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ELECTROMYOGRAPHIC, MECHANOMYOGRAPHIC, AND PEAK TORQUE RESPONSES DURING REPEATED CONCENTRIC ISOKINETIC MUSCLE ACTIONS WITH EYES-OPEN VERSUS EYES-CLOSED

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ELECTROMYOGRAPHIC, MECHANOMYOGRAPHIC, AND PEAK TORQUE RESPONSES DURING REPEATED CONCENTRIC ISOKINETIC MUSCLE ACTIONS WITH EYES-OPEN VERSUS EYES-CLOSED

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF HEALTH AND EXERCISE SCIENCE

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Abstract

The purpose of this study was to compare the peak torque and electromyographic (EMG) and mechanomyographic (MMG) amplitude and mean frequency (MNF) responses during fatiguing isokinetic muscle actions for eyes-open versus eyes-closed conditions. Twenty-one resistance-trained men (mean ± SD age = 23.0 ± 3.0 years; body mass = 86.9 ± 14.4 kg) volunteered to participate in this investigation. Following a familiarization session, each subject participated in four data collection trials. For each trial, the subjects performed 100 repeated maximal concentric isokinetic muscle actions of the dominant forearm flexors with 1) their eyes open (100Open), 2) their eyes closed (100Closed), 3) their eyes open and closed for the first and last 50 muscle actions (50Open50Closed), respectively, and 4) their eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. During each muscle action, EMG and MMG signals were detected from the biceps brachii. For each fatigue test, the data for the first and last 50 muscle actions served as the pre-test (Pre) and post-test (Post), respectively, and were compared for each condition. Initial peak torque (average from the three repetitions with the highest peak torque values), final peak torque (average from the three repetitions with the lowest peak torque values), percent decline ([initial peak torque – final peak torque/initial peak torque] × 100), average torque (average peak torque value across the 50 repetitions), and the linear slope coefficient for the decline in peak torque (ft.-lbs./repetition) were the five isokinetic peak torque variables in this study. In addition, for each subject and condition, the normalized EMG and MMG amplitude and MNF data points at initial and final peak torque were averaged and utilized for subsequent statistical analyses. The

results indicated that there were no mean differences among the conditions for the five isokinetic peak torque variables. The mean normalized EMG MNF values at final peak torque decreased from Pre to Post for 100Open and 50Closed50Open conditions, but not for the eyes-closed conditions (i.e., 100Closed and 50Open50Closed). For the 100Open and 100Closed conditions, there were no Pre versus Post mean differences for normalized MMG MNF at final peak torque. When the subjects opened (50Closed50Open) and closed (50Open50Closed) their eyes after 50 repetitions, however, the normalized MMG MNF values continued to decrease. These findings suggested that visual feedback did not influence maximal strength or fatigability, but did affect EMG and MMG MNF.

Chapter 1: Introduction

In 1903, Russian physiologist Ivan Sechenov performed a series of experiments on himself to study muscle fatigue. These experiments were performed on a machine that he constructed that allowed him to perform repetitive pushing and pulling movements similar to those of sawing. Sechenov noted that his fatigued right arm recovered faster if he exercised his left arm during a rest period. Although Sechenov was without the advanced technology needed to test his hypothesis, he believed that muscle fatigue was a result of inhibition from the brain. Sechenov died in 1905, but his findings were published 30 years later as part of Moscow's International Physiological Congress report (Sechenov, 1935). Subsequently, the "Sechenov phenomenon" (Asmussen, 1979, pg. 417) became a popular training technique in the early twentieth century among Danish gymnastics instructors (Asmussen, 1936; Alpert, 1969).

Researchers have continued to study the effects of diverting activities on recovery from fatigue (Asmussen, 1936; Alpert, 1969; Asmussen and Mazin, 1978a,b; Rotstein et al., 1999; Stock et al., 2011). In agreement with Sechenov's (1935) discovery, these investigations have shown that exercising a non-fatigued muscle group during a rest period enhanced performance during subsequent bouts of activity to a greater extent than resting quietly. However, two separate, plausible mechanisms responsible for the Sechenov phenomenon have been discussed in the literature. According to Asmussen (1993), the results from a study by Weber (1914) indicated that exercise performed with a non-fatigued muscle group facilitated recovery via increased blood flow. These findings were also reported by Alpert (1969). In that study, ten men performed repeated dynamic constant external resistance (DCER) dorsiflexion and

plantar flexion of the right foot, followed by two minutes of quiet rest or a diverting activity. Several different types of diverting activities were used as interventions, such as swinging 2.0 kg dumbbells, placing one's hand in ice, and pain stimuli. Calf blood flow and arterial blood pressure were monitored throughout each trial. The results from the study (Alpert, 1969) indicated that the interventions that produced the greatest increases in calf blood flow and blood pressure were associated with greater total work during subsequent experiments. Thus, these studies (Weber, 1914; Alpert, 1969) suggested that by performing physical diverting activities, recovery was likely improved by increasing the rate at which lactate and other metabolites (e.g., H^+, P_i) were cleared from the fatigued muscle. The second hypothesis was that the effects of diverting activities on recovery from fatiguing muscle actions were related to increased central nervous system activity. Asmussen and Mazin (1978a, b) performed many experiments in an attempt to determine the precise mechanisms responsible for the Sechenov phenomenon. The interventions for these experiments included activities that increased blood flow during recovery (exercise with the contralateral limb) and non-fatiguing activities that did not affect circulation (opening or closing one's eyes during exercise, performing math problems, or pinching one's fingers together). In one of their more interesting experiments, the authors (Asmussen and Mazin, 1978b) had the subjects perform fatiguing concentric muscle actions of the forearm flexors until exhaustion with their eyes closed. Once the subjects reached the point that they could no longer perform the muscle actions, they opened their eyes and attempted to continue. The authors (Asmussen and Mazin, 1978b) found that when complete exhaustion had been reached with the eyes closed, opening them allowed 15-30% more work to be

done. However, when the order was alternated (i.e., the subjects performed the fatiguing muscle actions to exhaustion with their eyes opened, then closed their eyes), none of the subjects were able to continue. Furthermore, the authors (Asmussen and Mazin, 1978b) collected electromyographic (EMG) signals from the rectus femoris (RF) during patellar reflex testing while the subjects performed diverting activities with or without their eyes closed. It was reported that when the subjects performed fatiguing muscle actions with their eyes open, brisker patellar reflexes were observed, which was interpreted as an enhanced cerebral excitatory state. Collectively, the results from each of their experiments led the authors (Asmussen and Mazin, 1978b, pg. 14) to conclude that diverting activities improved performance via central nervous system processes that were "independent of changes in local blood flow."

The fact that Asmussen and Mazin (1978b) reported differences in performance when exercise was performed with the eyes open versus closed is in agreement with electroencephalography (EEG) studies that have noted differences in brain activity during various states of wakefulness. Specifically, beta waves appear in the EEG signal when healthy adults are focused on a challenging task (Berger, 1931; Barry et al., 2007). In contrast, when an individual is relaxed with his/her eyes closed, alpha waves appear. Rojtbak and Dedrabrishvilli (1959) studied brain wave activity during fatiguing muscle actions with or without diverting activities. Their findings indicated that the EEG signal showed a gradual appearance of alpha waves as the muscle progressively fatigued, but when the subjects performed a diverting activity, the beta waves reappeared. More recent studies have shown differences in central nervous system

activity (Marx et al., 2003) and postural control during fatigue (Vuillerme et al., 2001) with the eyes-open versus eyes-closed conditions.

Surface EMG provides an objective tool for the assessment of muscle fatigue (Basmajian and De Luca, 1985). Researchers usually examine changes in amplitude and/or center frequency (e.g., mean or median) values during isometric muscle actions (Eason, 1960; Lindstrom et al., 1970; Masuda and De Luca, 1991). During a sustained isometric maximum voluntary contraction (MVC), EMG amplitude often decreases (Moritani et al., 1986), which is likely due to a decline in motor unit firing rates (Bigland-Ritchie et al., 1983). Studies have also examined changes in surface EMG amplitude and center frequency parameters during repeated maximal isokinetic muscle actions (Nilsson et al., 1977; Komi and Tesch, 1979; Gerdle et al., 2000; Beck et al., 2004). Komi and Tesch (1979) investigated the potential influence of muscle fiber-type composition on changes in EMG amplitude and mean frequency (MNF) during 100 maximal concentric isokinetic muscle actions of the leg extensors. The subjects with a high proportion of fast-twitch muscle fibers for the vastus lateralis (VL) demonstrated higher initial peak torque values and a greater susceptibility to fatigue than did individuals with muscles composed mainly of slow-twitch fibers. The authors (Komi and Tesch, 1979) also reported a significant decline in both EMG amplitude and MNF for the subjects with predominantly fast-twitch muscle fibers. These values did not change or declined slightly for the subjects with a high proportion of slow-twitch muscle fibers. It was concluded (Komi and Tesch, 1979) that the assessment of EMG amplitude and MNF during fatiguing isokinetic muscle actions may provide information regarding muscle contraction failure for fast-twitch versus slow-twitch muscle fibers.

Gerdle et al. (2000) examined the linearity of the EMG amplitude and MNF versus concentric peak torque relationships for the VL, RF, and vastus medialis (VM) on an individual subject basis. The authors (Gerdle et al., 2000) reported that the decline in peak torque during 100 consecutive maximal concentric isokinetic muscle actions was highly correlated with the decrease in EMG MNF values. In addition to EMG, recent investigations have examined mechanomyographic (MMG) amplitude and/or MNF during repeated maximal isokinetic muscle actions (Perry-Rana et al., 2002, 2003; Beck et al., 2004; Ebersole and Malek, 2008). In a study by Beck et al. (2004), ten subjects performed 50 maximal concentric isokinetic muscle actions of the dominant forearm flexors at a velocity of 180°/second as MMG signals were recorded from the biceps brachii. Both MMG amplitude and MMG MNF demonstrated linear decreases across the 50 muscle actions. According to the authors (Beck et al., 2004), the decreases in both MMG amplitude and MNF could have been related to de-recruitment of fast fatiguing motor units, muscle wisdom, or a reduction in muscle compliance. Ebersole and Malek (2008) investigated the ratio of normalized MMG amplitude to normalized EMG amplitude (termed "electromechanical efficiency" by Barry et al. [1990, pg. 289]) for the VL and VM during 75 consecutive maximal concentric isokinetic muscle actions of the leg extensors. The results indicated that there were linear decreases in torque, VM electromechanical efficiency, and VL electromechanical efficiency across the 75 muscle actions. It was concluded (Ebersole and Malek, 2008) that similar fatigue-induced changes in electromechanical coupling were found for the VL and VM, and that electromechanical efficiency may be useful for assessing asymmetries in quadriceps muscle function. Collectively, there is sufficient evidence to suggest that the

assessment of EMG and MMG amplitude and MNF values during repeated maximal isokinetic muscle actions provides valid information regarding the decline in muscle function during fatigue.

Other than the experiments performed by Asmussen and Mazin (1978b), no previous investigations have compared the effects of opening or closing one's eyes on muscle fatigue. Furthermore, although visual feedback does influence central nervous system activity (Berger, 1931; Marx et al., 2003; Barry et al., 2007), no previous experiments have studied the effects of opening or closing one's eyes on voluntary muscle activation. Therefore, the purpose of this study was to compare peak torque and EMG and MMG amplitude and MNF responses during 100 repeated concentric isokinetic muscle actions for eyes-open versus eyes-closed conditions.

Hypotheses

1. I hypothesize that the peak torque, normalized EMG and MMG amplitude and MNF values will decline throughout each fatigue test.
2. I hypothesize that when the subjects perform the muscle actions with their eyes open, there will be higher initial and average torque values, as well as a lower percent decline in peak torque than when the eyes are closed.
3. I hypothesize that the declines in normalized EMG and MMG amplitude and MNF will be greater when the eyes are closed versus open.

Definition of Terms

1. Action potential – an electrical impulse transmitted across the plasma membrane of a nerve fiber during the transmission of a nerve impulse and across the plasma membrane of a muscle fiber during contraction.

2. Concentric – a muscle action that involves the production of force while the muscle is shortening.
3. Dynamic constant external resistance – a muscle in which the external resistance remains constant thoughout the movement; also known as *isotonic*.
4. Eccentric – a muscle action that involves the production of force while the muscle is lengthening.
5. Electromyography – involves recording and quantifying the action potentials that activate skeletal muscle fibers.
6. Fatigue – the inability to maintain the desired or expected force.
7. Final Peak Torque – the average of the lowest three peak torque values during repeated maximal isokinetic strength testing.
8. Initial Peak Torque – the average of the highest three peak torque values during repeated maximal isokinetic strength testing.
9. Isometric – a muscle action involving tension production without movement at the joint or shortening of the muscle fibers; also known as static muscle action.
10. Isokinetic – a muscle action that has a constant velocity of movement.
11. Maximal voluntary contraction – an isometric muscle action in which the subject provides as much effort as possible.
12. Mechanomyography – records and quantifies the low-frequency lateral oscillations of active skeletal muscle fibers. These oscillations reflect the mechanical counterpart of the motor unit electrical activity.
13. Motor unit – a motor neuron and all of the muscle fibers it innervates.

14. One-repetition maximum – the greatest external load that can be lifted one time with correct technique.
15. Peak Torque – the highest torque value demonstrated during a single isokinetic muscle action.
16. Percent decline – ([Initial peak torque – Final peak torque/Initial peak torque] × 100); used as an index of fatigability during repeated maximal isokinetic strength testing.

Abbreviations

1. 1-RM = one-repetition maximum
2. ANOVA = analysis of variance
3. CSA = cross-sectional area
4. CV = conduction velocity
5. DCER = dynamic constant external resistance
6. EEG = electroencephalography
7. EMD = electromechanical delay
8. EMG = electromyography
9. ICC = intraclass correlation coefficient
10. IEMG = integrated electromyography
11. LDH = lactate dehydrogenase
12. MD = minimal difference needed to be considered real
13. MMG= mechanomyography
14. MNF = mean frequency
15. MVC = maximum voluntary contraction

16. POST = post-test
17. PRE = pre-test
18. RF = rectus femoris
19. SD = standard deviation
20. SEM = standard error of measurement
21. VL = vastus lateralis
22. VM = vastus medialis
23. $V0_2max$ = maximal oxygen consumption

Delimitations

Approximately twenty resistance-trained men between the ages of 18 and 35 years will be recruited for this study. All participants will complete a health history questionnaire and a written statement of informed consent prior to any testing. Volunteers for this study must be free from any current or ongoing neuromuscular diseases and cannot have sustained an injury to their dominant shoulder, wrist, or arm within the past 6 months.

Assumptions

Theoretical Assumptions

1. All equipment will function properly for all testing sessions.
2. Subjects will accurately answer the health history questionnaire.

Statistical Assumptions

1. The population from which the samples are drawn is normally distributed.
2. The variability of the samples in the experiment is equal.

3. The data meets the assumption of sphericity. Sphericity requires that the repeated measures data demonstrate both homogeneity of variance and homogeneity of covariance.
4. The data are based on a parametric scale.

Limitations

1. Subjects will be recruited as students from several departmental courses and advertisements located within and around the Huston Huffman Center. Thus, the process of subject selection may not truly be random.
2. The sample will be volunteers, therefore not meeting the underlying assumption of random selection.

Chapter 2: Review of literature

Effects of diverting activities on fatigue

Sechenov (1935)

Prior to his death in 1905, Russian physiologist Ivan Sechenov performed several experiments on himself to further understand the fatigue process in skeletal muscle. To do so, he built a device that allowed him to simulate movements identical to those of sawing. Sechenov (1935) reported that when the muscles of one arm became fatigued during these movements, they recovered faster if the contralateral arm was exercised during the rest period. Sechenov (1935, pg. 258) stated that by exercising his own contralateral arm during the rest period, he forgot how tired his muscles were, and that the effects of the diverting activities on fatigue could be explained by a ‘‘…recharging with energy of fatigued nerve centers.’’ This concept became known as the Sechenov Phenomenon, and was an important part of several athletic training and gymnastics programs in the early 1900s.

Alpert (1969)

The purpose of this study was to compare skeletal muscle blood flow, blood pressure, and performance following fatiguing muscle actions with diverting activities versus periods of quiet rest. Ten healthy men (age range = 25-40 years) participated in several experiments. For each trial, the subjects performed repeated DCER dorsiflexion and plantar flexion muscle actions of the right foot, followed by two minutes of quiet rest or a diverting activity. The use of quiet rest and diverting activities was alternated (i.e., muscle actions to exhaustion, quiet rest, muscle actions to exhaustion, diverting activity), and the subjects repeated this process five to ten times. Diverting activities

included interventions such as upper-body DCER muscle actions with 2.0 kg dumbbells, placing one's hand in ice, and pain stimuli. Calf blood flow and arterial blood pressure were monitored throughout each trial. The results from this study indicated that performing diverting activities between fatiguing bouts enhanced recovery to a greater extent than resting quietly. Furthermore, the interventions that produced the greatest increases in calf blood flow and blood pressure were associated with greater total work during subsequent experiments. Collectively, the author (Alpert, 1969, pg. 262) concluded that the beneficial effects associated with performing diverting activities following fatiguing muscle actions were due to increases in blood flow and arterial blood pressure, resulting in "...a more complete restitution of the muscle..."

Asmussen and Mazin (1978a)

The purpose of this study was to examine the effects of several different types of diverting activities on recovery from fatigue. Prior to this investigation, it was unclear if the Sechenov Phenomenon was related to central or peripheral mechanisms. Eighteen men and one woman (age range = 22-37 years) lifted and lowered weights with their right forearm flexors or finger flexors to the beat of a metronome while seated in a custom-built arm ergograph. For each experiment, the subjects performed the muscle actions until exhaustion, followed by either a two minute rest period or a diverting activity. These interventions included pinching one's fingers together, solving math problems, and both isometric and dynamic muscle actions of the left forearm flexors. Following each two minute rest or diverting activity, the process was repeated (i.e., unilateral muscle actions to exhaustion followed by either a two minute rest period or a

diverting activity) about twenty times. For each trial, total work was compared between bouts that followed a passive rest versus a diverting activity. In addition, for some of the experiments, blood flow to the right arm was measured during both the fatiguing muscle actions and the rest periods. The results indicated that performing a diverting activity following fatiguing unilateral muscle actions resulted in greater total work compared to that for passive rest. Beneficial effects were demonstrated for all of the interventions (math problems, pinching fingers together, and contralateral muscle actions). The authors (Asmussen and Mazin, 1978a, pg. 7) stated that as "... mental activity in the active pauses had the same positive effect as normal physical activity, it seems justifiable to conclude that Sechenov was right in postulating that the effect of diverting activity is of central-nervous origin."

