% MVC, respectively. Thus, the ECC trained group decreased force fluctuation ~13.8% and ~16.6%, ~13.4% and ~12%, and ~11.5% and ~8.9% more than the CON trained group in their trained and untrained arms at 30% MVC, 50% MVC, and 70% MVC, respectively. These results are different to those found in the investigations of Ye *et al*., (2015). In Ye *et al*., (2015), the authors found that after an acute training of CON or ECC bicep curls that there was a greater loss in force steadiness (increase in force fluctuation) for the ECC training group than the CON training group. These authors reasoned that the modulations of motor unit firing behavior, in addition to mechanical

property changes to the muscle after the ECC exercise at least partially contributed to the greater increase in force fluctuation.

4.12.9. Contralateral Strength Training

In our investigation, we found a positive percent change difference of 13.45 ± 7.82% and 12.67 ± 5.48%, and 30.78 ± 5.32% and 21.18 ± 5.04% for dynamic and isometric strength, respectively, in the untrained BB muscle from the CON and ECC trained groups, respectively. Thus, the ECC trained group increased ~17.3% and ~8.5% more than the CON trained group in their untrained BB muscle dynamic and isometric strength, respectively, from pre-to-post exercise, respectively. Our results are consistent to those found in the investigations of Hortobagyi *et al*., (1997), and Grabiner & Owings (1999), both of which reported a considerably greater cross-over responses and cross-educational adaptation after unilateral ECC as compared to CON training. Specifically, in the Hortobagyi *et al*., (1997) article, theses authors found that after 12 weeks of unilateral leg extension/curls, the ECC training group increased their contralateral ECC dynamic strength by 77% as compared to the 30% increase in dynamic strength observed with the CON training group. Additionally, the ECC training group also increase their contralateral isometric strength by 39%, as compared to 22% by the CON trained group. Furthermore, in the Grabiner & Owings (1999) article, these authors found that following 75 isokinetic CON and ECC MVCs with unilateral knee extensors there was a greater contralateral cross-over response for strength in the ECC training (when compared to the CON training). Both sets of authors reasoned that this increase in cross-over responses and cross-educational adaptations

following training with muscle lengthening was due to different activation patterns of afferent and efferent mechanisms that allowed the previously untrained subjects limb to increase their respective activation levels.

Summary

The results from this investigation suggested that when compared to CON training, ECC training provided a greater increase in trained and untrained muscle CSA, dynamic and isometric strength, and force steadiness (less force fluctuation). Furthermore, it would also appear that the contralateral cross-educational adaptation was more prominent for ECC training, when compared to the CON training. Given the conflicting evidence within the literature, it appears that our results could be attributed (at least in partially) to an array of independent variables. However, we believe that our results are due to the capacity to achieve higher forces, and using less energy, during ECC exercise. Specifically, one ATP must be used to detach each cross-bridge during CON exercise, while during ECC exercise most cross-bridges are forcibly detached without the use of any ATP, which inadvertently causes the myofilaments to experience sarcomere strain or "muscular damage". Additionally, it is common knowledge that even though the cross-bridges are uncoupling, an increased percentage of them remain attached, thus aiding in the force production capabilities during ECC exercise. Another possible reason could be attributed to an increase in neural drive and a decrease in corticospinal inhibition, which would cause a greater cross-education effect due to a larger percentage of neural impulses remaining on the ipsilateral side of the body and not crossing over (at the medulla oblongata) to the contralateral side.

4.12.10. Contributions to the Literature

We are the first investigators to provide evidence of an increase in CSA of the untrained arm following 8 weeks of unilateral CON and ECC exercise (with ECC training providing a greater CSA). Furthermore, we are also the first to suggest that MMG and EMG AMP increase (with ECC training providing a greater AMP), while MMG and EMG MNF signals decrease for CON and ECC exercise (with CON training providing a greater MNF) for the trained and untrained BB muscles across training time. Lastly, we are the first to show that force steadiness improves across time following unilateral CON and ECC exercise (with ECC training providing a greater improvement) for the trained and untrained BB muscles.

4.12.11. Possible weaknesses of the investigation

As stated previously, one weakness of this study was that we were not able to be with our subjects throughout the entire day. Thus, some subjects may have inadvertently used their untrained arm for other activities (i.e., walking a dog, painting a room in their house, planting a garden, etc.), which would have allowed their untrained arm to potentially increase in volume and become stronger as a result. Additionally, although this study was not powered to consider sex as an independent variable, it is possible that neural and hypertrophic changes could have influenced it. Therefore, if we were to separate data by gender, we may potentially observe different results than what was presented in this investigation. Lastly, any similarities and/or differences used for comparison between our investigation and the other investigations listed above should be inferred with caution since the specificity of exercise and mode

of evaluation are unique to this study alone. Hence, it is rather difficult to compare results when there are so very few similar investigation in the literature.

Chapter V

Conclusion

The primary focus of this investigation was to compare the training adaptations elicited from CON versus ECC exercise programs. The secondary focus was to evaluate which training stimulus provides a greater contralateral cross-educational adaptation between homologous muscles. Subjects were assessed for possible changes in upper arm CSA, dynamic and isometric strength, and force steadiness. The following conclusions were drawn:

1. Consistent with our original hypothesis, subjects experienced a greater increase in dynamic strength from ECC training when compared to CON training in the trained arm.
2. Consistent with our original hypothesis, subjects experienced a greater increase in isometric strength from ECC training when compared to CON training in the trained arm.
3. Consistent with our original hypothesis, subjects experienced a greater increase in force steadiness during the plateau phase of the submaximal trapezoidal force tracing from ECC training when compared to CON training in the trained arm.
4. Consistent with our original hypothesis, subjects experienced a greater cross-educational adaptation in dynamic strength from ECC training when compared to CON training in untrained arm.

5. Consistent with our original hypothesis, subjects experienced a greater cross-educational adaptation in isometric strength from ECC training when compared to CON training in untrained arm.
6. Consistent with our original hypothesis, subjects experienced a greater cross-educational adaptation in force steadiness during the plateau phase of the trapezoidal force tracing from the ECC training when compared to the CON training in untrained arm.