Asmussen (1993)

This review discussed many of the previous studies that had objectively examined muscle fatigue. The manuscript placed an equal emphasis on central and peripheral fatigue, which the author (Asmussen, 1993) described as events occurring proximal and distal to the motor neuron, respectively. The author (Asmussen, 1993) began his section on central fatigue by noting the significance of an experiment by Mosso (1892), which is believed to be the first study on muscle fatigue in humans. Mosso (1892) found that when examined immediately before and after an important academic presentation, his colleague's finger flexors were much more resistant to fatigue following the lecture. Although he was limited in technology, Mosso (1892) considered fatigue to be primarily a central nervous system phenomenon. The review also described the experiments performed by Ivan Sechenov (1935). According to

Asmussen (1993), the fact that previous studies had demonstrated improvements in exercise performance as a result of solving math problems or opening one's eyes suggested that central factors likely played an important role in muscle fatigue. Based on Sechenov's (1935) findings, as well as results from his own laboratory, Asmussen (1993, pg. 419) concluded that "...central fatigue is caused by nervous impulses from receptors (probably some kind of chemoreceptors) in the fatigued muscles. The inhibition may act on the motor pathways anywhere from the voluntary centers in the brain to spinal motor neurons. This kind of fatigue, therefore, should manifest itself by a decrease in the outflow of motor impulses to the muscles."

Rotstein et al. (1999)

This study examined the effects of physical diverting activities on recovery from fatiguing muscle actions. On three separate occasions, fifteen men (mean ± SD age = 17.4 ± 0.5 years) performed two 40-second bouts of maximal concentric isokinetic muscle actions of the dominant leg extensors at a velocity of 180°/second. Between these bouts, the subjects were instructed to rest quietly, perform unloaded leg extensions with the fatigued limb, or intermittently squeeze a rubber sponge for one minute. Following the intervention period, the subjects repeated the 40-second concentric isokinetic protocol. For each trial, the subjects were blindfolded to avoid the possibility of visual stimuli acting as a diverting activity. The authors (Rotstein et al., 1999) reported that the subjects demonstrated higher average torque values as a result of squeezing a rubber sponge, but no other differences among the trials were noted for peak torque, peak power, or total work. Since it is unlikely that squeezing a sponge for one minute resulted in significant alterations in blood flow, the findings from this study

may have been related to central nervous system factors. The authors (Rotstein et al., 1999, pg. 75) noted, however, that "...active recovery is very specific" and the effectiveness of diverting activities may depend on whether fatigue is related to central (e.g., motor cortex activity) or peripheral (e.g., metabolite accumulation) mechanisms.

Stock et al. (2011)

The purpose of this study was to examine the effects of both mental and physical diverting activities on recovery from fatiguing concentric isokinetic muscle actions. Nineteen adults (eleven men and eight women, mean ± SD age = 22.1 ± 1.7 years) performed two bouts of 50 repeated maximal concentric isokinetic muscle actions of the dominant leg extensors on three separate occasions. Between these bouts, the subjects either performed five sets of contralateral DCER leg extensions (physical diverting activity), math problems (mental diverting activity), or rested quietly (control). For each trial, the time between fatiguing bouts was three minutes. The peak torque data from the first and second fatiguing bouts served as the pre-test (PRE) and post-test (POST) data, respectively, for each trial. The results showed that when the subjects solved math problems between the fatiguing bouts, no decline in the initial peak torque values from Pre to Post was observed. In addition, a decline in the average torque values was observed from Pre to Post for the control trial, but not for the mental or physical diverting activities trials. No differences were observed among the trials for final peak torque, percent decline, or the linear slope of the decline in peak torque. These findings demonstrated that performing either mental or physical diverting activities after fatiguing isokinetic muscle actions enhanced recovery.

Effects of visual feedback on central nervous system activity and/or exercise performance

Asmussen and Mazin (1978b)

The primary purpose of this study was to examine the interaction between visual feedback and central nervous system activity. Using similar methods as those from a previous study (Asmussen and Mazin, 1978a), eighteen men and one woman (age range = 22-37 years) lifted and lowered weights with either the forearm flexors or finger flexors while seated in a custom-built arm ergograph. Whereas the preceding investigation (Asmussen and Mazin, 1978a) focused on the effects of diverting activities on recovery from fatigue, this study examined their effects during exercise. Specifically, the subjects were instructed to perform repeated concentric muscle actions and intermittently open or close their eyes. Total work was compared between bouts with the subjects' eyes open versus those with their eyes closed. The results indicated that during fatiguing concentric muscle actions of the forearm flexors and finger flexors, more work was performed with the eyes open than with the eyes closed. In a separate experiment, the authors (Asmussen and Mazin, 1978b) had the subjects perform fatiguing concentric muscle actions of the forearm flexors until exhaustion with their eyes closed. Once the subjects reached the point that they could no longer perform the muscle actions, they opened their eyes and attempted to continue. The authors (Asmussen and Mazin, 1978b) found that when complete exhaustion had been reached with the eyes closed, opening them allowed 15–30% more work to be done. However, when the order was switched (i.e., the subjects performed the fatiguing muscle actions to exhaustion with their eyes opened, then closed their eyes), none of the subjects were

able to continue. Collectively, the results from these experiments suggested that diverting activities may have application both for enhancing recovery and maintaining performance during fatiguing exercise. Referring to previous EEG studies, the authors (Asmussen and Mazin, 1978b) hypothesized that the beneficial effects of diverting activities could potentially be explained by changes in reticular formation activity.

Zhang and Tokura (1996)

The purpose of this investigation was to compare local muscular endurance and core temperature following exposure to dim versus bright light intensities on the day before testing. Eight healthy women (age range = 20-24 years) participated in two separate trials. For each trial, the subjects were monitored inside a climatic chamber from 10:00 AM until 8:00 AM the following day. Light intensities were set to either 50 or 5,000 lux from 10:00 AM to 6:00 PM. For both trials, core temperature was measured from the beginning of data collection (10:00 AM) to 6:00 AM the following day. Following eight hours of sleep (10:00 PM to 6:00 AM), the subjects performed as many handgrips as possible with a load corresponding to 10% of their maximal handgrip strength value while seated in a custom-built ergometer. The results from a paired-sample t-test indicated that the subjects performed significantly more handgrips the morning after being exposed to bright light compared to that for the dim light condition (mean ± standard error of the mean = 864.5 ± 54.8 for bright, 766.6 ± 43.3 for dim; $p < 0.01$). In addition, core temperature was significantly lower for the bright condition versus the dim condition during both rest ($p < 0.001$) and sleep ($p < 0.001$). It was concluded (Zhang and Tokura, 1996) that exposure to bright light intensity enhanced local muscular endurance during fatiguing muscle actions. The authors

(Zhang and Tokura, 1996) hypothesized that these findings were related to differences in melatonin concentrations between the two conditions.

Ohkuwa et al. (2001)

The purpose of this study was to compare anaerobic capabilities and metabolic responses during maximal cycle ergometry exercise with low versus high levels of light exposure. On two separate occasions, ten endurance-trained men (mean age = 20.1 years) cycled as quickly as possible against a load corresponding to 7.5% of their body weight for 45 seconds. Blood samples were obtained from the antecubital vein 1.0, 2.5, 5.0, and 7.5 minutes following the cycle ergometry test for lactate, ammonia, epinephrine, and norepinephrine concentration analysis. In a randomized fashion, these trials were performed under either a dim light (50 lux) or bright light (5000 lux) condition. The results indicated that there was no significant difference in the average power values for the two conditions. Blood glucose and epinephrine concentrations were significantly lower following exercise ($p < 0.05$) for the bright light condition compared those for the dim light condition. No significant differences were noted between the two conditions, however, for blood lactate, ammonia, and norepinephrine concentrations following exercise. Thus, it was concluded (Ohkuwa et al., 2001) that different light exposures affect glucose metabolism and epinephrine secretion following exercise, but do not influence anaerobic capabilities during cycle ergometry.

Vuillerme et al. (2001)

The purpose of this investigation was to examine the effects of visual feedback and muscle fatigue on postural control. Ten adult men (mean ± SD age = 22.3 ± 1.8 years) participated in the study. For each trial, the 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. Center of pressure was examined with the eyes opened and eyes closed under both fatigued and non-fatigued conditions (i.e., four total conditions). 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. During each trial, the subjects were instructed to open or close their eyes while attempting to balance on the force platform. The maximal range (mm) and speed of center of pressure (mm/second) 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). The results indicated that when the subjects began the trial with their eyes closed, opening their eyes compensated for the effects of fatigue. In addition, regardless of the degree of visual feedback, the mean ± SD center of pressure range and center of pressure speed were greater for the fatigued conditions. It was concluded (Vuillerme et al., 2001) that fatigue-related factors and visual feedback play important roles in posture, and that the availability of vision allowed the subjects to cope with the destabilizing effects of fatigue. Therefore, the authors (Vuillerme et al., 2001, pg. 106) concluded that "...an impairment of proprioceptive information (e.g., elderly persons or patients suffering from a sensory neuropathy) should be compensated for by an appropriate adaptation of the day life visual environment."

Marx et al. (2003)

The purpose of this study was to compare brain activation patterns under eyes-open and eyes-closed conditions in complete darkness. Twelve healthy adults (eight

women, four men; mean age = 26.3 years) rested quietly in a magnetic resonance imaging scanner in a dark room. The subjects were instructed to alternately open and close their eyes for periods of 22.5 seconds in response to an acoustic signal given via headphones. The study began with the eyes-closed condition, followed by 11 blocks in which the eyes-open and eyes-closed conditions were alternated. The subjects were asked to keep their eyes straight ahead and to remain still. Functional images were acquired from thirty-two transverse slices of the brain and upper parts of the cerebellum. Each scanning session included two series of 120 images each with alternating eyes-open and eyes-closed conditions. The results indicated that the two conditions resulted in consistent differences in the patterns of brain activation that were evident for both individual subject and group analyses. As a result, it was concluded (Marx et al., 2003, pg. 933) that the effects of eyes-open versus eyes-closed conditions reflected two different states of mental activity: an "interoceptive" state with the eyes closed, characterized by sensory activity and imagination, and an "exteroceptive" state, characterized by activation of parts of the brain responsible for attention and focus. The results from this study may, therefore, have important implications for individuals that work in neuroimaging.

Barry et al. (2007)

The purpose of this study was to examine arousal and cognitive processing differences in eyes-closed versus eyes-open resting conditions. EEG activity was recorded from 28 subjects (10 men and 18 women; age range = 17-46 years). EEG signals were recorded from 19 sites over the scalp using an electrode cap with tin electrodes. Each experiment required alternating two minute periods of eyes-open and

eyes-closed resting conditions for 32 minutes. During the eyes-open condition, the subjects were instructed to visually fixate on a small cross presented on a computer screen in front of them. The EEG data from each two minute segment were divided into two second epochs, and at each electrode, absolute power in the delta (1.5-3.5 Hz), theta (4-7.5 Hz), alpha (8-13 Hz), and beta (13.5-25 Hz) bands were calculated. Skin conduction levels, which the authors (Barry et al., 2007, pg. 2766) stated is "...the long-established gold-standard for arousal measurement in autonomic studies" were also examined. The results indicated that when the subjects' eyes were closed, skin conduction levels were negatively correlated with the mean alpha levels. Skin conduction levels also demonstrated a significant increase from the eyes-closed to eyes-opened conditions. In addition, when the subjects opened their eyes, decreased across-scalp EEG activity was shown for each of the frequency bands examined. Topographical changes between conditions were noted for the delta, theta, and beta bands, but not the alpha band. It was concluded (Barry et al., 2007) that eyes-open and eyes-closed resting conditions resulted in different alpha band activity than those observed in the delta, theta, and beta bands, and that these differences could be explained by the degree of cortical processing of visual input. The authors (Barry et al., 2007) stated that these differences should be considered when neurophysiologists design research studies with eyes-open or eyes-closed baseline conditions.

Spadaro et al. (2010)

The primary purpose of this study was to compare surface EMG amplitude values for the anterior temporalis muscle during eyes-open versus eyes-closed conditions. Twenty healthy adults (12 women, 8 men; mean ± SD age = 21.5 ± 1.2

years) participated in this investigation. While seated and resting quietly, the subjects were instructed to repeatedly open and close their eyes in 15 second intervals. The subjects were asked to remain as still as possible to minimize the influence of movement artifacts, and mandible position was examined throughout the testing session. Bipolar surface EMG signals were recorded from the right and left temporalis anterior, as well as the masseter, digastric, and sternocleidomastoid muscles. For each muscle, paired samples t-tests were performed to compare the mean EMG amplitude values for the two conditions. The results indicated that there were no significant differences between eyes-open versus eyes-closed conditions for each of the muscles examined. The authors (Spadaro et al., 2010) concluded that the results from previous investigations demonstrating differences in surface EMG amplitude values for eyes-open versus eyes-closed conditions could have been related to movement artifacts or cross-talk from other muscles of the face.

Peak torque responses during repeated isokinetic muscle actions

Thorstensson and Karlsson (1976)

The purpose of this study was to examine peak torque responses during repeated maximal concentric isokinetic muscle actions, and to determine whether the decline in peak torque was significantly related to muscle fiber-type composition for the VL. On two separate days, ten men (mean age = 30.0 years) performed 50 and 100 maximal concentric isokinetic muscle actions of the left leg extensors. Each test was performed on a Cybex II isokinetic dynamometer at a velocity of 180°/second through a full 90° range of motion. Passive leg flexion was performed between maximal extensions. Isokinetic peak torque was determined for each concentric muscle action, and the

average values for the first and last three muscle actions were used to calculate each subject's fatigue index ([initial peak torque-final peak torque/initial peak torque] × 100). In addition, the authors (Thorstensson and Karlsson, 1976) obtained muscle biopies from the VL in order to estimate the percentages of fast-twitch and slow-twitch muscle fibers. The results from this study indicated that the mean ± standard error of the mean initial peak torque value was 130 ± 8 Nm, and decreased to 72 ± 4 Nm and 64 ± 4 Nm after 50 and 100 muscle actions, respectively, suggesting that the majority of the decline for peak torque occurred during the first 50 muscle actions. Linear regression analyses indicated that there was a positive correlation ($r = 0.86$, $p < 0.01$) between fatigue index and the percentage of fast-twitch muscle fibers for the VL. In addition, there was a significant relationship ($r = 0.69$, $p < 0.05$) between each subject's initial peak torque value and the percentage of fast-twitch muscle fibers. The authors (Thorstensson and Karlsson, 1976) concluded that the decline in peak torque during repeated maximal concentric isokinetic muscle actions can largely be explained by the structural and biochemical differences between fast-twitch and slow-twitch muscle fibers.

Patton et al. (1978)

The purpose of this investigation was to examine the shape of isokinetic fatigue curves during repeated muscle actions of the forearm flexors. Sixteen men and 16 women (age range = 18-24 years) participated in the study. Each subject performed repeated maximal concentric isokinetic muscle actions of the forearm flexors at a velocity of 60°/second. These muscle actions were performed until exhaustion, which was defined as "...the inability to perform another contraction." Based on each subject's strength level (low strength and high strength) and gender, the subjects were

divided into four separate groups, and analyses of variance (ANOVAs) were used to examine the differences in the shape of each fatigue curve throughout the fatigue tests. The results indicated that when the data for the four groups were combined, the relationship between torque and time to exhaustion was quadratic ($p < 0.01$). Linear relationships ($p < 0.01$) were demonstrated, however, when each group was analyzed individually. In addition, the average torque values for each of the data points were different ($p < 0.01$) among the groups, except between the high strength women and the low strength men. The results also indicated that fatigue occurred at 30% of the total test time for the high strength men, low strength women, and high strength women. The low strength women did not demonstrate fatigue. These findings suggested that during repeated maximal concentric isokinetic muscle actions, the degree of fatigue that occurs is largely a function of one's initial strength level, and this phenomenon is largely independent of gender.

Tesch et al. (1978)

This investigation examined muscle lactate accumulation and lactate dehydrogenase (LDH) activity in both fast- and slow-twitch muscle fibers immediately following repeated maximal concentric isokinetic muscle actions. Nine healthy men (mean age = 23 years) participated in the study. For the first visit to the laboratory, muscle biopsy samples were obtained from each subject's VL to determine the relative percentages of slow- and fast-twitch (further sub-grouped into a and x) fibers. On two separate occasions separated by no more than seven days, the subjects performed 50 and 25 maximal concentric isokinetic muscle actions of the left leg extensors at a velocity of 180°/second. Passive leg flexion followed each maximal extension. For both trials, a

muscle sample was taken from the VL immediately after the fatigue test and analyzed for lactate, total LDH, and LDH isozyme activity for both the fast- and slow-twitch fibers. The results indicated that the average concentric isokinetic peak torque values declined 25% and 43% during the fatigue tests with 25 and 50 repeated muscle actions, respectively. As demonstrated previously by Thorstensson and Karlson (1976), both initial peak torque and the percent decline in peak torque were highly correlated with the percentage of fast-twitch fibers. Lactate concentrations in fast-twitch fibers averaged 22.2 and 29.0 mmol/kg wet weight following 25 and 50 muscle actions, respectively. For slow-twitch fibers, these corresponding average values were 15.7 and 27.0 mmol/kg wet weight. The results from the paired-samples t-tests indicated that lactate concentrations for the fast-twitch muscle fibers of the VL were significantly greater than those for the slow-twitch fibers after 25 muscle actions ($p < 0.01$), but not following 50 muscle actions. The authors (Tesch et al., 1978) concluded that the discrepancy between lactate concentrations for the different fiber types of the VL was likely related to the subjects' recruitment of high-threshold motor units early in the fatigue test, and that glycolytic enzymes may have become inhibited as more muscle actions were performed.