5.1. Recommendations for Future Studies

1. Future investigations need to be performed to examine the effect of gender on cross-education.
2. Future investigations need to examine age differences on cross-education and force steadiness.
3. Future investigations need to utilize a longer training time (i.e., 12 weeks).
4. Future investigations need to apply this training modality to clinical populations.
5. Future investigations need to apply this training modality to lower body dynamics.

References

Aboodarda S, Sambaher N, & Behm D. 2016 Unilateral elbow flexion fatigue modulates corticospinal responsiveness in non-fatigued contralateral biceps brachii. *Scand J Med Sci Sports* 26: 1301-1312.

Adrian E & Bronk D. 1929 The discharge of impulses in motor nerve fibres. Part II. The frequency of discharge in reflex and voluntary contractions. *J Physiol* 67: 119-151.

Allen R. 1948 Factors in mirror drawing. *J Educ Psychol* 39: 216-226.

Amiridis I, Martin A, Morlon B, Martin L, Cometti G, Pousson M, & van Hoecke J. 1996 Co-activation and tension-regulating phenomena during isokinetic knee extension in sedentary and highly skilled humans. *Eur J Appl Physiol* 73(1): 149-156.

Angel R. 1977 Antagonist muscle activity during rapid arm movements: central versus proprioceptive influences. *J Neurol Neurosurg Psychiatry* 40: 683-686.

Asmussen E & Mazin B. 1978 A central nervous component in local muscular fatigue. *Eur J Appl Physiol Occup Physiol* 38: p. 9-15.

Asmussen E. & Mazin B. 1978 Recuperation after muscular fatigue by "diverting activities". *Eur J Appl Physiol Occup Physiol* 38: p. 1-7.

Balshaw T, Massey G, Maden-Wilkinson T, Morales-Artacho A, McKeown A, Appleby C, & Folland J. 2017 Changes in agonist neural drive, hypertrophy and pre-training strength all contribute to the individual strength gains after resistance training. *Eur J Appl Physio* 117: 631-640.

Bajaj P, Madeleine P, Sjøgaard G, & Arendt-Nielsen L. 2002 Assessment of postexercise muscle soreness by electromyography and mechanomyography. *J Pain* 3: 126–136.

Baweja H, Patel B, Martinkewiz J, Vu J, & Christou E. 2009 Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Exp Brain Res* 197: 35-47.

Beck T, Housh T, Johnson G, Weir J, Cramer J, Coburn J, & Malek M. 2006 Mechanomyographic and electromyographic responses during submaximal to maximal eccentric isokinetic muscle actions of the biceps brachii. *J Strength Cond Res* 20: 184-191.

Beck T, Ye X, & Wages N. 2016 Differential effects of unilateral concentric vs. eccentric exercise on dominant and nondominant forearm flexors. *J Strength Cond Res* 30: 703-709.

Beck T, Kasishke P 2nd, Stock M, & DeFreitas J. 2012a. Eccentric exercise does not affect common drive in the biceps brachii. *Muscle Nerve* 46, 759-766.

Beck T, Stock M, & DeFreitas J. 2012b Effects of Fatigue on Intermuscular Common Drive to the Quadriceps Femoris. *Int J Neurosci* 122: 574-582.

Bell C. 1823 *The anatomy and physiology of the human body.* 7 ed. London: Philosoph Trans Roy Soc.

Bellemare F, Woods J, Johansson R, & Bigland-Ritchie B. 1983 Motor-unit discharge rates in maximal voluntary contractions of three human muscles. *J Neurophysiol* 50: 1380-1392.

Bigland B & Lippold O. 1954 Motor unit activity in the voluntary contraction of human muscle. *J Physiol* 125: 322-335.

Bonato C, Zanette G, Manganotti P, Tinazzi M, Bongiovanni G, Polo A, & Fiaschi A. 1996 'Direct' and 'crossed' modulation of human motor cortex excitability following exercise. *Neurosci Lett* 216: 97-100.

Broman H, De Luca C, & Mambrito B. 1985 Motor unit recruitment and firing rates interaction in the control of human muscles. *Brain Res* 337: 311-319.

Burnett R, Laidlaw D, & Enoka R. 2000 Coactivation of the antagonist muscle does not covary with steadiness in old adults. *J Appl Physiol* 89: 61-71.

Cadore E, González-Izal M, Pallarés J, Rodriquez-Falces J, Häkkinen K, Kraemer W, Pinto R, & Izquierdo M. 2014 Muscle conduction velocity, strength, neural activity, and morphological changes after eccentric and concentric training. *Scand J Med Sci Sports* 24: e343-e352.

Camic C, Housh T, Zuniga J, Bergstrom H, Schmidt R, & Johnson G. 2014 Mechanomyographic and electromyographic responses during fatiguing eccentric muscle actions of the leg extensors. *J Appl Biomech* 30: 255-261

Carolan B & Cafarelli E. 1992 Adaptations in coactivation after isometric resistance training. *J Appl Physiol* 73: 911-917.

Carroll T, Herbert R, Munn J, Lee M, & Gandevia S. 2006 Contralateral effects of unilateral strength training: evidence and possible mechanisms. *J Appl Physiol* 101: 1514-1522.

Carvalho A, Caserotti P, Carvalho C, Abade E, & Sampaio J. 2014 Effect of short time concentric versus eccentric training program on electromyography activity and peak torque of quadriceps. *J Hum Kinet* 41: 5-13.

Clamann H. 1970 Activity of single motor units during isometric tension. *Neurology* 20: 254-260.

Cramer J, Housh T, Weir J, Johnson G, Ebersole K, Perry S, & Bull A. 2002 Power output, mechanomyographic, and electromyographic responses to maximal, concentric, isokinetic muscle actions in men and women. *J Strength Cond Res* 16: 399-408.

Dalton P & Stokes M 1993 Frequency of acoustic myography during isometric contraction of fresh and fatigued muscle and during dynamic contractions. *Muscle Nerve* 16: 255-261.

Davis W. 1899 Cross-education. *Science* 10: 20-21.

Davies C & White M. 1981 Muscle weakness following eccentric work in man. *Pflügers Archiv* 392: 168–171

De Luca C & Contessa P. 2012 Hierarchical control of motor units in voluntary contractions. *J Neurophysiol* 107: 178-195.

De Luca C & Hostage E. 2010 Relationship between firing rate and recruitment threshold of motoneurons in voluntary isometric contractions. *J Neurophysiol* 104: 1034-1046.