Sinacore et al. (1994)

The three purposes of this study were 1) to examine the time course of recovery in strength following 50 maximal concentric isokinetic muscle actions of the dominant leg extensors, 2) to determine the test-retest reliability for initial peak torque, as well as percent decline at several time points during and following each fatiguing bout, and 3) to determine whether the recovery of peak torque is more closely associated with

maximal oxygen uptake ($V0_2max$) than the decline in isokinetic peak torque during repeated muscle actions. A total of 54 healthy men and women (age range = 21-47 years) participated in the study. The authors (Sinacore et al., 1994) purposefully recruited subjects with a wide range of $V0_2max$ values (29.9-75.5 ml/kg/min). Thirty-three subjects participated in the isokinetic peak torque test-retest reliability portion of the study (Phase 1), and 21 subjects participated in the aerobic endurance exercise portion of the investigation (Phase 2). For Phase 1, on two separate occasions, the subjects performed 50 maximal concentric isokinetic muscle actions of the leg extensors, followed by a single maximal contraction every 30 seconds after the fatigue test for four minutes (i.e., 30, 60, 90,120, 150, 180, 210, and 240 seconds). For Phase 2, the subjects performed 50 maximal concentric isokinetic muscle actions of the leg extensors, as well as a $V0_2max$ test, which allowed the authors (Sinacore et al., 1994) to examine the relationships among each of the isokinetic peak torque variables and aerobic power. The results from this study showed that the mean peak torque values were 69% and 75% of their initial values 30 and 60 seconds following the fatiguing bout, respectively. Furthermore, moderate-to-high intraclass correlation coefficients (0.67-0.98) were reported for initial peak torque, percent decline, and the peak torque values every 30 seconds following the fatiguing bout. High $V0_2max$ values were associated with a lower percent decline at 30 seconds following the fatiguing bout ($r = -0.84$). In contrast, the authors (Sinacore et al., 1994) reported weak-to-moderate negative relationships between $V0_2max$ and initial peak torque ($r = -0.33$), as well as $V0_2max$ and the percent decline during 50 maximal concentric isokinetic muscle actions ($r = -0.48$). Collectively, the results from this study suggested that recovery of

isokinetic peak torque values following repeated maximal concentric isokinetic muscle actions may be a reliable means of assessing the fatigability of the dominant leg extensors, and that the early recovery of peak torque may be a useful tool for predicting aerobic power. In their Conclusion Section, the authors (Sinacore et al., 1994) argued that due to the low variance between subjects, the assessments used in this study may be more appropriate than those described by Thorstensson and Karlsson (1976), especially for individuals working in clinical settings (e.g., physical therapists).

De Ste Croix et al. (2009)

The primary purpose of this study was to examine age- and gender-related differences in isokinetic peak torque percent decline for both the leg extensors and flexors. Thirty children (16 boys and 14 girls, age range = 11-12 years) and 21 adults (9 men and 12 women, age range = 18-35 years) performed 50 maximal isokinetic muscle actions of the dominant leg extensors and flexors at a velocity of 90°/second. For each contraction, the subjects were instructed to perform a maximal extension, followed by a maximal leg flexion. Average torque and average work for the first and last three muscle actions were determined and used to calculate each subject's percent decline. The results indicated that for each of the isokinetic peak torque percent decline variables examined, adults demonstrated a greater degree of fatigue compared to that for children. There were, however, no significant differences between the genders for both children and adults. The authors (De Ste Croix et al., 2009) concluded that children may be more resistant to fatigue during repeated maximal isokinetic muscle actions due to anatomical differences and an inability to recruit high-threshold motor units.

Factors that influence electromyographic amplitude and/or frequency

Eason (1960)

This investigation was among the first to suggest that the ability to maintain a constant force as a muscle progressively fatigues is accomplished by the recruitment of additional motor units. Twelve men (demographics not provided) performed sustained isometric muscle actions of the dominant forearm flexors at 25%, 50%, or 75% MVC until exhaustion on twelve separate occasions. The subjects then performed a second sustained muscle action with either the contralateral or previously fatigued forearm flexors. Bipolar surface EMG signals were detected during each muscle action with two silver discs (interelectrode distance = three inches). The results indicated that there was a linear relationship between initial EMG amplitude and force. In addition, EMG amplitude increased with time for each subject. The rate of increase for EMG amplitude was significantly greater for the 50% and 75% MVC muscle actions compared to that for the 25% MVC trial. Finally, there were no significant differences between arms for any of the dependent variables, suggesting that the residual effects from the sustained muscle actions were specific to the fatigued forearm flexors. It was concluded (Eason, 1960) that the increase in EMG amplitude for each trial was a result of the recruitment of higher threshold motor units.

Lindstrom et al. (1970)

This study was the first to examine the relationship between muscle fiber action potential conduction velocity (CV) and EMG frequency during fatiguing muscle actions. Six healthy men (age range = 24-30 years) participated in the investigation. The experiment required the subjects to perform several fatiguing isometric muscle

actions of the dominant forearm flexors while bipolar surface EMG signals were detected from the biceps brachii with two thin parallel silver plates. The EMG signals were recorded on FM tape, and frequency analyses were performed with a spectrum analyzer. The results indicated that the initial CV values for the six subjects ranged from 3.5 to 4.8m/s, and declined as the muscle progressively fatigued. The decline in CV was accompanied by a shift in the EMG power spectrum toward lower frequencies. The authors (Lindstrom et al., 1970) 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.

Masuda and De Luca (1991)

The purpose of this study was to examine the relationship between recruitment threshold and muscle fiber action potential CV for individual motor units. Three healthy subjects (two men, one woman; ages = 24, 24, and 35 years) performed isometric dorsiflexions at 75% MVC. Specifically, the subjects were required to linearly increase force from 0% to 75% MVC in ten seconds. The subjects then held the force constant at 75% MVC for ten seconds, followed by a linear decrease in force from 75% to 0% MVC in ten seconds. The subjects were provided with a visual template of their force production during the trapezoid muscle action. EMG signals were recorded from the tibialis anterior during the muscle action with a linear surface electrode array and a selective needle electrode. Sixteen separate bipolar EMG channels were detected with the surface array, and the intramuscular signals were decomposed with a Precision Decomposition Algorithm. The results indicated that muscle fiber CV for low-threshold motor units was significantly slower than the CV for high-threshold motor

units. In addition, there was a mean increase in CV of 21% for the lower threshold motor units. Thus, it was concluded (Masuda and De Luca, 1991) that the overall increase in CV during force-varying isometric muscle actions was due mainly to the recruitment of higher threshold motor units.

Kupa et al. (1995)

This study used in vitro methods to examine the relationships among EMG median frequency, CV, muscle fiber-type, and CSA. A total of 14 Wistar rats were used. Soleus and extensor digitorum longus muscles were excised from six animals, and the diaphragm was removed from eight animals. The soleus and extensor digitorum longus muscles were removed 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. Bipolar surface EMG signals were recorded during 20 second electrically-elicited tetanic muscle actions from the extensor digitorum longus, soleus, and diaphragm. The fibers from each muscle were classified as fast-glycolytic, fast-oxidative glycolytic, and slow-oxidative based on mATPase, succinate dehydrogenase, and α-glucose-6-phosphate dehydrogenase activities. CSA was also measured for each fiber. The results indicated that the muscles with a greater percentage of fast-glycolytic fibers showed higher initial values for EMG median frequency and CV. Specifically, the initial mean ± SD EMG median frequency values were 167.4 ± 8.1 Hz for the extensor digitorum longus, 158.3 ± 6.3 Hz for the diaphragm, and 134.3 ± 5.6 Hz for the soleus. The corresponding values for CV were 3.02 ± 0.50 m/s for the extensor digitorum longus, 1.89 ± 0.14 m/s for the diaphragm, and 1.70 ± 0.31 m/s for the soleus. In addition, fast-glycolytic muscle fibers were

associated with a greater reduction in median frequency and CV during the electrical stimulation. The results from the authors' (Kupa et al., 1995) 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. In addition, the initial median frequency versus CSA relationship was highly linear ($r = 0.92$, $p < 0.001$). It was concluded (Kupa et al., 1995) that the initial EMG median frequency values and the decline in CV during fatigue were related to both muscle fiber-type composition and CSA. The authors (Kupa et al., 1995, pg. 31) stated that their findings supported "...the possibility of utilizing surface EMG technologies to obtain a noninvasive electrophysiological 'muscle biopsy' for estimating muscle fiber composition."

Komi et al. (2000)

This investigation examined the effects of velocity and muscle length on EMG amplitude and median frequency during maximal concentric and eccentric muscle actions. Nine healthy men (age range = 18-27 years) performed muscle actions with their right forearm flexors while seated in a custom-built isokinetic dynamometer. The subjects performed maximal concentric and eccentric isokinetic muscle actions at four different velocities (57, 115, 172, and 229°/second). For all of the dynamic muscle actions, the subjects were instructed to activate their forearm flexors one second before the dynamometer's lever arm was initiated. In addition, the subjects performed isometric MVCs at joint angles corresponding to 55°, 110°, and 165° between the arm and forearm. Throughout all testing, bipolar surface EMG signals were detected from the biceps brachii, brachioradialis, and triceps brachii. For the dynamic muscle actions,

isokinetic peak torque and EMG amplitude and median frequency were examined for five separate portions of the range of motion (66°, 88°, 110°, 132°, and 154°). Similarly, these EMG parameters and MVC strength were determined for each of the isometric muscle actions. The results indicated that regardless of movement velocity and muscle action type, the greatest isokinetic peak torque values occurred at 110° (i.e., the middle of the range of motion). In addition, for each velocity, the eccentric torque values were greater than those for the concentric muscle actions at all portions of the range of motion except when the forearm flexors were at their greatest length (154°). The EMG amplitude results for each muscle showed that the greatest values were demonstrated for the concentric muscle actions, followed by the isometric and eccentric testing modes, respectively. In addition, the EMG amplitude values were generally greatest at slow movement velocities and short muscle lengths. Finally, the highest EMG median frequency values for each muscle occurred during the concentric muscle actions performed at fast movement velocities. It was concluded (Komi et al., 2000) that maximal eccentric isokinetic muscle actions are associated with greater peak torque values than those for concentric and isometric muscle actions. However, the EMG amplitude and median frequency results were highly dependent on movement velocity and muscle length. According to the authors (Komi et al., 2000), these results did not support the contention that fast-twitch muscle fibers are selectively recruited during eccentric muscle actions performed at high velocities.

<u>Factors that influence mechanomyographic amplitude and/or frequency</u>

Orizio et al. (1989a)

This investigation was the first to examine the relationship between MMG amplitude and isometric force throughout the entire force spectrum. Seven healthy men (mean ± SD age = 22.4 ± 1.4 years) performed a series of randomly-ordered isometric muscle actions of the dominant forearm flexors from 10% to 100% MVC in 10% increments. MMG signals were detected from the biceps brachii with a piezoelectric contact sensor during each muscle action. The results indicated that MMG amplitude increased linearly from 10-80% MVC, but decreased at 90% and 100% MVC. The authors (Orizio et al., 1989a) hypothesized that this finding reflected the fact that beyond 80% MVC, increases in force were due primarily to increased firing rates for the active motor units, and that the greater intramuscular pressure limited the degree of muscle fiber vibrations.

Marchetti et al. (1992)

This study compared MMG amplitude and frequency responses between the VL and soleus during supramaximal electrically-stimulated isometric twitches. Three healthy subjects (ages = 21, 32, and 58 years) participated in the investigation. The VL and soleus were electrically stimulated on two separate occasions while the MMG signal was detected with a piezoelectric contact sensor. The results indicated that the MMG median frequency values for the VL were significantly greater than those for the soleus. In addition, for each subject, the mean time to peak MMG amplitude was significantly greater for the soleus compared to that for the VL ($p < 0.01$). It was concluded (Marchetti et al., 1992) that the differences between the MMG responses for these two muscles were related to fiber-type differences. The authors (Marchetti et al., 1992) suggested that future investigations should examine MMG frequency responses

during supramaximal electrically-stimulated isometric twitches to examine differences among athletes.

Dalton and Stokes (1991)

This study was the first to examine the linearity of the MMG amplitude versus dynamic torque relationship. Eight healthy men (age range = 17-26 years) lifted and lowered weights with their right forearm flexors while MMG and EMG signals were detected simultaneously from the biceps brachii muscle. 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 kg, and the concentric and eccentric portions of the movement were analyzed separately. The results indicated that MMG amplitude increased linearly for both the concentric ($r = 0.94$) and eccentric ($r = 0.90$) testing modes. In addition, the MMG amplitude values for the concentric muscle actions were consistently greater than those for the eccentric muscle actions. EMG amplitude also showed linear increases for both the concentric ($r = 0.99$) and eccentric ($r = 0.94$) muscle actions. It was concluded (Dalton and Stokes, 1993) that MMG amplitude may be used to detect changes in torque during dynamic muscle actions.

Stokes (1993)

This review discussed many of the potential applications for MMG when studying muscle function. The manuscript provided a comprehensive background on the history of MMG and described many of the research questions that needed to be addressed. In the section that discussed muscle fatigue, the author (Stokes, 1993) argued that MMG amplitude provided a better indicator of the decline in force than EMG amplitude. It was also noted that the linear relationship between MMG and

torque during dynamic contractions suggested that clinicians might consider using this methodology to study muscle function when direct performance measurements cannot be made. The author (Stokes, 1993, pg. 14) cautioned, however, that "Applications of MMG in rehabilitation are fairly limited at present and further research is necessary to ensure that MMG is used properly. Premature use of MMG in rehabilitation might cause it to be misused and misunderstood so that its full potential might never be recognized."

Cramer et al. (2002)

The purpose of this study was to examine peak torque, mean power output, and MMG and EMG amplitude and MNF responses during maximal concentric isokinetic muscle actions. Twenty-three adults (twelve women, eleven men; mean ± SD age = 22 ± 3 years) performed maximal concentric isokinetic muscle actions of the dominant leg extensors at velocities of 60, 120, 180, 240, and 300°/second on a Cybex 6000 dynamometer. During each muscle action, MMG and EMG signals were detected from the VL, RF, and VM with piezoelectric contact sensors and bipolar surface electrodes, respectively. The results indicated that there were no sex-related differences among the velocity-related patterns for peak torque, mean power, MMG amplitude, MMG MNF, and EMG MNF. In addition, the results showed similar velocity-related increases in mean power output and MMG amplitude for all three muscles. MMG MNF increased significantly ($p < 0.05$) only between 240 and 300°/second. It was concluded (Cramer et al., 2002) that during maximal concentric isokinetic muscle actions, MMG amplitude was closely related to power output. The authors (Cramer et al., 2002) stated that "...MMG and EMG signals may be useful to athletic trainers and other allied

professionals for assessing the effects of rehabilitation programs after injury or surgery and for determining when athletes are ready to return to practice and competition."

Electromyographic and/or mechanomyographic amplitude and frequency responses during fatigue

Nilsson et al. (1977)

The purpose of this study was to examine fatigue-related responses for peak torque and EMG data during repeated concentric isokinetic muscle actions. Using similar methods as those described by Thorstensson and Karlsson (1976), twelve healthy men (mean ± SD age = 22 ± 3 years) performed 100 maximal concentric isokinetic muscle actions of the left leg extensors at a velocity of 180°/second. Peak torque, power, and work were calculated from each torque curve. During each muscle action, EMG signals were recorded from the VL, and both integrated EMG (IEMG) and peak EMG (defined as the highest point of the rectified and filtered curve) were calculated. In addition, muscle biopsy samples were obtained from the VL to determine the percentages of fast-twitch and slow-twitch fibers. The results from the study indicated that peak torque, work, and power declined rapidly during the first 50 muscle actions, but tended to plateau thereafter. Each of these variables was positively correlated ($r = 0.75$-0.81, $p < 0.01$) with the percentage of fast-twitch muscle fibers. Peak EMG was significantly greater ($p < 0.05$) for the 25th and 50th muscle actions than it was at the beginning of the fatigue test. However, the peak EMG per unit of peak torque and IEMG per unit of work values increased 2.0-2.3 times their initial values up to the 75th muscle action. Linear regression analyses indicated that during the initial 50 muscle actions, these ratios were positively correlated with the percentage of fast-twitch

muscle fibers ($r = 0.84$ and $r = 0.78$ for peak EMG per unit peak torque and IEMG per unit of work, respectively). The authors (Nilsson et al., 1977) concluded that the EMG results could be explained by local factors within the muscle fibers, and that the neuromuscular junction was not involved in the fatigue process.

Komi and Tesch (1979)

This study examined EMG spectral changes during repeated maximal isokinetic muscle actions at a high velocity. Eleven healthy men participated in the investigation. Following muscle biopsy sampling from the VL, the subjects were divided into two groups (Group I = < 50% fast-twitch muscle fiber area, n = 5, mean ± SD age = 27.8 ± 2.8 years; Group II = > 50% fast-twitch muscle fiber area, n = 6, mean ± SD age = 23.1 ± 1.1 years). The subjects performed 100 maximal concentric isokinetic muscle actions of the leg extensors at a velocity of 180°/second while the EMG signal was recorded from the VL. The power spectral density function, the IEMG, and EMG MNF were calculated for the middle portion of the range of motion of each isokinetic torque curve. The results indicated that during the fatigue test, both the absolute and relative decline in peak torque were greater in group II ($p < 0.01$ and $p < 0.05$, respectively). In addition, when examined across all subjects, the decline in peak torque was positively correlated with the percentage of fast-twitch muscle fiber area ($r = 0.73$, $p < 0.01$). The authors (Komi and Tesch, 1979) reported a significant decline in both IEMG ($p < 0.01$) and EMG MNF ($p < 0.001$) for the subjects in Group II. These parameters did not change or declined slightly for the subjects in Group I, however. It was concluded (Komi and Tesch, 1979, pg. 47) that the decline in EMG MNF for Group II, but not Group I, can be explained by "...differential fatigability of the fast-twitch and slow-

twitch fibers," and that fatigue-related contraction failure during high velocity movements may be related to qualitative changes in motor unit recruitment.