De Luca C & Kline J. 2012 Influence of proprioceptive feedback on the firing rate and recruitment of motoneurons. *J Neural Eng* 9: 016007. DOI: 10.1088/1741-2560/ 9/1/016007.

De Luca C & Mambrito B. 1987 Voluntary control of motor units in human antagonist muscles: coactivation and reciprocal activation. *J Neurophysiol* 58: 525-542.

De Luca C & Nawab S. 2011 Reply to Farina and Enoka: The Reconstruct-and-Test Approach Is the Most Appropriate Validation for Surface EMG Signal Decomposition to Date. *J Neurophysiol* 105: 983-984.

De Luca C, LeFever R, McCue M, & Xenakis A. 1982 Behaviour of human motor units in different muscles during linearly varying contractions. *J Physiol* 329: 113-128.

De Luca C, LeFever R, McCue M, & Xenakis A. 1982 Control scheme governing concurrently active human motor units during voluntary contractions. *J Physiol* 329: 129-142.

De Luca C, Adam A, Wotiz R, Gilmore L, & Nawab S, 2006 Decomposition of surface EMG signals. *J Neurophysiol* 96: 1646-1657.

De Luca C, Gonzalez-Cueto J, Bonato P, & Adam A. 2009 Motor unit recruitment and proprioceptive feedback decrease the common drive. *J Neurophysiol* 101: 1620-1628.

Denny-Brown D & Pennybacker J. 1938 Fibrillation and fasciculation in voluntary muscle. *Brain* 61: 311-312.

Descartes R. 1662 *De homine figuris et latinitate.* **Trans. Schuyl F.** Leiden: Apud Petrum Leffen & Franciscum Moyardum.

Doix A-C, Lefèvre F, & Colson S. (2013). Time course of the cross-over effect of fatigue on the contralateral muscle after unilateral exercise. Plos One 8: e64910. DOI: 10.1371/journal.pone.0064910.

Eason R. 1960 Electromyographic study of local and generalized muscular impairment. *J Appl Physiol* 15: 479-482.

Farthing J & Chilibeck P. 2003 The effects of eccentric and concentric training at different velocities on muscle hypertrophy. *Eur J Appl Physiol* 89: 578-586.

Fridén J, Sfakianos P, Hargens A, & Akeson W. 1988 Residual muscular swelling after repetitive eccentric contractions. *J Orthop Res* 6: 493-498.

Geertsen S, Stecina K, Meehan C, Nielsen J., & Hultborn H. 2011 Reciprocal Ia inhibition contributes to motoneuronal hyperpolarisation during the inactive phase of locomotion and scratching in the cat. *J Physiol* 589: 119-134.

Gilson A & Mills W. 1941 Activities of single motor units in man during slight voluntary efforts. *Am J Physiol* 133: 658-669.

Gordon G & Holbourn A. 1948 The sounds from single motor units in a contracting muscle. *J Physiol* 107: 456–464.

Grabiner M & Owings T. 1999 Effects of eccentrically and concentrically induced unilateral fatigue on the involved and uninvolved limbs. *J Electromyogr Kinesiol* 9: 185-189.

Gydikov A & Kosarov D. 1974 Some features of different motor units in human biceps brachii. *Pflügers Archiv* 347: 75-88.

Henneman E, Somjen G, & Carpenter D. 1965 Excitability and inhibitibility of motoneurons of different sizes. *J Neurophysiol* 28: 599-620.

Henneman E, Somjen G, & Carpenter D. 1965 Functional significance of cell size in spinal motoneurons. *J Neurophysiol* 28: 560-580.

Henneman E & Olson C 1965 Relations between structure and function in the design of skeletal muscles. *J Neurophysiol* 28: 581-598.

Henneman E. 1957 Relation between size of neurons and their susceptibility to discharge. *Science* 126: 1345-1347.

Hermens H, Freriks B, Merletti R, Stegeman D, Blok J, Rau G, Disselhorst-Klug C, & Hägg G. 1999 *SENIAM European recommendations for surface electromyography: results of the SENIAM project.* Enschede, The Netherlands: Roessingh Research and Development.

Higbie E, Cureton K, Warren G 3rd, & Prior B. 1996 Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J Appl Physiol* 81: 2173-2181.

Hill A. 1925 Length of muscle, and the heat and tension developed in an isometric contraction. *J Physiol* 60: 237-263.

Hortobágyi T, Barrier J, Beard D, Braspennincx J, Koens P, Devita P, Dempsey L, & Lambert J. 1996 Greater initial adaptations to submaximal muscle lengthening than maximal shortening. *J Appl Physiol* 81: 1677–1682.

Hortobágyi T, Lambert N, & Hill J. 1997 Greater cross education following training with muscle lengthening than shortening. *Med Sci Sports Exerc* 29: 107-112

Hortobágyi T, Dempsey L, Fraser D, Zheng D, Hamilton G, Lambert J, & Dohm L. 2000 Changes in muscle strength, muscle fibre size and myofibrillar gene expression after immobilization and retraining in humans. *J Physiol* 524: 293-304

Housh D, Housh T, Weir J, Weir L, Evetovich T, & Donlin P. 1998 Effects of unilateral eccentric-only dynamic constant external resistance training on quadriceps femoris cross-sectional area. *J Strength Cond Res* 12: 192-198

Hu X, Rymer W, & Suresh N. 2013a Assessment of validity of a high-yield surface electromyogram decomposition. *J Neuroeng Rehabil* 10: 99. DOI: 10.1186/1743-0003-10-99.

Hu X, Rymer W, & Suresh N. 2013b Motor unit pool organization examined via spike-triggered averaging of the surface electromyogram. *J Neurophysiol* 110: 1205-1220.

Hu X, Rymer W, & Suresh N. 2014a Accuracy assessment of a surface electromyogram decomposition system in human first dorsal interosseous muscle. *J Neural Eng* 11: 026007. DOI: 10.1088/1741-2560/11/2/026007.

Hu X, Rymer W, & Suresh N. 2014b Motor unit firing rate patterns during voluntary muscle force generation: a simulation study. *J Neural Eng* 11: 026015. DOI:10.1088/1741-2560/11/2/026015.

Hubal M, Rubinstein S, & Clarkson P. 2007 Mechanisms of variability in strength loss after muscle-lengthening actions. *Med Sci Sports Exerc* 39: 461-468.

Hubal M, Rubinstein S, & Clarkson P. 2008 Muscle function in men and women during maximal eccentric exercise. *J Strength Cond Res* 22: 1332-1338.

Hufschmidt H & Hufschmidt T. 1954 Antagonist inhibition as earliest sign of a sensory-motor reaction. *Nature* 174: 607. DOI:10.1038/174607a0

Hwangbo P. 2015 The effects of squatting with visual feedback on the muscle activation of vastus medialis oblique and the vastus lateralis in young adults with an increased quadriceps angles. *J Phys Ther Sci* 27: 1507-1510.

Jaskólska A, Kisiel K, Brzenczek W, & Jaskólski A. 2003 EMG and MMG of synergists and antagonists during relaxation at three joint angles. *Eur J Appl Physiol* 90: 58-68.

Kawczyński A, Nie H, Jaskólska A, Jaskólski A, Arendt-Nielsen L, & Madeleine P. 2008 Mechanomyography and electromyography during and after fatiguing shoulder eccentric contractions in males and females. *Scand J Med Sci Sports* 17: 172–179.

Kleine B, Blok J, Oostenveld R, Praamstra P, & Stegeman D. 2000 Magnetic stimulation-induced modulations of motor unit firings extracted from multi-channel surface EMG. *Muscle Nerve* 23: 1005-1015.

Kleine B, van Dijk J, Lapatki B, Zwarts M, & Stegeman D. 2007 Using two-dimensional spatial information in decomposition of surface EMG signals. *J Electromyogr Kinesiol 17*: 535-548.

Knight C & Kamen G. 2008 Relationships between voluntary activation and motor unit firing rate during maximal voluntary contractions in young and older adults. *Eur J Appl Physiol* 103: 625-630.

Komi P, Linnamo V, Silventoinen P Sillanpää M. 2000 Force and EMG power spectrum during eccentric and concentric. *Med Sci Sports Exerc* 32: 1757-1762

Kroon G & Naeije M. 1991 Recovery of the human biceps electromyogram after heavy eccentric, concentric or isometric exercise. *Eur J Appl Physiol Occup Physiol* 63: 444-448.

Kukulka C & Clamann H. 1981 Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor pollicis during isometric contractions. *Brain Res* 219: 45-55.

Kupa E, Roy S, Kandarian S, & De Luca C. 1995 Effects of muscle fiber type and size on EMG median frequency and conduction velocity. *J Appl Physiol* 79: 23-32.

Kwatny E, Thomas D, & Kwatny H 1970 An application of signal processing techniques to the study of myoelectric signals. *IEEE Trans Biomed Eng* 17:303–313.

Lastayo P, Reich T, Urquhart M, Hoppeler H, & Lindstedt S 1999 Chronic eccentric exercise: improvements in muscle strength can occur with little demand for exygen. *Am J Physiol* 276: R611-R615.

Liddell E & Sherrington C. 1925 Recruitment and some other features of reflex inhibition. *Proc Royal Soc London, Series B* 97: 488-518.

Lindstrom L, Magnusson R, & Petersén I. 1970 Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. *Electromyography* 10: 341-356

Linnamo V, Bottas R, & Komi P. 2000 Force and emg power spectrum during and after eccentric and concentric fatiuge. *J Electromyogr Kinesiol* 10: 293-300.

Madeleine P, Jørgensen L, Søgaard K, Arendt-Nielsen L, & Sjøgaard G. 2002 Development of muscle fatigue as assessed by electromyography and mechanomyography during continuous and intermittent low-force contractions: effects of the feedback mode. *Eur J Appl Physiol* 87: 28-37.

Marchetti M, Felici F, Bernardi M, Minasi P, & Di Filippo L. 1992 Can evoked phonomyography be used to recognize fast and slow twitch muscle in man? *Int J Sport Med* 13: 65-68.

Martin P & Rattey J. 2007 Central fatigue explains sex differences in muscle fatigue and contralateral cross-over effects of maximal contractions. *Pflügers Archiv* 454: 957-969.

Marx E, Stephan T, Nolte A, Deutschländer A, Seelos K, Dieterich M, & Brandt T. 2003 Eye closure in darkness animates sensory systems. *Neuroimage* 19: 924-934

Masuda T & De Luca C. 1991 Recruitment threshold and muscle fiber conduction velocity of single motor units. *J Electromyogr Kinesiol* 1: 116-123.

McKay W, Jacobson P, Chilibeck P, & Daku B. 2006 Effects of graded levels of exercise on ipsilateral and contralateral post-exercise resting rectus femoris mechanomyography. *Eur J Appl Physiol* 98: 566-574.

Merletti R, Farina D, & Gazzoni M. 2003 The linear electrode array: a useful tool with many applications. *J Electromyogr Kinesiol* 13: 37-47.

Merletti R, Holobar A, & Farina D. 2008 Analysis of motor units with high-density surface electromyography. *J Electromyogr Kinesiol* 18: 879-890.

Milner-Brown H, Stein R, & Yemm R. 1973 Changes in firing rate of human motor units during linearly changing voluntary contractions. *J Physiol* 230: 371-390.

Milner-Brown H, Stein R, & Yemm R. 1973 The contractile properties of human motor units during voluntary isometric contractions. *J Physiol* 228: 285-306.

Milner-Brown H, Stein R, & Yemm R. 1973 The orderly recruitment of human motor units during voluntary isometric contractions. *J Physiol* 230: 359-370.

Mjølsnes R, Arnason A, Østhagen T, Raastad T, & Bahr R. 2004 A 10-week randomized trail comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports* 14: 311-317.

Moritani T, & deVries H. 1980 Potential for gross muscle hypertrophy in older men. *J Gerontol* 35: 672–682.

Nonaka H, Mita K, Akataki K, Watakabe M, & Itoh Y. 2006 Sex differences in mechanomyographic responses in voluntary isometric contractions. *Med Sci Sport Exerc* 38: 1311-1316.

Nawab S, Chang S, & De Luca C. 2010 High-yield decomposition of surface EMG signals. *Clin Neurophysiol* 121: 1602-1615.