Barry et al. (1985)

The two purposes of this study were 1) to determine the linearity of the mechanomyographic (MMG) amplitude versus isometric force relationship, and 2) to examine MMG and EMG amplitude responses during fatiguing isometric muscle actions. Five and ten subjects participated in two separate experiments, respectively (subject demographics not provided). For the first experiment, the subjects held weights corresponding to 0, 5, 10, 12.5, 15, and 20 lbs for 20 seconds while MMG and surface EMG signals were recorded from the biceps brachii muscle. Linear regression analyses were used to examine the relationships for MMG and EMG amplitude versus isometric force. For the second experiment, MMG and EMG amplitude responses were assessed while the subjects held a constant force level corresponding to 75% of the MVC. The trial was terminated when the subject's isometric force level dropped below 35% of the MVC. For each subject, normalized MMG and EMG amplitude values corresponding to 5% increments of the total trial time were examined. For the first experiment, the authors (Barry et al., 1985, pg. 191) reported that the MMG amplitude versus isometric force relationship was "...approximately linear in the mid-range, with nonlinearities appearing in both low load and high load conditions." The results from the second experiment indicated that normalized MMG amplitude followed the decline in isometric force, whereas normalized EMG amplitude remained relatively stable throughout the fatiguing bout, but decreased at approximately 45% MVC. It was concluded (Barry et al., 1985) that MMG amplitude was highly correlated with the

amount of force produced by the biceps brachii. In addition, the results from this study suggested that by simultaneously examining MMG and EMG amplitude, researchers can monitor the dissociation between the electrical and mechanical events that occur during fatiguing muscle actions.

Gerdle et al. (1987)

The purpose of this study was to examine the time-course for the change in several isokinetic torque and EMG variables during fatiguing muscle actions. Twelve healthy middle-aged (age range = 42-46 years) men performed 200 maximal isokinetic plantar flexions at a velocity of 60°/second as three separate bipolar surface EMG signals were recorded from the triceps surae (soleus and two heads of the gastrocnemius). For each isokinetic muscle action, peak torque, mean power, and time were determined. The EMG signals were full-wave rectified, low-pass filtered, and IEMG and MNF values were calculated. The results indicated that throughout each trial, all of the isokinetic variables decreased during the initial 70 muscle actions, followed by a plateau for the remainder of the fatiguing bout. As a result, the authors (Gerdle et al., 1987, pg. 502) defined the first 70 and last 130 muscle actions as the "fatigue phase" and the "endurance phase," respectively. For all three parts of the triceps surae, the EMG MNF values decreased during the first 20 muscle actions, with no significant decline thereafter. When the fatigue phase was examined in detail, the results showed that the IEMG values did not decrease until the last 30 muscle actions (i.e., muscle actions 40-70). It was concluded (Gerdle et al., 1987) that during repeated maximal plantar flexions, mechnical fatigue of the triceps surae occurs in two distinct phases before reaching a steady-state level.

Horita and Ishiko (1987)

The purpose of this investigation was to examine the relationships among EMG activity, muscle lactate accumulation, and the decline in peak torque during repeated isokinetic muscle actions. Eleven healthy men (mean ± SD age = 23.6 ± 1.5 years) participated in the study. On two separate occasions, each subject performed maximal concentric isokinetic muscle actions with their right leg extensors at a velocity of 180°/second for either 30 seconds (approximately 25 muscle actions) or 60 seconds (approximately 50 muscle actions). During these fatigue tests, bipolar surface EMG signals were recorded from the VL. For each concentric isokinetic muscle action, EMG analyses included the median frequency value, the IEMG/peak torque ratio, and electromechanical delay (EMD). Immediately following each fatigue test, muscle biopsy samples were obtained from the VL in order to measure muscle lactate accumulation. The results indicated that during the 60 second fatigue test, the mean ± SD isokinetic peak torque values declined from 135.2 ± 15.6 to 55.6 ± 9.0 Nm, which represented a 59.0% decline. The corresponding mean ± SD lactate concentrations for the VL increased from 5.9 ± 1.9 to 16.7 ± 4.4 mmol/kg wet weight. As expected, the EMG median frequency values decreased, whereas the IEMG/peak torque ratio and EMD increased through the fatigue test. It was concluded that the EMG data during fatigue was well-correlated with the metabolic state of the muscle. Specifically, the authors (Horita and Ishiko, 1987, pg. 18) stated that the "...decrease in the efficiency of the electrical activity in the muscle suggested peripheral fatigue."

Lorentzon et al. (1988)

The purpose of this study was to examine the relationships among isokinetic performance, IEMG, and muscle cross-sectional area for both elite sprint- and endurance-trained men. Five sprinters (mean ± SD age = 23 ± 3 years) and five endurance-trained athletes (mean ± SD age = 29 ± 4 years) participated in the investigation. Each subject performed 200 maximal concentric isokinetic muscle actions of the right or left leg extensors at a velocity of 90°/second. However, in the event that a subject could not complete the full fatiguing protocol due to "...feelings of exhaustion or pain," (Lorentzon et al., 1988, pg. 532) the test was discontinued. Contractional work, defined as "the time-integral of the torques over that part of a full circle covered by the isokinetic manoeuvre" (Lorentzon et al., 1988, pg. 532) and mean power were calculated for each muscle action. In addition, during each muscle action, bipolar surface EMG signals were recorded from the VL, RF, and VM. These signals were full-wave rectified, low-pass filtered, and integrated. Quadriceps femoris and VL muscle cross-sectional area (CSA) were assessed via computerized tomography. Muscle biopsies were performed to determine the percentages of fast- and slow-twitch fibers for the VL, as well as the mean area of each fiber-type. The results indicated that regardless of training background, the initial contractional work was highly correlated with fast-twitch muscle fiber area, but not quadriceps femoris CSA. During the first 25 muscle actions, the sprinters demonstrated a greater reduction in contractional work than that for the endurance-trained athletes, and this decline was related to absolute fast-twitch muscle fiber area. The contractional work/IEMG ratio decreased significantly for the sprint-trained athletes, while no change was demonstrated for the endurance-trained athletes. Finally, whereas all five of the endurance-trained athletes were able to

complete the fatiguing protocol, only two sprinters were able to perform more than 50 muscle actions, and each of these subjects reported "...pain in their warm and swollen thighs" (Lorentzon et al., 1988, pg. 535). It was concluded (Lorentzon et al., 1988) that the decline in contractional work during repeated maximal isokinetic muscle actions of the leg extensors is largely related to VL muscle structure, and that decreased muscle fiber pH may lead to inhibition of central drive.

Orizio et al. (1989b)

The primary purpose of this study was to examine MMG and EMG amplitude responses during exhaustive isometric muscle actions at several submaximal force levels. Eight healthy men (mean ± SD age = 22.9 ± 2.0 years) participated in the investigation. Following several familiarization sessions, the subjects performed sustained isometric muscle actions of the right forearm flexors at 20%, 40%, 60%, and 80% MVC on four separate days. During each muscle action, MMG and bipolar surface EMG signals were detected from the biceps brachii with a contact sensor transducer and two silver-silver chloride electrodes (interelectrode distance = 4 cm), respectively. The results indicated that the mean times to exhaustion were 480, 134, 68, and 39 seconds at 20%, 40%, 60%, and 80% MVC, respectively. During the sustained muscle action at 20% MVC, MMG amplitude increased linearly across time. At 40% MVC, however, MMG amplitude showed only a very slight increase across time. Finally, during the sustained muscle actions at 60% and 80% MVC, MMG amplitude decreased curvilinearly. What was particularly noteworthy, however, was that EMG amplitude increased across time for all of the target force levels. The authors (Orizio et al., 1989) hypothesized that the different patterns of response for MMG amplitude were

due to differences in recruitment of motor units and changes in their firing rates, as well as different levels of intramuscular pressure and stiffness. It was concluded (Orizio et al., 1989) that the MMG signal may provide more information than EMG regarding motor control strategies during sustained isometric muscle actions.

Mealing et al. (1990)

The purpose of this investigation was to examine changes in the MMG power spectrum during fatigue. Three healthy men (demographics not provided) performed a sustained isometric muscle action of the leg extensors at 80% MVC. The muscle action continued until the subject's force output dropped below 10% MVC. The MMG signal was detected throughout the fatiguing protocol from the RF with a piezoelectric contact sensor. The results indicated that during the fatiguing muscle action, the MMG power spectrum alternated between wide and narrow bandwidths. The authors (Mealing et al., 1990) speculated that this cycling may have been due to rotation of activity between different fiber types during fatigue.

Goldenberg et al. (1991)

Noting that many previous MMG investigations had examined relatively large muscles, the purpose of this study was to examine MMG amplitude responses during sustained submaximal isometric muscle actions of the abductor digiti minimi. Twelve healthy subjects (six men, six women; age range = 19-29 years) participated in the study. On four separate occasions, the subjects performed an exhaustive isometric muscle action with the fifth digit at 15%, 25%, 50%, and 75% MVC. For each trial, data collection was terminated when the subjects' target force declined by 10% in a five second time period. During each muscle action, the MMG signal was detected from the

abductor digiti minimi with an omnidirectional electret microphone, which was placed halfway between the pisiform bone of the wrist and the head of the fifth metacarpal bone of the hand. Normalized MMG amplitude values were determined for five second epochs at the beginning, middle, and end of each muscle action. To minimize the influence of physiological tremor, frequencies below 14 Hz were attenuated. The results indicated that the mean times until exhaustion were 45, 90, 334, and 992 seconds for the target force levels corresponding to 75%, 50%, 25%, and 15% MVC, respectively. For both the 15% and 25% MVC trials, MMG amplitude was significantly greater at the end of the fatiguing bout compared to that for the middle and the beginning ($p < 0.05$). For the 50% MVC trial, MMG amplitude decreased from the beginning to the middle ($p < 0.05$), as well as the middle to the end ($p < 0.05$). For the 75% MVC muscle action, however, MMG amplitude did not change. It was concluded (Goldenberg et al., 1991) that when synergist muscles do not contribute to an isometric muscle action (as is the case for the abductor digiti minimi), MMG amplitude changes over time do not accurately reflect force production. The authors (Goldenberg et al., 1991) stated, however, that making comparisons among studies was difficult due to the fact that different muscles were examined previously and physiological tremor did not influence their results. Collectively, the results from this study (Goldenberg et al., 1991) suggested that MMG amplitude changes during fatigue may be dependent on motor unit recruitment strategies and muscle fiber-type, but not necessarily force production.

Orizio and Veicsteinas (1992)

This study examined the responses for MMG amplitude and MNF during a fatiguing isometric muscle action in sprinters, endurance athletes, and sedentary subjects. Twenty healthy adults (age range = 18-30 years) participated in the study. Seven of these subjects were sprinters (100 meter dash time less than eleven seconds), seven were long distance runners (marathon time less than 150 minutes), and seven were sedentary controls (physically active less than three days per week). The fatiguing protocol for this study required the subjects to attempt to sustain an MVC of the dominant leg extensors for as long as possible. Visual feedback was provided, and each trial was terminated when the subject reached volitional exhaustion. Throughout the muscle action, MMG signals were detected from the VL with a piezoelectric contact sensor. MMG amplitude, MMG MNF, and isometric force were determined for 21 data segments that were normalized to each subject's total contraction time. The results indicated that the sprinters demonstrated the highest initial leg extension strength values, followed by the sedentary individuals, and the endurance athletes (mean ± standard error of the mean = 773 ± 34 N, 705 ± 55 N, and 558 ± 43 N, respectively). The mean ± standard error of the mean times to exhaustion were 48 ± 4, 62 ± 4, and 95 ± 10 seconds for the sprinters, sedentary individuals, and the endurance athletes, respectively. For the endurance athletes, the mean MMG amplitude values at the beginning of the trial were significantly lower than those for the other two groups, and remained virtually unchanged throughout the muscle action. In contrast, the mean MMG amplitude values for the sprinters and sedentary individuals declined approximately 50% in a linear pattern. There were also decreases in MMG MNF throughout the muscle action for all three groups, but the endurance athletes

demonstrated the smallest decrease. Although the authors (Orizio and Veicsteinas, 1992) did not perform muscle biopsies, it was hypothesized that the results for this study were likely related to differences in muscle fiber-type among the groups. Specifically, the authors (Orizio and Veicsteinas, 1992, pg. 598) stated "...the onset values and the time courses of the time and frequency domain parameters seem to be strongly affected by the muscle fast and slow-twitch fibers proportion. Thus it can be hypothesized that the SMG (MMG) can be used as an adjunct to electromyogram for the non invasive muscles fiber typing."

Orizio et al. (1992)

The purpose of this study was to examine changes in MMG and EMG amplitude and MNF during fatiguing isometric muscle actions. Thirteen healthy men (age range = 22-24 years) participated in the investigation. Following several familiarization sessions, the subjects performed an exhaustive isometric muscle action of the forearm flexors at 20%, 40%, 60%, and 80% MVC. The four muscle actions were performed on separate days and were completed in a randomized fashion. During each muscle action, MMG and bipolar surface EMG signals were detected from the biceps brachii muscle with a contact sensor transducer and two silver-silver chloride electrodes (interelectrode distance = 3 cm), respectively. For each trial, MMG and EMG amplitude and MNF were determined from 11 evenly distributed two second epochs. The results indicated that the mean ± standard error of the mean times until exhaustion for the 20%, 40%, 60%, and 80% MVC muscle actions were 492 ± 47, 123 ± 11, 54 ± 3, and 29 ± 2 seconds, respectively. For each submaximal force level, EMG amplitude increased and EMG MNF decreased with fatigue. In contrast, MMG amplitude increased across time

for the 20% and 40% MVC muscle actions, but declined for those at 60% and 80% MVC. The MMG MNF responses across time were fairly complex. Specifically, for the 20% MVC muscle action, the mean ± standard error of the mean values increased from 11.5 ± 0.7 Hz to 12.8 ± 0.5 Hz after 30% of the total contraction time, but remained relatively stable thereafter. At 40% MVC, MMG MNF increased slightly during the first 10% of the muscle action and then decreased slowly. At 60% MVC, however, MMG MNF remained relatively stable during the first 40% of the muscle action, and then progressively declined. Finally, for the 80% MVC trial, MMG MNF increased during the first 30% of the muscle action and then decreased for the remainder. According to the authors (Orizio et al., 1992), the MMG results from this study were consistent with those from previous investigations that had examined changes in motor unit firing rates during fatiguing isometric muscle actions. The authors (Orizio et al., 1992) also stated that the increase in MMG amplitude at 20% MVC was likely related to motor unit synchronization, while the reduction in MMG amplitude at high force levels was due to the decline in firing rates for the high-threshold motor units. Thus, it was suggested (Orizio et al. 1992) that when combined with EMG, MMG may be useful for investigating the neural and peripheral mechanisms underlying muscle fatigue.

Dalton and Stokes (1993)

The primary purpose of this investigation was to compare the relationship between MMG MNF and isometric force during fresh versus fatigued conditions. Six healthy men (age range = 24-32 years) performed a series of intermittent isometric muscle actions in an attempt to fatigue the leg extensors. Immediately before and after

this fatiguing protocol, the subjects performed isometric muscle actions of the leg extensors at force levels corresponding to 10, 25, 60, 75, and 100% MVC while MMG signals were detected from the RF with a condenser microphone. The results indicated that prior to the fatiguing bout, the MMG MNF values ranged from 7.1-16.9 Hz. Following the fatiguing bout, the MMG MNF values ranged from 8.4-17.5 Hz. For both conditions, the MMG MNF values increased quadratically with higher force levels ($r = 0.81$ and 0.77 for the fresh and fatigued conditions, respectively). It was concluded (Dalton and Stokes, 1993) that the MMG MNF values were not altered by fatigue, which was in contrast to previous studies that examined changes in the frequency content of the MMG signal during fatigue.

Rodriquez et al. (1993)

This study examined changes in MMG and EMG amplitude, as well as EMG median frequency, during and immediately following sustained isometric muscle actions. Seven healthy men (mean ± SD age = 34.7 ± 5.5 years) performed sustained isometric muscle actions of the dominant leg extensors at 20%, 40%, and 80% MVC on three separate occasions. Each trial was terminated when the subject could not maintain the target force. Strength recovery was assessed by having the subjects perform an MVC 1.5, 4, 6, 8, and 10 minutes following the fatiguing bout. During each muscle action, MMG signals were detected from the RF with a piezoelectric contact sensor, while EMG signals were detected simultaneously from the VM. The amplitudes of the MMG and EMG signals were calculated, but median frequency was determined only for the EMG data. The mean ± SD isometric endurance time was 433 ± 98 seconds for the 20% MVC trial, 176 ± 27 seconds for the 40% MVC trial, and 51 ± 9 seconds for

the 80% MVC trial. The results indicated that EMG median frequency for the VM decreased for each trial ($p < 0.05$). In addition, the mean EMG amplitude values increased significantly ($p < 0.05$) for each trial, whereas MMG amplitude increased ($p < 0.05$) at 20% and 40% MVC, but remained constant ($p > 0.05$) throughout the 80% MVC contraction. During recovery, MMG amplitude for the RF and median frequency for the VM had fully recovered to their initial values within 1.5 minutes for all three trials. After the 40% MVC trial, maximal strength of the leg extensors and EMG amplitude had recovered by the four and six minute marks, respectively. Following the 80% MVC muscle action, the EMG amplitude and MVC values had fully recovered by 1.5 minutes. Interestingly, following the 20% MVC muscle action, EMG amplitude and MVC did not fully recover within the ten minute testing period. It was concluded (Rodriquez et al., 1993) that these variables each provided different information regarding the recovery process, and that MMG amplitude for the RF responded differently than EMG amplitude and median frequency for the VM.

Herzog et al. (1994)

This study examined MMG and EMG median frequency responses during an isometric fatiguing activity. Eleven healthy men (age range = 22-35 years) participated in the investigation. All data collection for this study occurred on one day. Following a brief warm-up, the subjects performed a sustained isometric muscle action of the dominant leg extensors at 70% MVC. Onset of fatigue was defined as the point at which the subject could no longer maintain 70% MVC, and the trial was terminated when isometric force dropped below 50% MVC. During the muscle action, bipolar surface EMG and MMG signals were detected from the VL and RF with Ag-AgCl

electrodes (interelectrode distance = 30 mm) and accelerometers, respectively. For all four signals, median frequency values were calculated for one second segments throughout the fatiguing protocol. The results indicated that the mean ± SD time that the subjects were able to maintain the 70% MVC force level was 45 ± 13 seconds. In addition, the corresponding time until exhaustion was 64 ± 17 seconds. For both muscles, EMG median frequency values declined throughout the entire protocol. In contrast, the results for MMG median frequency indicated that the mean values tended to remain constant when the force was maintained at 70% MVC. Once the subjects' force dropped below 70% MVC, the median frequency "...tended to decrease rather abruptly within a few seconds" (Herzog et al., 1994, pg. 1158). The authors (Herzog et al., 1994) suggested that the decreases in MMG median frequency values were likely due to muscle tremor, which is an important part of the fatigue process and should not be removed from the MMG signal.