Nielsen J. & Kagamihara Y. 1992 The regulation of disynaptic reciprocal Ia inhibition during co-contraction of antagonistic muscles in man. *J Physiol* 456: 373-391.

Newham D, McPhail G, Mills K, & Edwards R. 1983 Ultrastructural changes after concentric and eccentric contractions of human muscle. *J Neurol Sci* 61: 109-122.

Newham D, Jones D, & Clarson P. 1987 Repeated high-force eccentric exercise: effects on muscle pain and damage. *J Appl Physiol* 63: 1381-1386.

Orizio C, Perini R, & Veicsteinas A. 1989 Muscular sound and force relationship during isometric contraction in man. *Eur J Appl Physiol Occup Physiol* 58: 528-533.

Orizio C, Perini R, & Veicsteinas A. 1989 Changes of muscular sound during sustained isometric contraction up to exhaustion. *J Appl Physiol* 66: 1593–1598.

Orizio C, Diemont B, Esposito F, Alfonsi E, Parrinello G, Moglia A, & Veicsteinas A. 1999 Surface mechanomyogram reflects the changes in the mechanical properties of muscle at fatigue. *Eur J Appl Physiol Occup Physiol* 80: 276-284.

Orizio C, Perini R, Diemont B, & Veicsteinas A 1992 Muscle sound and electromyogram spectrum analysis during exhausting contractions in man. *Eur J Appl Physiol Occup Physiol* 65, 1–7.

Orizio C. 1993 Muscle sound: bases for the introduction of a mechanomyographic signal in muscle studies. *Crit Rev Biomed Eng* 21: 201–243.

Patton N & Mortensen O. 1971 An electromyographic study of reciprocal activity of muscles. *Anat Rec* 170: 255-268.

Perry S, Housh T, Johnson G, Ebersole K, Bull J, Evetovich T, & Smith D. 2001 Mechanomyography, electromyography, heart rate, and ratings of perceived exertion during incremental cycle ergometry. *J Sports Med Phys Fitness* 41: 183-188.

Person R. 1958 An electromyographic investigation on coordination of the activity of antagonistic muscles in man during the development of a motor habit. *Pavlov J Higher Nerv Act* 8: 13-23.

Petrofsky J & Laymon M. 2005 Muscle temperature and EMG amplitude and frequency during isometric exercise. *Aviat Space Environ Med* 76: 1024-1030.

Prablanc C, Pélisson D, Goodale M 1986 Visual control of reaching movements without vision of the limb. I. Role of retinal feedback of target position in guiding the hand. *Exp Brain Res* 62: 293-302.

Proske U & Morgan D. 2001 Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *J Physiol* 537: 333-345.

Qi L, Wakeling J, & Ferguson-Pell M. 2011 Spectral properties of electromyographic and mechanomyographic signals during dynamic concentric and eccentric contractions of the human biceps brachii muscle. *J Electromyogr Kinesiol* 21: 1056-1063.

Ratty J, Martin P, Kay D, Cannon J, & Marino F. 2006 Contralateral muscle fatigue in human quadriceps muscle: evidence for a centrally mediated fatigue response and cross-over effect. *Pflügers Archiv* 452: 199-207.

Sayers S, Knight C, & Clarkson P. 2003 Neuromuscular variables affecting the magnitude of force loss after eccentric exercise. *J Sports Sci* 21: 403-410.

Seger J, Arvidsson B, & Thorstensson A. 1998 Specific effect of eccentric and concentric training in muscle strength and morphology in humans. *Eur J Appl Physiol Occup Physiol* 79: 49-57.

Seger J & Thorstensson A. 2005 Effects of eccentric versus concentric training on thigh muscle strength and EMG. *Int J Sport Med* 26: 45–52.

Semmler J, Tucker K, Allen T, & Proske U. 2007 Eccentric exercise increases EMG amplitude and force fluctuations during submaximal contractions of elbow flexor muscles. *J Appl Physiol* 103: 979-989.

Sherrington C. 1892 Note on the knee-jerk and the correlation of action of antagonistic muscles. *Proc Royal Soc London, Series B* 52: 556-564.

Sherrington C. 1982 Note toward the Localisation of the Knee-Jerk. *Br Med J* 1: 545.

Sherrington C. 1983 Further experimental note on the correlation of action of antagonistic muscles. *Br Med J* 53: 1218.

Sherrington C. 1894 On the anatomical constitution of nerves of skeletal muscles; with remarks on recurrent fibres in the ventral spinal nerve-root. *J Physiol* 17: 210-258.

Sherrington C. 1896 On reciprocal innervation of antagonistic muscles. Third note. *Proc Royal Soc London, Series B* 60: 414-417.

Sherrington C & Hering E. 1898 On reciprocal innervation of antagonist muscles. Fourth note. *Proc Royal Soc London, Series B* 62: 183-187.

Sherrington C. 1898 On the Reciprocal Innervation of Antagonistic Muscles. Fifth Note. *Proc Royal Soc London, Series B* 64: 179-181.

Sherrington C. 1899 On the innervation of antagonistic muscles. Sixth note. *Proc Royal Soc London, Series B* 66: 66-67.

Sherrington C. 1905 On Reciprocal Innervation of Antagonistic Muscles: Seventh Note. *Proc Royal Soc London, Series B* 76: 160-163.

Sherrington C. 1905 On Reciprocal Innervation of Antagonistic Muscles. Eighth Note. *Proc Royal Soc London, Series B* 76: 269-297.

Sherrington C. 1906 On Innervation of Antagonistic Muscles. Ninth Note. Successive Spinal Induction. *Proc Royal Soc London, Series B* 77: 478-497.

Sherrington C. 1907 On Reciprocal Innervation of Antagonistic Muscles. Tenth Note. *Proc Royal Soc London, Series B* 79: 337-349.

Sherrington C. 1908 On Reciprocal Innervation of Antagonistic Muscles. Eleventh Note. Further Observations on Successive Induction. *Proc Royal Soc London, Series B* 80: 53-71.

Sherrington C. 1908 On Reciprocal Innervation of Antagonistic Muscles. Twelfth Note. Proprioceptive Reflexes. *Proc Royal Soc London, Series B* 80: 552-564.

Sherrington C. 1908 Reciprocal Innervation of Antagonistic Muscles. Thirteenth Note. On the Antagonism between Reflex Inhibition and Reflex Excitation. *Proc Royal Soc London, Series B* 80: 565-578.

Sherrington C. 1909 Reciprocal Innervation of Antagonistic Muscles. Fourteenth Note. On Double Reciprocal Innervation. *Proc Royal Soc London, Series B* 81: 249-268.

Shima N, Ishida K, Katayama K, Morotome Y, Sato Y, & Miyamura M. 2002. Cross education of muscular strength during unilateral resistance training and detraining. *Eur J Appl Physiol* 86: 287-294.

Smith D, Housh T, Johnson G, Evetovich T, Ebersole K, & Perry S 1998 Mechanomyographic and electromyographic responses to eccentric and concentric isokinetic muscle actions of biceps brachii. *Muscle Nerve* 21: 1438-1444.

Sosnoff J & Newell K. 2005 Intermittent visual information and the multiple time scales of visual motor control of continuous isometric force production. *Perception & Psychophysics* 67: 335-344.

Starch D. 1910 A demonstration of the trial and error method of learning. *Psychological Bulletin* 7: 20-23.

Stock M, Beck T, & Defreitas J. 2012 Effects of fatigue on motor unit firing rate versus recruitment threshold relationships. Muscle Nerve 45: 100-109.

Tax A, Danier van der Gon J, Gielen C, & Tempel C. 1989 Differences in the activation of m. biceps brachii in the control of slow isotonic movements and isometric contractions. *Exp Brain Res* 76: 55-63.

Tesch P, Dudley G, Duvoisin M, Hather B, & Harris R. 1990 Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. *Acta Physiol Scand* 138: 263-271.

Tillin N, Pain M, & Folland J. 2011 Short-term unilateral resistance training affects the agonist-antagonist but not the force-agonist activation relationship. *Muscle Nerve* 43: 375-384.

Tilney F & Pike F. 1925 Muscular coordination experimentally studied in its relation to the cerebellum. *Arch NeurPsych* 13: 289-334.

Todd G, Petersen N, Taylor J, & Gandevia S. 2003 The effect of a contralateral contraction on maximal voluntary activation and central fatigue in elbow flexor muscles. *Exp Brain Res* 150: 308-313.

Viitasalo J & Komi P 1975 Signal characteristics of EMG with special reference to reproducibility of measurements. *Acta Physiol Scand* 93: 531-539

Vikne H, Refsnes P, Ekmark M, Medbø J, Gundersen V, & Gundersen K. 2006 Muscular performance after concentric and eccentric exercise in trained men. *Med Sci Sports Exerc* 38: 1770-1781

Vuillerme N, Nougier V, & Prieur J 2001 Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? *Neurosci Lett* 308: 103-106.

Walker S, Davis L, Avela J, & Häkkinen K. 2012 Neuromuscular fatigue during dynamic maximal strength and hypertrophic resistance loadings. *J Electromyogr Kinesiol* 22: 356-362.

Warren G, Lowe D, & Armstrong R. 1999 Measurement tools used in the study of eccentric contraction-induced injury. *Sports Med* 27: 43-59.

Weerakkody N, Percival P, Morgan D, Gregory J, & Proske U. 2003 Matching different levels of isometric torque in elbows flexor muscles after eccentric exercise. *Exp Brain Res* 149: 141-150.

Yasuda Y & Miyamura M. 1983 Cross transfer effects of muscular training on blood flow in the ipsilateral and contralateral forearms. *Eur J Appl Physiol Occup Physiol* 51: 321–329

Ye X, Beck T, Defreitas J, & Wages NP. 2014a An examination of the strength and electromyographic responses after concentric vs. eccentric exercise of the forearm flexors. *J Strength Cond Res* 28: 1072-1080.

Ye X, Beck T, & Wages N. 2014b Influences of dynamic exercise on force steadiness and common drive. *J Musculoskelet Neuronal Interactions* 14: 377-386.

Ye X, Beck T, DeFreitas J, & Wages N. 2015a Acute effects of dynamic exercises on the relationship between the motor unit firing rate and the recruitment threshold. *Hum Mov Sci* 40: 24-37.

Ye X, Beck T, & Wages N. 2015b Acute effects of concentric vs. eccentric exercise on force steadiness and electromyographic responses of the forearm flexors. *J Strength Cond Res* 29: 604-611.

Zhou S. 2000 Chronic neural adaptations to unilateral exercise: mechanisms of cross education. *Exerc Sport Sci Rev* 23: 177-184.

Appendices

Appendix A – Institutional Review Board Approval Letter

The UNIVERSITY of OKLAHOMA

Institutional Review Board for the Protection of Human Subjects

Approval of Initial Submission – Expedited Review – AP01

Date: July 15, 2016 **IRB#:** 7047

Principal Investigator: Nathan Paul Wages **Approval Date:** 07/15/2016 **Expiration Date: 06/30/2017**

Study Title: Examination of eccentric versus concentric unilateral exercise on ipsilateral and contralateral motor unit control strategies

Expedited Category: 4

Collection/Use of PHI: No

On behalf of the Institutional Review Board (IRB), I have reviewed and granted expedited approval of the above-referenced research study. To view the documents approved for this submission, open this study from the *My Studies* option, go to *Submission History*, go to *Completed Submissions* tab and then click the *Details* icon.

As principal investigator of this research study, you are responsible to:

- Conduct the research study in a manner consistent with the requirements of the IRB and federal regulations 45 CFR 46.
- Obtain informed consent and research privacy authorization using the currently approved, stamped forms and retain all original, signed forms, if applicable.
- Request approval from the IRB prior to implementing any/all modifications.
- Promptly report to the IRB any harm experienced by a participant that is both unanticipated and related per IRB policy.
- Maintain accurate and complete study records for evaluation by the HRPP Quality Improvement Program and, if applicable, inspection by regulatory agencies and/or the study sponsor.
- Promptly submit continuing review documents to the IRB upon notification approximately 60 days prior to the expiration date indicated above.
- Submit a final closure report at the completion of the project.

If you have questions about this notification or using iRIS, contact the IRB @ 405-325-8110 or irb@ou.edu.

Cordially,

Aimee Franklin, Ph.D.
Chair, Institutional Review Board

Appendix B – Informed Consent

Signed Consent to Participate in Research

Would you like to be involved in research at the University of Oklahoma?