Vaz et al. (1996)

This investigation was a follow-up to a previous study by Herzog et al. (1994). The purpose of the investigation was to examine differences between EMG and MMG amplitude and median frequency responses during a fatigue-recovery protocol. Eleven healthy men (age range = 22-35 years) performed a sustained isometric muscle action of the dominant leg extensors at 70% MVC for as long as possible. The trial was discontinued when the subject's force dropped below 50% MVC. During the recovery period, the subjects performed a ten second isometric muscle action at 70% of the original MVC at 20 seconds, 50 seconds, two, three, four, five, six, seven, eight, nine, ten, and fifteen minutes after the fatigue test. During each muscle action, EMG and

MMG signals were detected simultaneously from the VL and RF, and amplitude and median frequency values were calculated for several time points throughout the experiment. Specifically, the authors (Vaz et al., 1996, pg. 223) examined data for six specific time points, which they defined as "trials." Trials one through six were obtained from the following data, respectively: the MVC, the first five seconds of the fatigue protocol, the last five seconds at which 70% MVC was maintained, the last five seconds of the fatigue trial at a level below 70% MVC, 20 seconds after the fatigue protocol, and fifteen minutes after the fatigue protocol. The results showed that the duration of the fatigue protocol ranged from 52 to 107 seconds. For both muscles, EMG and MMG median frequency declined throughout the entire fatigue protocol, and returned to their initial values during the recovery period. When the six trials were examined in detail, the results indicated that for both muscles, the mean EMG and MMG median frequency values were greatest during trial two (first five seconds of the fatigue protocol) and trial six (last five seconds of the recovery period). Similar patterns for EMG amplitude were demonstrated for the two muscles, and the values were highest during trial one, decreased throughout the fatigue protocol, and progressively increased during recovery. MMG amplitude, however, revealed slightly different patterns across the six trials for the VL and RF. It was concluded (Vaz et al., 1996) that MMG amplitude did not change in a predictable manner during fatigue and recovery. As discussed by Herzog et al. (1994), the authors (Vaz et al., 1996, pg. 221) believed that the decline in MMG median frequency for both muscles during fatigue was consistent with "...low-frequency tremor that typically occurs towards the end of exhausting isometric contractions."

Shinohara et al. (1997)

The purpose of this study was to examine EMG and MMG amplitude responses during incremental cycle ergometry. Nine healthy men (mean ± SD age = 25.6 ± 3.1 years) performed a cycle ergometry test while bipolar surface EMG and MMG signals were detected simultaneously from the right VL muscle. Following a three minute warm-up, the subjects pedaled at a cadence of 60 revolutions per minute, and the workload was increased 20 watts each minute until exhaustion. In addition, heart rate and oxygen uptake were measured throughout the testing trial. The EMG and MMG signals from the last six revolutions at each workload were full-wave rectified, integrated, averaged, and normalized to the maximal value at exhaustion. The results indicated that oxygen uptake plateaued at the end of the testing trial, and the mean ± SD heart rate, workload, and work rate were 194.4 ± 3.1 beats per minute, 44.1 ± 5.5 Nm, and 276.7 ± 34.7 watts, respectively. When examined on an individual subject basis, the relationship between MMG amplitude and workload ranged from r = 0.868-0.995, whereas these patterns were either linear or curvilinear for EMG amplitude versus workload. The results for the grouped data also indicated that MMG amplitude was linearly related to workload (r = 0.995). It was concluded (Shinohara et al., 1997) that MMG amplitude for the VL muscle increased linearly with power output during incremental cycle ergometry, and that this relationship was more linearly related to power output than was EMG amplitude, which tended to increase curvilinearly at high power outputs.

Stout et al. (1997)

This investigation examined the patterns for oxygen consumption rate and MMG amplitude from the VL during an incremental cycle ergometer test performed to exhaustion. Twenty-four healthy men (mean ± SD age = 22.1 ± 2.0 years) participated in the study. While seated on a calibrated electronically braked cycle ergometer, each subject pedaled at a cadence of 70 revolutions per minute. The trial began at a power output of 60 watts, and increased 30 watts every three minutes until voluntary exhaustion. $V0_2$ was measured every fifteen seconds with a metabolic cart. Throughout the trial, the MMG signal was detected from the VL with a piezoelectric contact sensor, and the amplitude values were determined for the last ten seconds of each stage. The results indicated that the MMG amplitude and $V0_2$ versus power output relationships were highly linear (r^2 range = 0.79–0.99 and 0.97–0.99, respectively). In addition, for 20 of the 24 subjects, the linear slope coefficients for the normalized MMG amplitude and $V0_2$ versus power output relationships were statistically equivalent. It was concluded (Stout et al., 1997) that MMG could be useful for quantifying muscular activity and monitoring changes in exercise intensity during incremental cycle ergometry. Furthermore, the authors (Stout et al., 1997) stated that the similar slope coefficients for the normalized MMG amplitude and $V0_2$ versus power output relationships suggested that there may be a close relationship between the metabolic and mechanical aspects of muscle function.

Esposito et al. (1998)

The purpose of this study was to examine changes in EMG and MMG amplitude and MNF during prolonged isometric muscle actions prior to and following a fatiguing protocol. Seven healthy men (age range = 22-31 years) participated in the study. The

experimental procedures for this study began with an isometric muscle action of the dominant forearm flexors at 80% MVC until the subjects were unable to keep the force level constant within ± 5% of the target (Test 1). Following Test 1, the subjects rested for ten minutes. The subjects then performed repeated submaximal muscle actions at 50% MVC for six seconds, followed by four seconds of rest (i.e., six seconds "on," four seconds "off") until the target force could no longer be maintained. The authors (Esposito et al., 1998, pg. 496) specifically used this protocol because it was "...similar to contractions found in daily life and various occupations." Following another ten minute rest period, the subjects performed an isometric muscle action at 80% of the new MVC until exhaustion (Test 2). During both exhaustive 80% MVC muscle actions (Tests 1 and 2), EMG and MMG signals were detected simultaneously from the biceps brachii muscle. The results indicated that the mean MVC values were 412 N and 304 N for fresh and fatigued muscle (26% decline), respectively. There was no significant difference between the duration for Test 1 (mean ± standard error of the mean = 25 ± 5 seconds) versus that for Test 2 (mean ± standard error of the mean = 24 ± 9 seconds [$p > 0.05$]). For Test 1 and Test 2, the EMG amplitude values increased during the first 10 and 14 seconds, respectively, and then plateaued thereafter. The EMG MNF values declined in a similar manner for both tests. The results for the MMG amplitude data indicated that for Test 1, the mean values declined from 9.4 to 5.7 mV, but remained constant thereafter. In the fatigued state, however, the MMG amplitude values remained relatively constant throughout the entire sustained muscle action. Finally, for Test 1, the MMG MNF values increased initially ($p < 0.05$), followed by a significant decrease from six seconds until exhaustion ($p < 0.05$). In contrast, the MMG MNF

values declined throughout the entire protocol for Test 2 ($p < 0.05$). The authors (Esposito et al., 1998) hypothesized that the differences between the EMG and MMG responses were related to elongation of the muscle fiber twitch response with fatigue and/or muscle stiffness. It was also concluded (Esposito et al., 1998) that that the effects of fatigue on the biceps brachii may be better reflected in the MMG signal than the EMG signal.

Kouzaki et al. (1999)

This study examined EMG and MMG responses during repeated MVCs. Seven men (mean ± SD age = 24.4 ± 1.4 years) performed 50 repeated maximal unilateral isometric muscle actions of the leg extensors at a joint angle of 90°. Each maximal muscle action was held for 3 seconds, followed by 3 seconds of rest (i.e., 3 seconds "on," 3 seconds "off"). EMG signals were detected from the VL, RF, and VM with bipolar electrode configurations (interelectrode distance = 50 mm). The MMG signals were simultaneously detected with piezoelectric microphones, which were placed between the EMG electrodes. The EMG and MMG signals were full-wave rectified and integrated to yield IMMG and IEMG. In addition, the median frequency of each signal was calculated using the Fast Fourier Transform. The results indicated that the mean isometric leg extension force value decline by 49.5%. The normalized IEMG values declined throughout the fatigue test, with no significant differences among the three muscles. Conversely, IMMG declined throughout the test, but the magnitude of the decrease for the RF was significantly greater than that for the VM. In addition, for both MMG and EMG median frequency, the values at the beginning of the test were greatest for the RF and declined to a greater extent than those for the VM and VL. In their

Discussion Section, the authors (Kouzaki et al., 1999) speculated that the different responses among the muscles were related to fiber-type. Specifically, the authors (Kouzaki et al., 1999) noted that the percent declines in IMMG for the VL, RF, and VM were very similar to the percentages of slow-twitch muscle fibers reported in an autopsy study by Johnson et al. (1973). Collectively, it was concluded (Kouzaki et al., 1999, pg. 15) that "...for the quadriceps muscles investigated, it would seem that RF is most susceptible to fatigue by repeated MVC."

Gerdle et al. (2000)

The purpose of this investigation was to examine the EMG amplitude (root-mean-square [RMS]) and MNF versus dynamic torque relationships during fatiguing isokinetic muscle actions on an individual subject basis. Eleven men and ten women (age range = 20-38 years) performed 100 maximal concentric isokinetic muscle actions of the right leg extensors at a velocity of 90°/second as bipolar surface EMG signals were recorded from the VL, VM, and RF. For each concentric isokinetic muscle action, peak torque, EMG RMS, and EMG MNF values were determined. For each fatigue test, subject, and muscle, linear regression analyses were used to determine the correlation coefficients for the peak torque versus EMG RMS, as well as the peak torque versus EMG MNF relationships. The results indicated that the highest correlation coefficients were found for the peak torque versus EMG MNF relationships for the RF. For the peak torque versus EMG MNF analyses, only one out of the 63 (21 subjects, three muscles) linear regressions resulted in a negative relationship. The peak torque versus EMG RMS relationships demonstrated no consistent pattern (i.e., some were positive, some were negative, and some showed no relationship). In summary, the

results from this study suggested that the decline in peak torque during 100 maximal concentric isokinetic muscle actions is highly correlated with the decrease in EMG MNF values. In contrast, researchers should not assume that EMG RMS will increase or decrease in a predictable manner during repeated dynamic muscle actions.

Weir et al. (2000)

The purpose of this investigation was to examine the influence of muscle length on EMG and MMG responses during fatiguing isometric muscle actions. Thirteen healthy subjects (eight men, five women; mean ± SD age = 25 ± 3 years) visited the laboratory on two occasions separated by at least 48 hours. For these two trials, the subjects performed isometric dorsiflexions at 50% MVC for 60 seconds at either 40° of plantarflexion (long muscle length) or 5° of dorsiflexion (short muscle length). During these muscle actions, bipolar surface EMG and MMG signals were detected from the tibilias anterior muscle with surface electrodes and an accelerometer, respectively. For both fatiguing muscle actions, the EMG and MMG signals were divided into 60, 1-second segments, and the normalized amplitude and MNF values were calculated. Linear regression analyses were performed to determine the linear slope coefficients for the changes in normalized amplitude and MNF over time (units = % max/second). Six separate paired samples t-tests were used to compare long versus short muscle lengths for the mean force of the 50% MVC muscle actions, the MVC following the fatiguing protocols, and the linear slope coefficients for MMG and EMG amplitude and MNF. The results indicated that there were no significant differences for the mean force during the 50% MVC muscle actions and the MVCs following the fatiguing protocols at long versus short lengths, indicating that any differences for MMG and EMG

parameters were related to muscle length, and not differences in force between the trials. Both the mean MMG and EMG amplitude versus time linear slope coefficients were greater for the long muscle length compared to those for the short muscle length. However, there were no mean differences between these relationships for MMG and EMG MNF. Thus, the authors (Weir et al., 2000) concluded that when the tibialis anterior was lengthened, a greater rate of motor unit recruitment was necessary to maintain a steady force. However, the similar MNF versus time linear slope coefficients for the two conditions suggested comparable changes in motor unit firing rate, and the authors (Weir et al., 2000, pg. 358) stated "...fatigue differences between muscle lengths are driven by motor control processes and not necessarily by cellular metabolic factors."

Madeleine et al. (2002)

This study compared the combined influences of feedback (visual versus proprioceptive) and testing (continuous versus intermittent) modes on the development of muscle fatigue. Six healthy men (mean ± SD age = 28.8 ± 2.4 years) participated in two trials. For each trial, the subjects were seated in a chair with their elbows flexed at 90°, and a belt that was attached to a force transducer was fixed to the left or right wrist (depending on the recording side). Both trials required the subjects to perform submaximal isometric muscle actions of the left and right forearm flexors using visual and proprioceptive feedback, and the order of testing (i.e., left arm visual feedback, right arm visual feedback, left arm proprioceptive feedback, and right arm proprioceptive feedback) was randomized. For the visual feedback mode, the target force level was displayed on a computer screen as a vertical bar, and the subjects had to

adjust their force output accordingly. For the proprioceptive feedback condition, the subjects were required to maintain elbow posture so that the weight corresponding to the required percentage of the MVC was kept above the floor. For the first trial, the subjects performed sustained isometric muscle actions at 10% and 30% MVC for ten minutes and until exhaustion, respectively, as well as intermittent muscle actions (six seconds "on," four seconds "off") at 10% MVC. The second trial, however, only involved intermittent muscle actions at 30% MVC. Throughout all testing, isometric force and ratings of perceived exertion were assessed as bipolar surface EMG and MMG signals were detected from the biceps brachii. The amplitude and MNF values were calculated and normalized to those from a non-fatigued MVC. In addition, the MMG amplitude to EMG amplitude ratio was calculated for each one-second epoch, a measure known as electromechanical efficiency (Barry et al., 1990). The results indicated that there was no significant difference for time to exhaustion between visual (mean = 255 seconds) and proprioceptive (mean 214 seconds) feedback for the sustained isometric muscle actions at 30% MVC. In addition, there were no significant differences in the mean force values between feedback modes for the sustained muscle actions at both 10% and 30% MVC, indicating that the MMG and EMG data were not influenced by the different force levels. The results also indicated that MMG and EMG amplitude increased over time, while EMG MNF decreased for all conditions. The increase in normalized MMG amplitude was more marked than that for EMG amplitude, while the opposite was observed for MNF. Finally, the proprioceptive feedback condition was associated with a greater rating of perceived exertion compared to that for the visual feedback condition during the intermittent 30% MVC and

sustained 10% MVC muscle actions. It was concluded (Madeleine et al., 2002) that during both sustained and intermittent muscle actions at low force levels, MMG provides complementary information to EMG, and the mechanisms underlying fatigue may be feedback dependent.

Perry-Rana et al. (2002)

The purpose of this study was to examine MMG and EMG amplitude responses during repeated dynamic muscle actions at three different velocities. On three separate days, ten adults (mean ± SD age = 21.8 ± 2.4 years) performed 50 maximal concentric isokinetic muscle actions of the dominant leg extensors at three randomly selected velocities (60, 180, and 300°/second) while bipolar surface EMG and MMG signals were recorded from the VL, RF, and VM. Peak torque and EMG and MMG amplitude were calculated for each concentric isokinetic muscle action, normalized, and averaged across subjects. The results indicated that the mean ± SD percent decline in peak torque values was 44 ± 18%, 65 ± 14%, and 63 ± 8% at 60, 180, and 300°/second, respectively. For all three muscles, the normalized EMG amplitude and repetition number relationships were best fit with cubic models at each velocity. In contrast, the normalized MMG amplitude values were characterized by either a linear, quadratic, or cubic decrease during the fatigue test. It was concluded (Perry-Rana et al., 2002) that MMG amplitude more closely tracked the fatigue-induced decline in torque production at each velocity than did EMG amplitude. Furthermore, the authors (Perry-Rana et al., 2002) concluded that during maximal concentric isokinetic muscle actions of the leg extensors, MMG amplitude may be useful for examining the individual contributions of

the VL, RF, and VM to torque production. This information could, therefore, be helpful for clinicians that assess muscle function in both diseased and healthy populations.

Orizio et al. (2003)

This publication included both a brief review of the physiological basis of MMG research and experimental data related to muscle fatigue. For the research study, the authors (Orizio et al., 2003) hypothesized that EMG and MMG could be used to investigate motor unit activation strategies under fatigued conditions. Ten healthy adults (age range = 20-30 years) performed isometric muscle actions of the dominant forearm flexors at a joint angle of 115° between the arm and forearm. The experimental protocol began with determination of the non-fatigued MVC. Following the maximal strength assessment, the subjects performed a 6.75 second isometric muscle action that required force to be increased from 0% to 90% MVC at a rate of 13.3% MVC/second. Immediately thereafter, the subjects performed intermittent isometric muscle actions at 50% MVC (6 seconds "on," 3 seconds "off") until the force could no longer be maintained within ± 5% MVC of the target value for the full 6 seconds. Once the muscle was fatigued, the subjects performed another ramp muscle action, but at 45% of the fresh muscle MVC. EMG and MMG data were collected from the biceps brachii before and after the fatiguing bout, and the amplitude and MNF values were calculated for 5% MVC increments from 15% to 85% MVC. The results for EMG amplitude showed that there were no differences between fresh versus fatigued conditions during the ramp muscle actions. For EMG MNF, the same general pattern across force for the two conditions was noted, but the values for fatigued muscle were typically 25 Hz lower than those for fresh muscle. The most dramatic difference between fresh and

fatigued conditions was that for MMG amplitude. For fresh muscle, MMG amplitude increased linearly from 20-65% MVC, but declined thereafter. In contrast, for the fatigued condition, MMG amplitude decreased slightly throughout the isometric muscle action. Finally, MMG MNF increased from 15-85% MVC for both conditions, but the mean values were significantly lower when the muscle was fatigued. It was concluded (Orizio et al., 2003) that out of all the variables examined in this study, MMG amplitude was the most affected by fatigue. The authors (Orizio et al., 2003) hypothesized that this finding was likely related to fatigue of high-threshold motor units. Thus, the results from this study further supported the use of MMG amplitude and frequency for studying motor control strategies as a muscle fatigues.