I am Nathan Wages from the Department of Health and Exercise Science and I invite you to participate in my research project entitled "Examination of eccentric vs. concentric unilateral exercise on ipsilateral and contralateral motor unit control strategies". This research is being conducted at the University of Oklahoma, on the Norman Campus, in the Collums Building for a total of 30 separate visits. You were selected as a possible participant because you are healthy, between the ages of 18 and 35, not upper body resistance trained, and you appear to have no injury to either of your arms. You must be at least 18 years of age to participate in this study.

Please read this document and contact me to ask any questions that you may have BEFORE agreeing to take part in my research.

What is the purpose of this research? The purpose of this research is to examine the motor unit control strategies of the upper arm. Specifically, we are investigating the recruitment/decruitment (increase/decrease in the active number of motor units within a muscle) and rate coding (increase/decrease the rate at which neurons fire within the motor units of a muscle) patterns, using electromyographic and mechanomyographic sensors, of the biceps brachii muscles of the upper arm following either eccentric (causes muscles to elongate) or concentric (causes muscles to shorten) exercise. Furthermore, electromyography and mechanomyography are non-invasive methods for examining the electrical and mechanical aspects of muscle function, respectively.

How many participants will be in this research? A maximum of approximately 80 people (40 males and 40 females) will take part in this research.

What will I be asked to do? If you agree to be in this research, you will asked to complete 30 separate visits, which include the following:

For the consultation visit, you will be explained all parameters of this study and you will have the opportunity to ask any question/concerns that you may have about any aspect of the program design. Following this discussion, you will then be given ample time to decide if you would still like to participate in this study.

For the 1st familiarization visit, you will be asked to come into the lab for 1 hour and will practice performing a maximum voluntary contraction (MVC) followed by trapezoidal force tracing of 30%, 50%, and 70% of your MVC on the isometric contraction machine. Furthermore, for those tracings, you will contract your biceps muscle to match the angle and force for the trapezoid picture you are tracing on the computer. Additionally, you will also be asked to perform the exercise protocol, using either eccentric or concentric exercise on a preacher curl apparatus. Most importantly, no signal recordings will be performed during this visit.

For the 2nd familiarization visit, you will be asked to perform the same protocol as with the 1st familiarization visit. Specifically, you will be asked to come into the lab for 1 hour and will practice performing a maximum voluntary contraction (MVC) followed by trapezoidal force tracing of 30%, 50%, and 70% of your MVC on the isometric contraction machine. Furthermore, for those tracings, you will contract your biceps muscle to match the angle and force for the trapezoid picture you are tracing on the computer. Additionally, you will also be asked to perform the exercise protocol, using either

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eccentric or concentric exercise on a preacher curl apparatus. Again, no signal recordings will be performed during this visit.

For the isometric testing protocols, you will be asked to sit at a table with your arm placed in a custom-built, isometric strength testing apparatus. Your arm will be flexed 90° at the shoulder with the elbow resting on a soft pad. Your forearm will be flexed 90° at the elbow and a soft cuff will be secured around your wrist. The cuff will be secured to the apparatus perpendicular to your forearm with a load cell to measure your isometric force. Furthermore, your forearm flexion force will be measured when you are facing the apparatus. Additionally, you will perform a MVC followed by trapezoidal force tracings of 30%, 50%, and 70% of your MVC on the isometric contraction machine.

For the testing visits, you will be asked to either perform concentric or eccentric contractions only. Contractions will be performed using free weight, handheld dumbbells (between 5 and 80 lbs) and will incorporate 5 sets of 10 repetitions for your dominant arm only. The duration for each repetition will last approximately three seconds and following the conclusion of each repetition the primary investigator will place the dumbbell back to your starting position. Furthermore, regardless of contraction type, you will sit in a chair with a preacher curl pad attachment to isolate the biceps brachii muscle during exercise. Specifically, if you are part of the concentric contraction only group, you will begin with your forearm extended approximately 180° and will finish with your forearm flexed at approximately 60°, while if you are part of the eccentric contraction only group you will begin with you forearm flexed approximately 60° and will finish with your forearm extended at approximately 180°.

For the electromyographic and mechanomyographic recordings, the sensors will be placed over the muscle belly of your biceps brachii muscles and secured with tape. A reference sensor will also be placed on the back of your neck at the 7th vertebrae of the cervical spinal region and also secured with tape. All recordings will be saved on a lab computer for subsequent analysis.

How long will this take? Your participation will take approximately 20 minutes for the consultation visit, two hours for both familiarization visits, 1 hour for all isometric testing, and 30 minutes for each training visit. Thus, total commitment time will be approximately 19 hours across a total of 30 visits. Furthermore, there will be a minimum of 24 hours between all visits.

What are the risks and/or benefits if I participate? There is a small risk of muscle injury and or soreness to the upper arm muscles due to contracting the biceps muscle for multiple repetitions. Furthermore, there are no direct benefits from participation.

What do I do if I am injured? If you are injured during your participation, report this to a researcher immediately. Emergency medical treatment is available. However, you or your insurance company will be expected to pay the usual charge from this treatment. The University of Oklahoma Norman Campus has set aside no funds to compensate you in the event of injury.

Will I be compensated for participating? You will not be reimbursed for your time and participation in this research.

Who will see my information? In research reports, there will be no information that will make it possible to identify you. Research records will be stored securely and only approved researchers and the OU Institution Review Board will have access to the records.

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You have the right to access the research data that has been collected about you as a part of this research. However, you may not have access to this information until the entire research has completely finished and you consent to this temporary restriction.

Do I have to participate? No. If you do not participate, you will not be penalized or lose benefits or services unrelated to the research. If you decide to participate, you don't have to answer any question and can stop participating at any time.

Will my identity be anonymous or confidential? Your name will not be retained or linked with your responses to be identified. The data you provide will be destroyed unless you specifically agree for data retention or retention of contact information at the end of the research. Please check all of the options that you agree to:

I agree for the researcher to use my data in future studies. ___Yes ___ No

Will I be contacted again? The researcher would like to contact you again to recruit you into this research or to gather additional information.