Perry-Rana et al. (2003)

This investigation examined the patterns of responses for MMG and EMG amplitude for the superficial quadriceps femoris muscles during repeated maximal eccentric isokinetic muscle actions. Seven healthy women (mean ± SD age = 22.1 ± 2.4 years) participated in the study. Following two familiarization sessions, the subjects performed 25 maximal eccentric isokinetic muscle actions of the dominant leg extensors at a velocity of 120°/second as bipolar surface EMG and MMG signals were recorded from the VL, RF, and VM. Polynomial regression models were used to examine the relationships for normalized peak torque, EMG amplitude, and MMG amplitude versus repetition number. The results indicated that there was a cubic relationship ($p < 0.05$) between normalized peak torque and repetition number. Specifically, these values increased initially (the first 10 repetitions) and plateaued thereafter. In addition, there were muscle-specific patterns for EMG amplitude across

the 25 repetitions, as the VL, RF, and VM each demonstrated different responses. MMG amplitude demonstrated a negative linear relationship ($p < 0.05$) for both the VL and VM, and a cubic relationship ($p < 0.05$) for the RF over the 25 repetitions. It was concluded (Perry-Rana et al., 2003) that there were muscle-specific differences in the patterns of responses for MMG and EMG amplitude across the 25 muscle actions, and that these findings were unique to eccentric muscle actions (Perry-Rana et al., 2002). The authors (Perry-Rana et al., 2003) hypothesized that the decline in MMG amplitude for each muscle could have been related to muscular compliance, muscle fiber-type, muscle architecture, and muscle wisdom.

Søgaard et al. (2003)

This study examined the sensitivity of MMG and EMG amplitude and MNF following long term fatiguing muscle actions of the forearm flexors. Six healthy men (age range = 26-33 years) performed three trials on two separate days. These trials involved 30 minutes of intermittent muscle actions at 10% MVC with visual feedback, 30% MVC with visual feedback, and 30% MVC with proprioceptive feedback. For each trial, the MVC was determined, followed by separate muscle actions at both 5% and 80% MVC. The subjects then performed the intermittent isometric muscle actions (six seconds "on," four seconds "off") for a time period of 30 minutes to induce muscle fatigue. Once in the fatigued state, the subjects performed isometric MVCs to measure strength ten and 30 minutes following the fatiguing protocol. For each trial, bipolar surface EMG and MMG signals were detected from the biceps brachii muscle, and the normalized amplitude and MNF values were calculated for one second epochs. The results indicated that for all three trials, forearm flexion MVC strength did not fully

recover in 30 minutes, even for the 10% MVC condition. The normalized MMG and EMG amplitude values were greater during the post-fatigue 5% MVC test than at the same force level before the fatiguing protocol. No fatigue-related responses were demonstrated for the MMG and EMG amplitude and MNF values for the 80% MVC muscle action, however. It was concluded (Søgaard et al., 2003) that MMG and EMG may be sensitive to the slight changes in motor control strategies that occur in the biceps brachii muscle during long term fatigue.

Tarata (2003)

This study examined MMG and EMG responses during sustained isometric muscle actions of the forearm flexors at 25% MVC. Eighteen subjects (nine men, nine women; age range = 23-35 years) participated in the investigation. While seated in a chair, the subjects held a weight corresponding to 25% MVC while maintaining a 90° joint angle between the arm and forearm until exhaustion. Throughout the trial, bipolar surface EMG (interelectrode distance = 25 mm) and MMG signals were detected from both the biceps brachii and brachioradialis muscles, and the amplitude and median frequency values were calculated for both signals. The results indicated that both MMG and EMG amplitude increased throughout the duration of the muscle action, while MMG and EMG median frequency decreased. Thus, it was concluded (Tarata, 2003) that simultaneous examination of MMG and EMG amplitude and frequency responses is useful for describing the neural and mechanical aspects of muscle fatigue.

Beck et al. (2004)

This investigation examined MMG and EMG amplitude and frequency responses during fatiguing dynamic muscle actions. Three women (mean ± SD age =

20 ± 2 years) and seven men (mean ± SD age = 23 ± 3 years) performed 50 maximal concentric isokinetic muscle actions of the dominant forearm flexors at a velocity of 180°/second as MMG and EMG signals were recorded simultaneously from the biceps brachii muscle. As a result of the fatiguing protocol, the mean ± SD isokinetic peak torque values declined 70 ± 17%. Both MMG amplitude and MMG MNF demonstrated linear decreases across the 50 muscle actions ($R^2 = 0.774$ and $R^2 = 0.238$, respectively). EMG amplitude demonstrated a cubic pattern ($R^2 = 0.707$) across repetitions. Specifically, EMG amplitude increased during the first 20 muscle actions, followed by a plateau, and a second increase during repetitions 40-50. EMG MNF showed a quadratic ($R^2 = 0.939$) decline. According to the authors (Beck et al., 2004, pg. 431), the decreases in both MMG amplitude and MNF could have been related to de-recruitment of fast fatiguing motor units, "muscle wisdom," or a reduction in muscle compliance. The authors (Beck et al., 2004) further speculated that the EMG amplitude and MNF responses were associated with peripheral fatigue, decreases in muscle fiber action potential CV, and/or non-maximal efforts by the subjects.

Blangsted et al. (2005)

The primary purpose of this study was to determine if MMG and EMG analyses are sensitive enough to detect low-frequency fatigue. Seven healthy adults (three females, four males; age range = 27-54 years) participated in two testing sessions, one of which was considered a control trial. The fatiguing protocol for the study involved maintaining a 10% MVC wrist extension for ten minutes. For each trial, a series of tests were performed 20 minutes and immediately before, immediately after, and 10, 30, 90, and 150 minutes following the fatiguing protocol. Each test series consisted of an

electrical stimulation protocol of the extensor carpi radialis muscle, an MVC assessment of the wrist extensors, and isometric muscle actions at 5% of the initial MVC and 80% of the new MVC. MMG and EMG signals were detected from the extensor carpi radialis during the 5% and 80% MVC muscle actions, and the amplitude and MNF values were determined for one second epochs. The results indicated that although the subjects reported an increased rating of perceived exertion, MVC wrist extension strength was not affected by the fatiguing protocol. However, during the 5% MVC muscle action, the mean MMG and EMG amplitude values 30 minutes after fatigue were greater than those at the beginning of the test. In addition, electromechanical efficiency during the 80% MVC muscle action was elevated 150 minutes after the fatiguing protocol. The authors (Blangsted et al., 2005, pg. 146) stated that the discrepancy for the 5% versus 80% MVC results was related to the "...recruitment of non-fatigued high-threshold motor units being recruited during these contractions, which may blur any indications of fatigue in the low-threshold motor units. Therefore, low-force test contractions appear to be of great importance when identifying fatigue after low-force, nonexhaustive contractions." Therefore, it was concluded (Blangsted et al., 2005) that MMG may be particularly useful for examining the mechanical aspects of low-frequency fatigue.

Ebersole and Malek (2008)

The purpose of this investigation was to examine the influence of fatigue on electroechanical efficiency for the VL and VM. Ten healthy males (mean ± SD age = 23.2 ± 1.2 years) with no history of knee injury performed 75 repeated maximal concentric isokinetic muscle actions of the dominant leg extensors at a velocity of

180°/second. During each muscle action, bipolar surface EMG and MMG signals were detected from the VL and VM. For each of the 75 muscle actions, MMG and EMG amplitude and isokinetic peak torque were calculated from the middle 30° of the range of motion. Electromechanical efficiency was calculated as the ratio of normalized MMG amplitude to normalized EMG amplitude, and the group mean data were regressed against muscle action number using polynomial regression analyses. The results indicated that there were linear decreases in torque ($R^2 = 0.96$), VM electromechanical efficiency ($R^2 = 0.73$), and VL electromechanical efficiency ($R^2 = 0.73$) across the 75 muscle actions. There was no significant difference between muscles for the mean linear slope coefficients. It was concluded (Ebersole and Malek, 2008) that the fatigue-induced declines in electromechanical efficiency for the VL and VM suggested that there were similar electrical and mechanical responses for these muscles. The authors (Ebersole and Malek, 2008) also stated that electromechanical efficiency may be useful in assessing asymmetries in VL and VM muscle function in individuals with knee injuries.

Al-Zahrani et al. (2009)

The purpose of this study was to determine both within- and between-day test-retest reliability for MMG RMS, MNF, median frequency, and the linear slope coefficients for the decline in these variables during a series of fatiguing isometric muscle actions. Fifteen healthy men (mean ± SD age = 32.3 ± 7.6 years) and 16 healthy women (mean ± SD age = 30.3 ± 10.3 years) visited the laboratory on three occasions separated by a minimum of 48 hours. The testing procedures for these three trials were identical. Each trial began with an MVC assessment of the dominant leg extensors.

Following the MVC test, each subject performed three 40-second isometric muscle actions separated by five minutes of rest at a force corresponding to 75% MVC. During these muscle actions, the MMG signal was detected from the RF with a triaxial accelerometer, and the data from each fatiguing bout was divided into 40, one second epochs. Test-retest reliability was assessed for each variable with the intraclass correlation coefficient (ICC), standard error of measurement (SEM), and smallest detectable difference (analogous to the minimal difference needed to be considered real) statistics described by Weir (2005). The results for the within-day assessments indicated good to excellent test-retest reliability for MMG RMS, MNF, and median frequency (ICCs = 0.72-0.96), but very poor consistency for the linear slope coefficients (ICCs = 0.42-0.75, SEMs = 182.2-440.9% of the mean value). Similarly, the results from the between-day assessments indicated that the test-retest ICCs for MMG RMS, MNF, and median frequency were moderate to high (ICCs = 0.78-0.83) with poor consistency for the linear slope coefficients. It was concluded (Al-Zahrani et al., 2009) that slightly better reliability was demonstrated for the within-day assessments versus the between-day assessments, which may have been related to the removal and replacement of the accelerometer for each trial. The authors (Al-Zahrani et al., 2009, pg. 701) stated "The poor between-days reliability found in this study suggests caution in using RMS, MNF and median frequency and their corresponding linear slopes in assessing fatigue."

Chapter 3: Methods

Subjects

Twenty-one men (mean ± SD age = 23.0 ± 3.0 years; height = 180.9 ± 6.9 cm; body mass = 86.9 ± 14.4 kg) volunteered to participate in this investigation. The subjects for this study were experienced in upper-body resistance-training (i.e., participation in an organized weight training program for at least six months before the study). Each subject completed an informed consent and a pre-exercise health and exercise status questionnaire, which indicated no current or recent neuromuscular or musculoskeletal problems. All procedures for this study were approved by the University Institutional Review Board for Human Subjects. Each subject visited the laboratory on five separate occasions, with a minimum of 48 hours of rest between each trial. To eliminate the potential for reduced force production due to delayed onset muscle soreness, each subject was asked to avoid strenuous upper-body exercise 24 hours prior to each trial. Each subject visited the laboratory at the same time of day (± 1 hour) for each of the five visits.

Familiarization Session

Prior to the first of the four data collection trials, the subjects participated in a familiarization session. The purpose of this visit was for each subject to become acquainted with the equipment, as well as to minimize the influence of a learning effect on each of the study's dependent variables. In addition, this session allowed for calculation of test-retest reliability statistics. For the familiarization session, the subjects performed 100 maximal concentric isokinetic muscle actions of the dominant (based on throwing preference) forearm flexors with their eyes open. Upon arrival, the

subjects were seated in a chair in front of the isokinetic dynamometer (LIDO Multi-Joint II, Loredan Biomedical, West Sacramento, CA). Each subject was positioned such that the posterior aspect of the arm rested comfortably on the seat of the isokinetic dynamometer (Figure 1). The subject's hand was supinated, and the elbow joint was visually aligned with the dynamometer's axis of rotation. Familiarization with the isokinetic dynamometer began with a warm-up of ten submaximal concentric muscle actions of the dominant forearm flexors in which the subjects were instructed to provide an effort corresponding to 50% of their maximum. Each concentric muscle action was performed at a velocity of 180°/second through a full 90° range of motion. After the warm-up, the subjects were instructed on the procedures for the fatigue test. Specifically, each subject was told to perform 100 repeated maximal concentric muscle actions of the forearm flexors with passive forearm extension after each muscle action.

Testing Sessions

A minimum of 48 hours following the familiarization session, the subjects returned to the laboratory for the first of the four data collection trials. Upon arrival, the subjects were positioned in the dynamometer as described previously. Following a brief warm-up of ten submaximal concentric isokinetic muscle actions of the dominant forearm flexors, the subjects rested for one minute. The subjects then performed one 6-second isometric MVC at a 90° joint angle in which EMG and MMG signals for the biceps brachii were collected. For each trial, these data were used to normalize the EMG and MMG amplitude and MNF values during the fatigue tests. Thus, all EMG and MMG amplitude and MNF values for this study are expressed as a percentage of a non-fatigued MVC of the dominant forearm flexors. Using the same procedures as

those from the familiarization session, the subjects then performed 100 maximal concentric isokinetic muscle actions of the dominant forearm flexors with 1) their eyes open (100Open), 2) their eyes closed (100Closed), 3) their eyes open and closed for the first and last 50 muscle actions, respectively (50Open50Closed), or 4) their eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. These four conditions were randomly performed. For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). Therefore, the data from muscle actions 1-50 were compared to those from muscle actions 51-100. Each subject was instructed to open (50Closed50Open) or close (50Open50Closed) his eyes upon noticing a tap of the right shoulder. During all eyes open conditions, the subjects were instructed to fixate on a visual target directly in front of them. In an attempt to eliminate the influence of auditory factors, the subjects wore noise-cancelling earmuffs (3M Professional Earmuff, Model #90561-80025, St. Paul, MN) during data collection. Other than the different visual interventions, identical testing procedures were used for each condition. Example peak torque, EMG, and MMG values for one subject are shown in Figures 2, 3, and 4, respectively.

Torque Measurements

For each trial, the torque signal from the isokinetic dynamometer was sampled continuously by a 12-bit analog-to-digital converter (NI 9201 Voltage Input Module, National Instruments, Austin, TX) at a rate of 2,000 samples/second. The isokinetic peak torque value for each repetition was determined based on the highest value in the torque curve. The initial peak torque was defined as the average from the three

repetitions with the highest peak torque values, and the final peak torque was determined as the average from the three repetitions with the lowest peak torque values. For both Pre and Post, the percent decline was calculated as follows: ([initial peak torque – final peak torque]/initial peak torque) × 100. The average torque value was defined as the average across the 50 repetitions. Finally, for each trial, linear regression was performed on the torque values for Pre and Post to determine the linear slope for the decrease in isokinetic peak torque (ft.-lbs./repetition).

Electromyography Procedures

Surface EMG signals were detected during the isometric and concentric isokinetic muscle actions from the biceps brachii of the dominant forearm flexors. The signals were detected with a DE-2.1 sensor (interelectrode distance = 10 mm [Delsys Inc., Boston, MA]) and amplified (gain = 1000) by a Bagnoli™ 16-channel Desktop system (Delsys Inc., Boston, MA) with a band pass of 20-450 Hz. The sensor was placed over the biceps brachii in accordance with the SENIAM project (Hermens et al., 1999), and a reference electrode (Dermatrode, American Imex, Irvine, CA) was placed on the volar aspect of the wrist. The skin over the wrist and the belly of the biceps brachii muscle was prepared prior to testing by shaving and cleansing with rubbing alcohol. The EMG signals were digitized at a sampling rate of 2,000 samples/second and stored in a personal computer (Dell Optiplex 755, Round Rock, TX) for subsequent analyses. Upon completion of the first trial, the skin was marked with a permanent marker to ensure that the sensor was placed in the same location for each subsequent visit to the laboratory.

Mechanomyography Procedures

Surface MMG signals were detected from the biceps brachii with a miniature accelerometer (PCB Piezotronics, Model 352A24, bandwidth 1.0 to 8000 Hz, dimensions: 0.19 × 0.48 × 0.28 in, mass 0.8 g, sensitivity 100 mV g^{-1}). Specifically, the accelerometer was placed over the belly of the muscle just distal to the EMG sensor (Figure 5). The accelerometer was fixed to the skin with double-sided foam tape. The raw MMG signals were also digitized at 2,000 samples/second.

Signal Processing

All signal processing was performed using custom programs written with LabVIEW programming software (version 8.2, National Instruments, Austin, TX). The MMG signals were bandpass filtered (fourth-order Butterworth) at 5-100 Hz. For each fatigue test, the EMG and MMG signals from the biceps brachii were selected visually for analysis. Specifically, for each of the 100 concentric isokinetic muscle actions, the amplitude (RMS) and MNF values were calculated for a time period that corresponded to the entire range of motion. For the MNF analyses, each selected signal was processed with a Hamming window and the Discrete Fourier Transform was used to generate the power spectrum. As described previously, for each trial, these data were normalized to the RMS and MNF values corresponding to those for a non-fatigued isometric MVC. For each subject and trial, the normalized EMG and MMG amplitude and MNF data points corresponding to the initial peak torque (three repetitions with the highest peak torque) and final peak torque (three repetitions with the lowest peak torque) values were averaged and utilized for subsequent statistical analyses.

Statistical Analyses

A total of thirteen separate two-way repeated measures ANOVAs were performed in this study. Five separate two-way (time [Pre and Post] × condition [100Open, 100Closed, 50Open50Closed, and 50Closed50Open]) repeated measures ANOVAs were used to examine the isokinetic peak torque data (i.e., initial peak torque, final peak torque, average torque, percent decline, and the linear slope coefficient for the decline in peak torque). In addition, eight separate two-way (time [Pre and Post] × condition [100Open, 100Closed, 50Open50Closed, and 50Closed50Open]) repeated measures ANOVAs were used to examine the normalized EMG and MMG amplitude and MNF values for the biceps brachii. When appropriate, follow-up analyses included one-way repeated measures ANOVAs, paired samples t-tests, and Bonferroni post hoc comparisons. An alpha level of 0.05 was used to determine significance for all statistical analyses. The partial eta squared (η^2) statistic was used to evaluate effect size for each ANOVA. Stevens (2007) characterizes $\eta^2 = .01$ as corresponding to a small effect size, $\eta^2 = .06$ to a medium effect size, and $\eta^2 = .14$ to a large effect size. Test-retest reliability statistics were assessed using data for the familiarization session and the first testing session, and are shown in Table 1.

Chapter 4: Results

Initial Peak Torque

There was no significant time × condition interaction ($\eta^2 = .087$), no main effect for condition ($\eta^2 = .011$), but there was a main effect for time ($\eta^2 = .799$). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 6).

Final Peak Torque

There was a significant time × condition interaction ($\eta^2 = .177$). For both Pre and Post, the one-way repeated measures ANOVAs were not statistically significant ($\eta^2 =$ .043 and .080, respectively). The results for the four separate paired samples t-tests indicated that the final peak torque values for Pre were significantly greater than those for Post (Figure 7).

Percent Decline

There was no significant time × condition interaction ($\eta^2 = .042$), no main effect for condition ($\eta^2 = .037$), but there was a main effect for time ($\eta^2 = .720$). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 8).

Average Torque

There was no significant time × condition interaction ($\eta^2 = .123$), no main effect for condition ($\eta^2 = .010$), but there was a main effect for time ($\eta^2 = .881$). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 9).

Linear Slope Coefficient for the Decline in Peak Torque

There was no significant time × condition interaction ($\eta^2 = .014$), no main effect for condition ($\eta^2 = .074$), but there was a main effect for time ($\eta^2 = .735$). The results from the marginal mean pairwise comparisons indicated Pre < Post (Figure 10).

Normalized EMG Amplitude for Initial Peak Torque

There was no significant time × condition interaction ($\eta^2 = .047$), no main effect for time ($\eta^2 = .114$), and no main effect for condition ([$\eta^2 = .020$] Figure 11).

Normalized EMG Amplitude for Final Peak Torque

There was no significant time × condition interaction ($\eta^2 = .098$), no main effect for time ($\eta^2 = .175$), and no main effect for condition ([$\eta^2 = .042$] Figure 12).

Normalized EMG MNF for Initial Peak Torque

There was no significant time × condition interaction ($\eta^2 = .101$), no main effect for condition ($\eta^2 = .077$), but there was a main effect for time ($\eta^2 = .912$). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 13).

Normalized EMG MNF for Final Peak Torque

There was a significant time × condition interaction ($\eta^2 = .295$). For both Pre and Post, the one-way repeated measures ANOVAs were not statistically significant ($\eta^2 = .117$ and .146, respectively). For 100Open and 50Closed50Open, the results from the paired samples t-tests indicated that the mean final peak torque values for Pre were significantly greater than those for Post. For 100Closed and 50Open50Closed, however, the decrease in EMG MNF from Pre to Post was not statistically significant (Figure 14).

Normalized MMG Amplitude for Initial Peak Torque

There was no significant time × condition interaction ($\eta^2 = .080$), no main effect for condition ($\eta^2 = .056$), but there was a main effect for time ($\eta^2 = .503$). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 15).

Normalized MMG Amplitude for Final Peak Torque

There was no significant time × condition interaction (η^2 = .060), no main effect for condition (η^2 = .057), but there was a main effect for time (η^2 = .184). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 16).

Normalized MMG MNF for Initial Peak Torque

There was no significant time × condition interaction (η^2 = .050), no main effect for condition (η^2 = .029), but there was a main effect for time (η^2 = .746). The results from the marginal mean pairwise comparisons indicated Pre > Post (Figure 17).

Normalized MMG MNF for Final Peak Torque

There was a significant time × condition interaction (η^2 = .192). For both Pre and Post, the one-way repeated measures ANOVAs were not statistically significant (η^2 = .091 and .097, respectively). For 50Open50Closed and 50Closed50Open, the results from the paired samples t-tests indicated that the mean MMG MNF values for Pre were significantly greater than those for Post. For 100Open and 100Closed, however, the results from the paired samples t-tests indicated that the decreases in MMG MNF were not statistically significant (Figure 18).

Chapter 5: Discussion

The purpose of this study was to compare the peak torque and EMG and MMG amplitude and MNF responses during fatiguing isokinetic muscle actions for eyes-open versus eyes-closed conditions. The results indicated no differences among these conditions for initial peak torque, final peak torque, percent decline, average torque, and the linear slope coefficient for the decline in peak torque. In addition, out of the eight separate two-way repeated measures ANOVAs that were used to examine the normalized EMG and MMG amplitude and MNF values for the biceps brachii, there were only two significant time × condition interactions. Follow-up analyses showed decreases from Pre to Post for mean normalized EMG MNF at final peak torque for both of the eyes-open conditions, but not for the eyes-closed conditions. For the 100Open and 100Closed conditions, there were no Pre versus Post mean differences for normalized MMG MNF at final peak torque. When the subjects opened (50Closed50Open) and closed (50Open50Closed) their eyes after 50 repetitions, however, the normalized MMG MNF values continued to decrease. These findings suggested that visual feedback did not influence maximal strength early in the repetition series (i.e., initial peak torque) or fatigability, but did affect EMG and MMG MNF.

The peak torque results of this study are in contrast to those of Asmussen and Mazin (1978b). In that study (Asmussen and Mazin, 1978b), the subjects performed fatiguing concentric DCER muscle actions of the forearm flexors until exhaustion with their eyes closed. Once the subjects reached the point that they could no longer perform the muscle actions, they opened their eyes and attempted to continue. The subjects also performed this experiment in the opposite order (i.e., the subjects performed the

fatiguing muscle actions with their eyes open, and then closed their eyes). The authors (Asmussen and Mazin, 1978b) found that when complete exhaustion had been reached with the eyes closed, opening them allowed the subjects to continue. When the order was alternated, none of the subjects were able to continue. As a result of these findings, as well as those from other experiments (Asmussen and Mazin, 1978a), Asmussen and Mazin (1978b) concluded that muscle fatigue was primarily a result of inhibition from the brain, and more specifically, the reticular formation. This hypothesis was supported by EEG studies that have shown changes in brain activity with diverting activities (Rojtbak and Dedrabrishvilli, 1959), as well as those that have compared eyes-open versus eyes-closed experimental conditions (Berger, 1931; Marx et al., 2003; Barry et al., 2007). In light of the findings for the present study, there are two important points that are worthy of discussion. First, the differences between the results of this investigation and those of Asmussen and Mazin (1978b) could be due to methodological factors. Specifically, Asmussen and Mazin (1978b) used a custom-built ergometer and measured total work. Although having subjects simply lift and lower constant loads is practical and inexpensive, isokinetic strength testing provides much more information than can be obtained from DCER testing. The major difference between these two modes of testing is that with DCER muscle actions, volitional fatigue is defined as the repetition number or time when the subject is no longer able to lift the weight through the entire range of motion. With isokinetic testing, a subject can experience the same degree of muscle fatigue, but continue to perform maximal concentric muscle actions at very low torque levels. Although it is possible that the testing protocol used in the present investigation and that of Asmussen and Mazin

(1978b) resulted in similar fatigue rates for the forearm flexors, the fact that each of the five peak torque variables in this study showed no mean differences among the conditions supports that the diverting activities had no effect on overall performance. Secondly, some of the research hypotheses in the present investigation were predicated on the assumption that beta and alpha waves appear in the EEG signal when subjects close and open their eyes (Berger, 1931; Marx et al., 2003; Barry et al., 2007), respectively. However, EEG was not used in this study. Therefore, it would be inappropriate to speculate on the extent of central versus peripheral fatigue among the four conditions in this study.

It has been suggested (Beck et al., 2005) that simultaneous examination of the time and frequency domains of the EMG and MMG signals may provide insight regarding motor control strategies (i.e., motor unit recruitment and firing rate) during dynamic muscle actions. Several previous investigations (Perry-Rana et al., 2002; Perry-Rana et al., 2003; Beck et al., 2004; Ebersole and Malek, 2008) have examined EMG and MMG amplitude and/or MNF responses during fatiguing isokinetic muscle actions. In the present study, the normalized EMG MNF, MMG amplitude, and MMG MNF values decreased across the 100 muscle actions for all conditions. The normalized EMG amplitude values did not change, however, as there were no main effects for time at either initial or final peak torque. This finding was in agreement with previous studies showing that the frequency content of the EMG signal more closely follows the decline in peak torque during maximal concentric isokinetic muscle actions (Gerdle et al., 2000; Beck et al., 2004). The two most important findings, however, were that 1) the decline in mean normalized EMG MNF was greater when the subjects

had their eyes open, and 2) both opening and closing of the eyes after 50 maximal concentric isokinetic muscle actions resulted in greater declines in the normalized MMG MNF values when compared to the control conditions of eyes open and closed for all 100 muscle actions. The fact that there were mean differences among the conditions for normalized EMG and MMG MNF, but not for the five isokinetic peak torque variables, makes the interpretation of these findings very complex. Nonetheless, it is important to briefly discuss the physiological implications of these results. It is well documented that the frequency content of the EMG signal provides information regarding the CVs of the active muscle fibers (Lindstrom, 1970; Basmajian and De Luca, 1985; Kupa et al., 1995). In an important study, Komi and Tesch (1979) examined EMG frequency responses during 100 maximal concentric isokinetic muscle actions of the leg extensors. Muscle biopsies from the VL were performed, and the subjects were divided into two groups based on fiber-type areas (Group I = < 50% fast-twitch muscle fiber area; Group II = > 50% fast-twitch muscle fiber area). The authors (Komi and Tesch, 1979) reported a significant decline in EMG MNF for the subjects in Group II, but very little or no change for those in Group I. The authors (Komi and Tesch, 1979) concluded that increased metabolite (e.g., lactate and H^+) accumulation for fast-twitch fibers resulted in decreased CVs that in turn caused a decline in EMG MNF. Thus, while the mechanism(s) responsible for the differences in EMG MNF among the conditions in the present study are unclear, it is possible that less metabolite accumulation occurred when the eyes were closed. The reason(s) for the differences among the conditions for MMG MNF are even less clear. The present investigation was only the second to examine MMG MNF responses during fatiguing isokinetic

muscle actions. In a study by Beck et al. (2004), ten adults performed 50 maximal concentric isokinetic muscle actions of the forearm flexors at a velocity of 180°/second. The authors (Beck et al., 2004) reported that there was a linear decrease in MMG MNF across the 50 repetitions. In addition to decreased motor unit firing rates, it was hypothesized that the decrease in MMG MNF was related to de-recruitment of fast fatiguing motor units (Beck et al., 2004). This hypothesis was supported by the findings of Kouzaki et al. (1999), who reported a greater decline in MMG median frequency for the RF than those for the VL and VM during 50 consecutive MVCs of the leg extensors. Thus, although additional studies are needed to determine the exact mechanisms responsible for the decreases in MMG MNF during fatiguing isokinetic muscle actions, it is possible that differences in motor unit firing rates and/or de-recruitment of fatigued motor units caused the differences between the eyes-open and eyes-closed conditions. Finally, it should be emphasized that not all of the normalized EMG and MMG amplitude and MNF values were examined in this study. Only the values that corresponded to the initial and final peak torque contractions were analyzed.

Aside from the results for the primary research question, these data provided further insight into issues related to both muscle fatigue and research design. When designing this study, it was important to ensure that the peak torque values declined for each subject, and to have enough data points to examine the effects of opening versus closing the subjects' eyes during the test (i.e., Pre versus Post). Four studies have examined peak torque responses during 100 maximal concentric isokinetic muscle actions for the leg extensors (Thorstensson and Karlsson, 1976; Nilsson et al., 1977; Komi and Tesch, 1979; Gerdle et al., 2000). The present investigation, however, was

the first to examine peak torque responses during 100 maximal concentric isokinetic muscle actions for the forearm flexors. As shown for one subject in Figure 2, the majority of the decline in the peak torque values occurred during the first 50 muscle actions. Specifically, when collapsed across the four trials, the mean ± SD initial peak torque value was 37.8 ± 7.4 ft.-lbs. (Figure 6), and declined to 20.6 ± 5.1 ft.-lbs. and 18.0 ± 4.5 ft.-lbs (Figure 7) after 50 and 100 muscle actions, respectively. These findings were in agreement with those reported by Thorstensson and Karlson (1976) that showed a mean initial peak torque value of 130 Nm, followed by a decrease to 72 Nm and 64 Nm after 50 and 100 muscle actions, respectively. Thus, the results from the present investigation demonstrated that the plateau in isokinetic peak torque shown in previous studies (Thorstensson and Karlsson, 1976; Nilsson et al., 1977; Komi and Tesch, 1979; Gerdle et al., 2000) is not unique to the leg extensors, and may reflect the similarities in fiber-type distribution for the biceps brachii and VL (Johnson et al., 1973). Future investigators should be aware that most of the decline in peak torque occurs during the first 50 muscle actions. It is also important to acknowledge that each of the thirteen dependent variables in this study showed varying degrees of test-retest reliability. Table 1 shows the p-values for paired samples t-tests, ICCs (model 2,1), SEMs (expressed as a percentage of the mean value), and the minimal differences (MDs) for these variables. As described previously, these values were generated by comparing the familiarization session data to that from the first trial. The most noteworthy finding was that the mean linear slope coefficient for the decline in peak torque was significantly greater (i.e., less negative) for the initial trial compared to that for the familiarization session. This demonstrates the importance of familiarizing

research subjects with laboratory equipment and study procedures prior to data collection. In addition, the ICCs, SEMs, and MDs for each of the four MMG variables are indicative of poor test-retest reliability. For example, the MD for normalized MMG amplitude at initial peak torque was 199.6%. In other words, nearly a 200% change (i.e., increase or decrease) in MMG amplitude was necessary to be considered meaningful in this study. The ICCs and SEMs were comparable to those reported for DCER muscle actions of the biceps brachii (Stock et al., 2010), but lower than those for submaximal isometric muscle actions of the VL (Herda et al., 2008; Beck et al., 2009). Thus, it is possible that the findings for this study were influenced by error that could have come from movement artifact.

In summary, the results of the present study demonstrated that there were no mean differences for initial peak torque, final peak torque, percent decline, average torque, and the linear slope coefficient for the decline in peak torque when the subjects performed repeated maximal concentric isokinetic muscle actions with their eyes open versus closed. From a practical standpoint, these findings suggested that visual feedback does not affect muscular strength and fatigability for the forearm flexors. There were, however, differences among the conditions for normalized EMG and MMG MNF at final peak torque. These findings are in contrast to those of Asmussen and Mazin (1978b), who speculated that differences in muscle fatigue and recovery for eyes-open versus eyes-closed conditions were related to central nervous system activity. However, the fact that the subjects in the Asmussen and Mazin (1978b) study performed submaximal muscle actions to failure is important, since those in the present investigation did a fixed number (i.e., 100) of maximal muscle actions. Future

investigators should consider examining the precise mechanism(s) responsible for the decline in MMG MNF during maximal concentric isokinetic muscle actions.

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Appendix A: Tables

Table 1. Test-retest reliability statistics for the isokinetic peak torque, electromyographic (EMG), and mechanomyographic (MMG) variables in this study. Statistics include the p-value for a paired samples t-test, intraclass correlation coefficient ([ICC] model 2,1), standard error of measurement ([SEM] expressed as a percentage of the mean value), and the minimal difference (MD) needed to be considered real. Data for the familiarization session and the first testing session were used to assess test-retest reliability.

Variable	P-value	ICC	SEM (%)	MD
Initial Peak Torque (ft.-lbs.)	0.295	0.801	8.4	8.9
Final Peak Torque (ft.-lbs.)	0.300	0.641	13.6	6.9
Percent Decline (%)	0.077	0.714	12.1	17.1
Average Torque (ft.-lbs.)	0.726	0.752	8.1	6.1
Linear Slope Coefficient for Decline in Peak Torque (ft.-lbs./repetition)	0.036	0.755	20.6	0.224
Normalized EMG Amplitude for Initial Peak Torque (%)	0.555	0.455	13.3	25.9
Normalized EMG Amplitude for Final Peak Torque (%)	0.897	0.213	23.7	50.2
Normalized EMG Mean Frequency for Initial Peak Torque (%)	0.654	0.459	9.8	26.8
Normalized EMG Mean Frequency for Final Peak Torque (%)	0.442	0.680	10.5	18.3
Normalized MMG Amplitude for Initial Peak Torque (%)	0.905	0.444	27.6	199.6
Normalized MMG Amplitude for Final Peak Torque (%)	0.632	0.437	27.7	144.9
Normalized MMG Mean Frequency for Initial Peak Torque (%)	0.564	0.197	20.5	101.1
Normalized MMG Mean Frequency for Final Peak Torque (%)	0.272	0.398	22.1	83.5

Appendix B: Figures

Figure 1. Subject positioning in the isokinetic dynamometer.

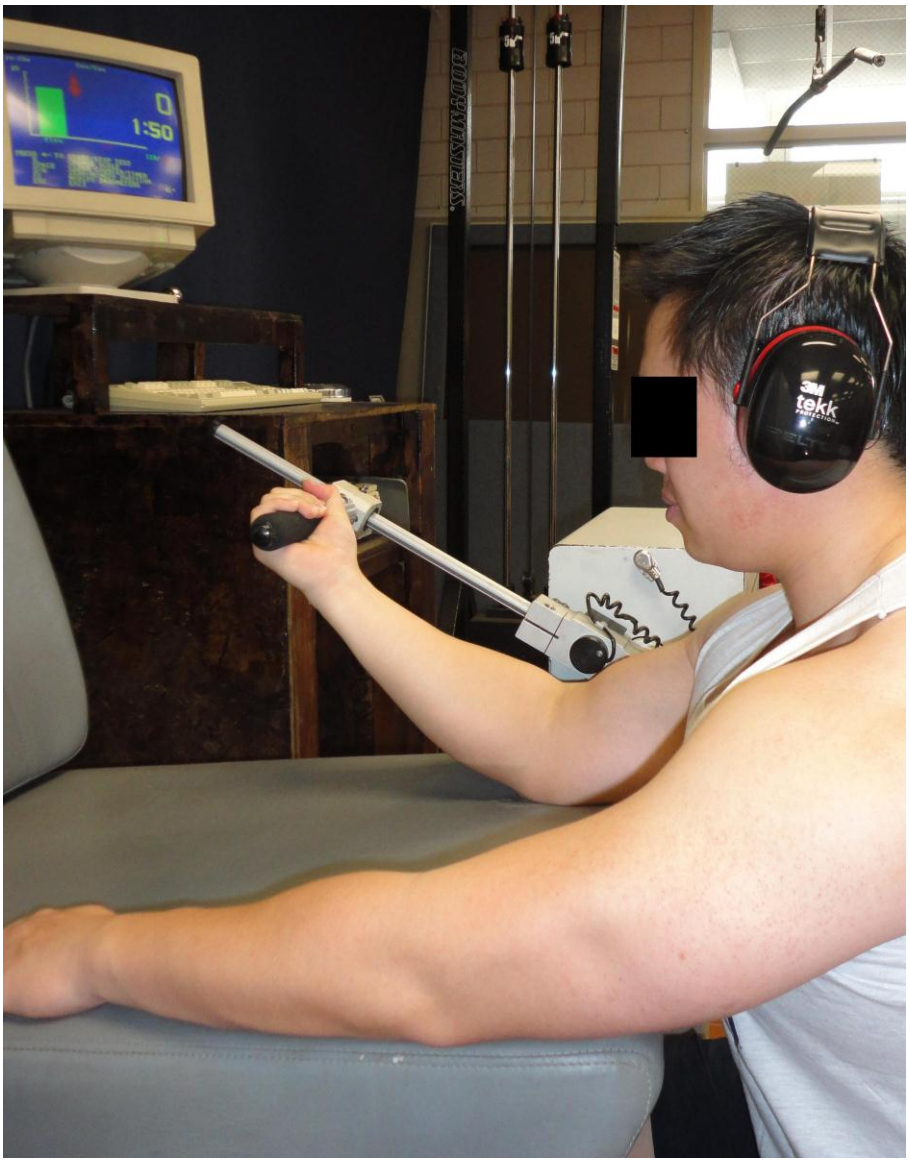


Figure 2. Example peak torque values during 100 repeated maximal concentric isokinetic muscle actions for one subject.