_____ I give my permission for the researcher to contact me in the future.

_____ I do not wish to be contacted by the researcher again.

Who do I contact with questions, concerns or complaints? If you have questions, concerns or complaints about the research or have experienced a research-related injury, contact me by phone (405-640-6537) or by email (Nathan.P.Wages-1@ou.edu), or my adviser Dr. Travis Beck by phone (405-325-1378) or by email (tbeck@ou.edu).

You can also contact the University of Oklahoma – Norman Campus Institutional Review Board (OU-NC IRB) at 405-325-8110 or irb@ou.edu if you have questions about your rights as a research participant, concerns, or complaints about the research and wish to talk to someone other than the researcher(s) or if you cannot reach the researcher(s).

You will be given a copy of this document for your records. By providing information to the researcher(s), I am agreeing to participate in this research.

Participant Signature	Print Name	Date
Signature of Researcher Obtaining Consent	Print Name	Date
Signature of Witness (if applicable)	Print Name	Date

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Appendix C – Pre-Exercise Health Questionnaire

PRE-EXERCISE TESTING HEALTH & EXERCISE STATUS QUESTIONNAIRE

The University of Oklahoma
DEPARTMENT OF HEALTH AND EXERCISE SCIENCE

Name _____ Date_____

Home Address_____

Phone _____

Person to contact in case of emergency _____

Emergency Contact Phone _____ Birthday (mm/dd/yy)____/_____/_____

Gender_____ Age _____(yrs) Height _____(ft)_____(in) Weight_____(lbs)

Does the above weight indicate: a gain____ a loss____ no change____ in the past year?
If a change, how many pounds?_____(lbs)

A. JOINT-MUSCLE STATUS (✓Check areas where you currently have problems)

Joint Areas
( ) Wrists
( ) Elbows
( ) Shoulders
( ) Upper Spine & Neck
( ) Lower Spine
( ) Hips
( ) Knees
( ) Ankles
( ) Feet
( ) Other_____

Muscle Areas
( ) Arms
( ) Shoulders
( ) Chest
( ) Upper Back & Neck
( ) Abdominal Regions
( ) Lower Back
( ) Buttocks
( ) Thighs
( ) Lower Leg
( ) Feet
( ) Other_____

B. HEALTH STATUS (✓Check if you currently have any of the following conditions)

( ) High Blood Pressure
( ) Heart Disease or Dysfunction
( ) Peripheral Circulatory Disorder
( ) Lung Disease or Dysfunction
( ) Arthritis or Gout
( ) Edema
( ) Epilepsy
( ) Multiply Sclerosis
( ) High Blood Cholesterol or Triglyceride Levels
( ) Allergic reactions to rubbing alcohol
( ) Acute Infection
( ) Diabetes or Blood Sugar Level Abnormality
( ) Anemia
( ) Hernias
( ) Thyroid Dysfunction
( ) Pancreas Dysfunction
( ) Liver Dysfunction
( ) Kidney Dysfunction
( ) Phenylketonuria (PKU)
( ) Loss of Consciousness

** NOTE: If any of these conditions are checked, then a physician's health clearance will be required.*


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C. PHYSICAL EXAMINATION HISTORY

Approximate date of your last physical examination_____

Physical problems noted at that time_____

Has a physician ever made any recommendations relative to limiting your level of physical exertion? _____YES _____NO
If YES, what limitations were recommended?_____
_____

D. CURRENT MEDICATION USAGE (List the drug name and the condition being managed)

MEDICATION	CONDITION
_____	_____
_____	_____
_____	_____

E. PHYSICAL PERCEPTIONS (Indicate any unusual sensations or perceptions. ✓Check if you have recently experienced any of the following during or soon after *physical activity* (PA); or during *sedentary periods* (SED))

PA	SED		PA	SED	
( )	( )	Chest Pain	( )	( )	Nausea
( )	( )	Heart Palpitations	( )	( )	Light Headedness
( )	( )	Unusually Rapid Breathing	( )	( )	Loss of Consciousness
( )	( )	Overheating	( )	( )	Loss of Balance
( )	( )	Muscle Cramping	( )	( )	Loss of Coordination
( )	( )	Muscle Pain	( )	( )	Extreme Weakness
( )	( )	Joint Pain	( )	( )	Numbness
( )	( )	Other_____	( )	( )	Mental Confusion

F. EXERCISE STATUS

Do you regularly engage in aerobic forms of exercise (i.e., jogging, cycling, walking, etc.)? **YES** **NO**

How long have you engaged in this form of exercise? _____ years _____ months

How many hours per week do you spend for this type of exercise? _____ hours

Do you regularly lift weights? **YES** **NO**

How long have you engaged in this form of exercise? _____ years _____ months

How many hours per week do you spend for this type of exercise? _____ hours

Do you regularly play recreational sports (i.e., basketball, racquetball, volleyball, etc.)? **YES** **NO**

How long have you engaged in this form of exercise? _____ years _____ months

How many hours per week do you spend for this type of exercise? _____ hours

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Appendix D – Recruitment Flyer

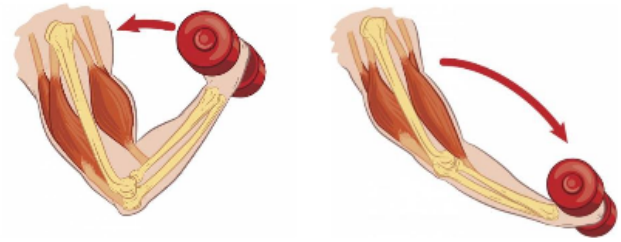
PARTICIPANTS WANTED

Examination of eccentric vs. concentric unilateral exercise on ipsilateral and contralateral motor unit control strategies

30 VISITS REQUIRED

(Time commitment per visit: ~ 30 - 45 minutes)

You must be a healthy, recreationally active, but not be upper body trained adult (between ages of 18 & 35). Also, you must not previously/presently have any signs/symptoms of arm injuries. Testing will involve isometric exercise, while training will involve free weight dumbbell exercise.



Possible risks may include: muscle soreness and fatigue

If you are interested, please contact:

Nathan Wages
Department of Health and Exercise Science
Nathan.P.Wages-1@ou.edu

The University of Oklahoma is an equal opportunity institution.

Nathan Wages Ph.D. (c)
Office: Collums Bldg Rm 150B
Email: Nathan.P.Wages-1@ou.edu

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