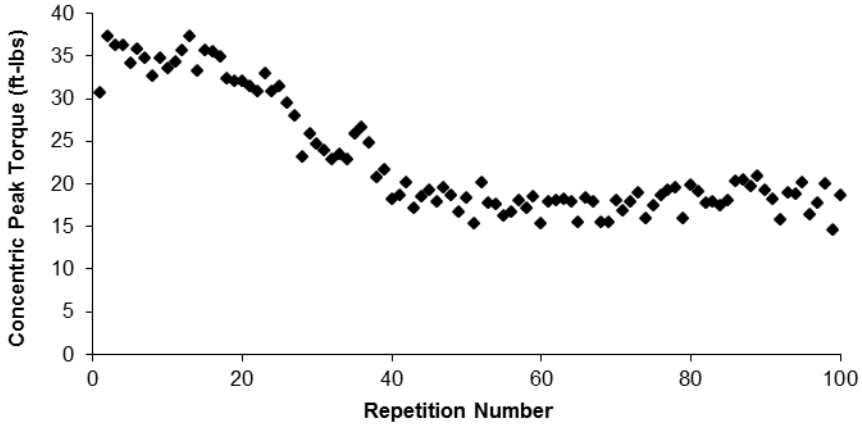


Figure 3. Example normalized electromyographic (EMG) amplitude and mean frequency (MNF) values during 100 repeated maximal concentric isokinetic muscle actions for one subject. These data correspond to the peak torque values displayed in Figure 2.

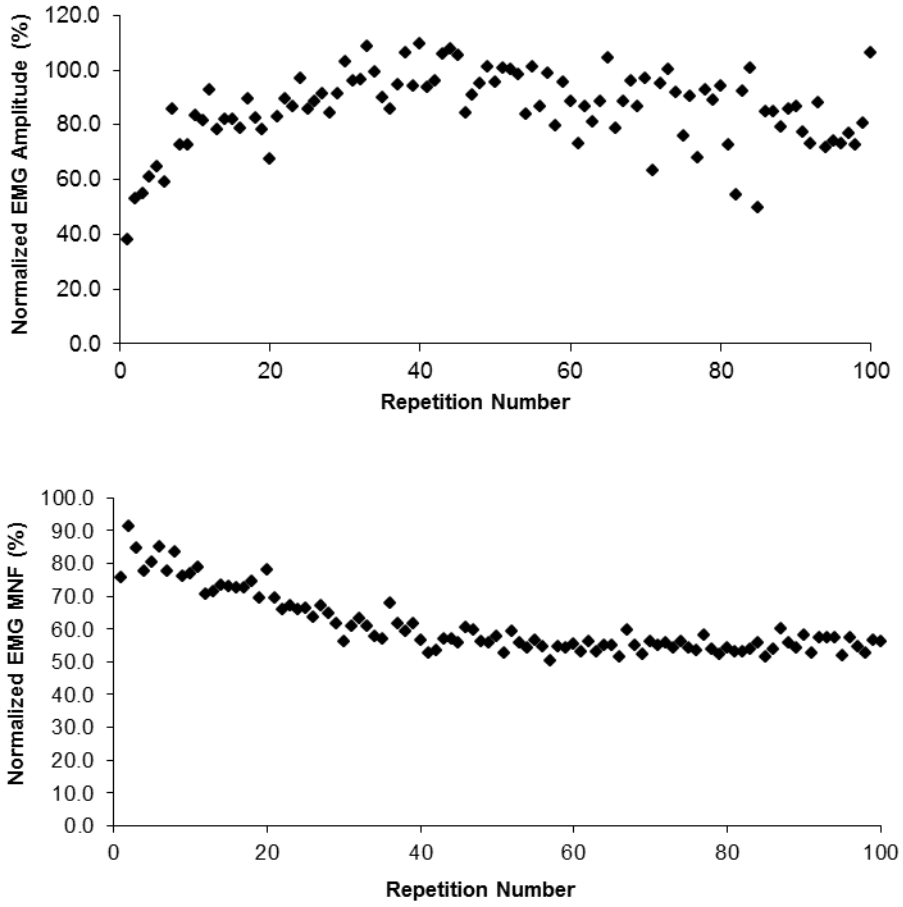


Figure 4. Example normalized mechanomyographic (MMG) amplitude and mean frequency (MNF) values during 100 repeated maximal concentric isokinetic muscle actions for one subject. These data correspond to the peak torque values displayed in Figure 2.

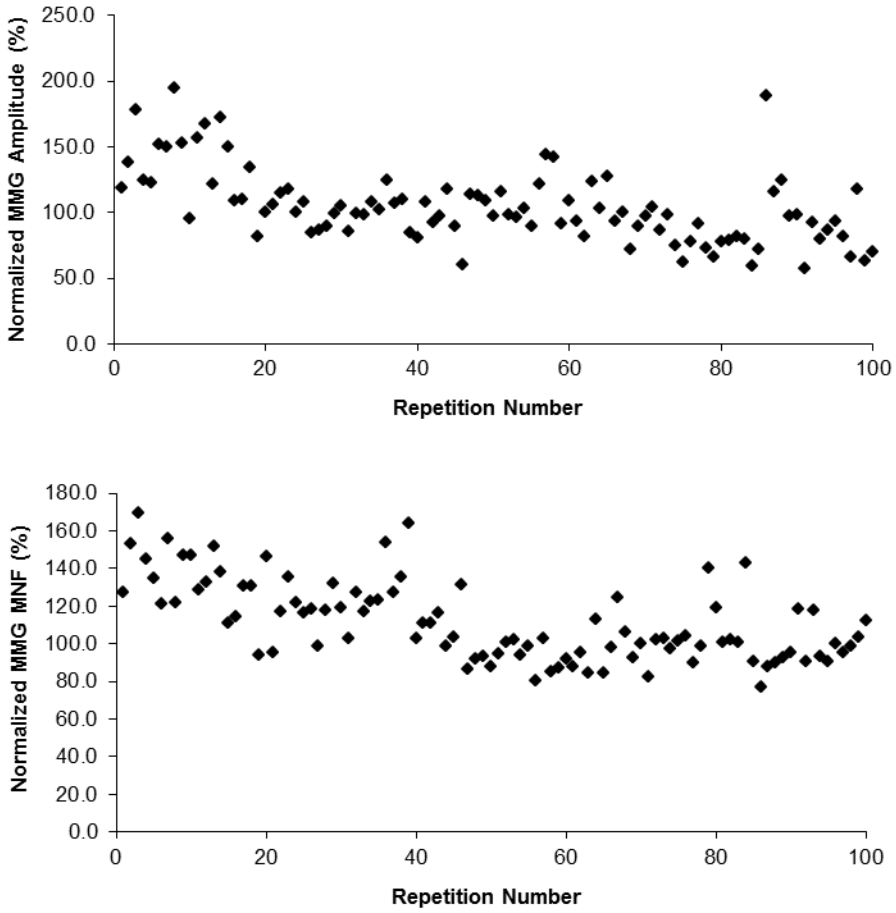


Figure 5. Example electromyographic sensor and accelerometer placements over the biceps brachii.

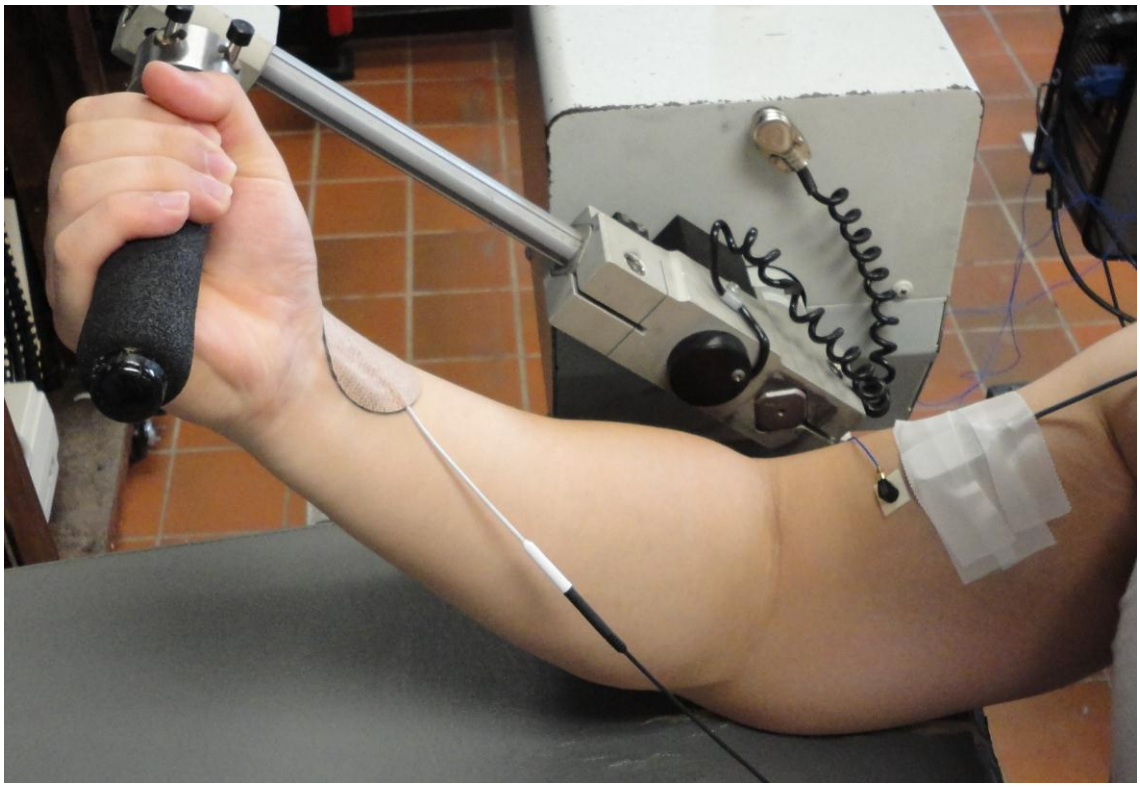


Figure 6. Mean ± SD initial peak torque values corresponding to the first (Pre) and second (Post) 50 maximal concentric isokinetic muscle actions with eyes open (100Open), eyes closed (100Closed), eyes open and closed for the first and last 50 muscle actions, respectively (50Open50Closed), and eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. The initial peak torque was defined as the average from the three repetitions with the highest peak torque values.

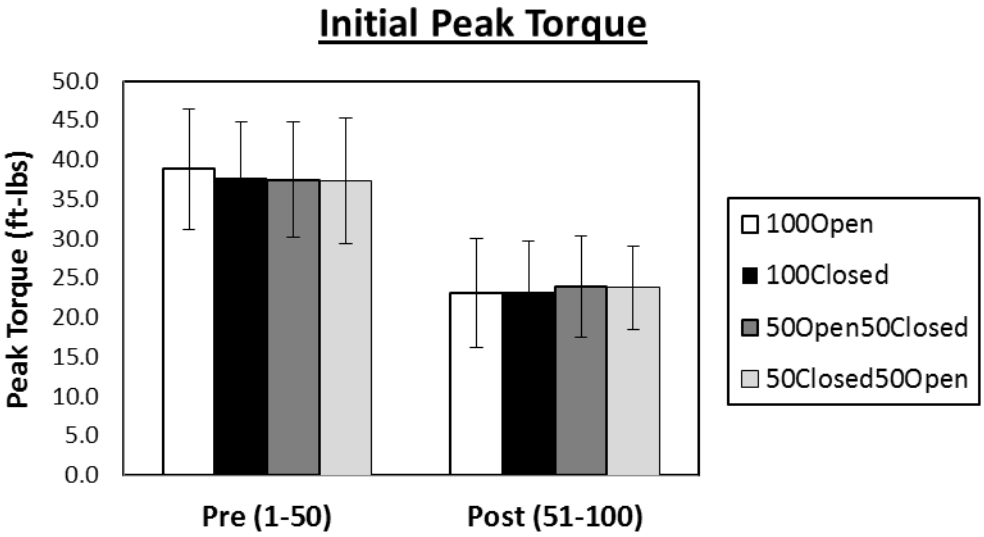


Figure 7. Mean ± SD final peak torque values corresponding to the first (Pre) and second (Post) 50 maximal concentric isokinetic muscle actions with eyes open (100Open), eyes closed (100Closed), eyes open and closed for the first and last 50 muscle actions, respectively (50Open50Closed), and eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. The final peak torque was determined as the average from the three repetitions with the lowest peak torque values.

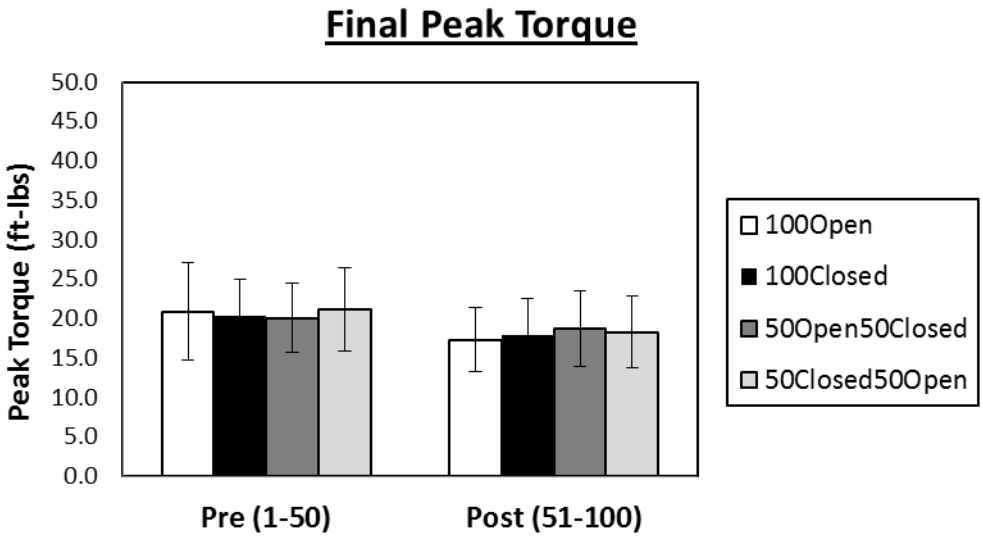


Figure 8. Mean ± SD percent decline values corresponding to the first (Pre) and second (Post) 50 maximal concentric isokinetic muscle actions with eyes open (100Open), eyes closed (100Closed), eyes open and closed for the first and last 50 muscle actions, respectively (50Open50Closed), and eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. Percent decline was calculated as follows: ([initial peak torque – final peak torque]/initial peak torque) × 100.

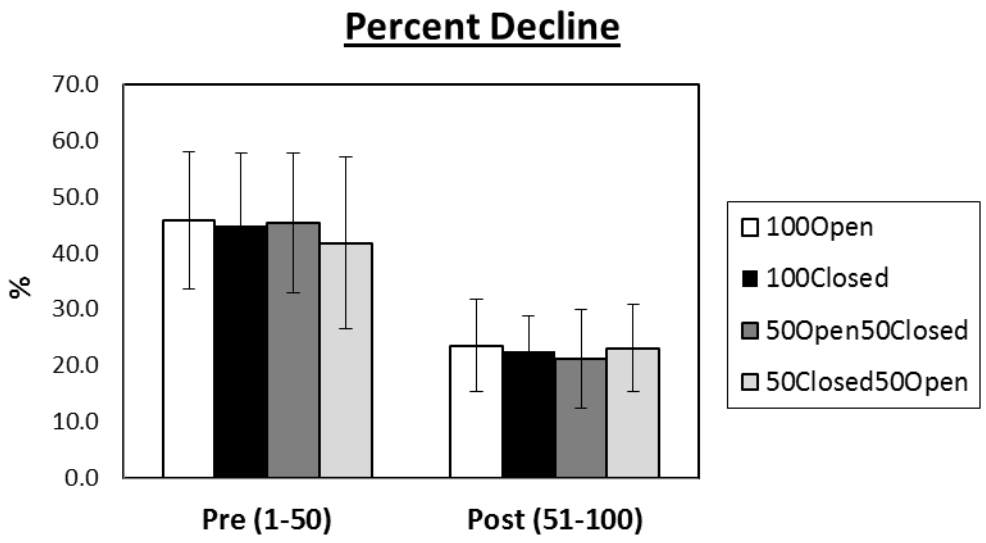


Figure 9. Mean ± SD average torque values corresponding to the first (Pre) and second (Post) 50 maximal concentric isokinetic muscle actions with eyes open (100Open), eyes closed (100Closed), eyes open and closed for the first and last 50 muscle actions, respectively (50Open50Closed), and eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. The average torque was defined as the average across all 50 repetitions.

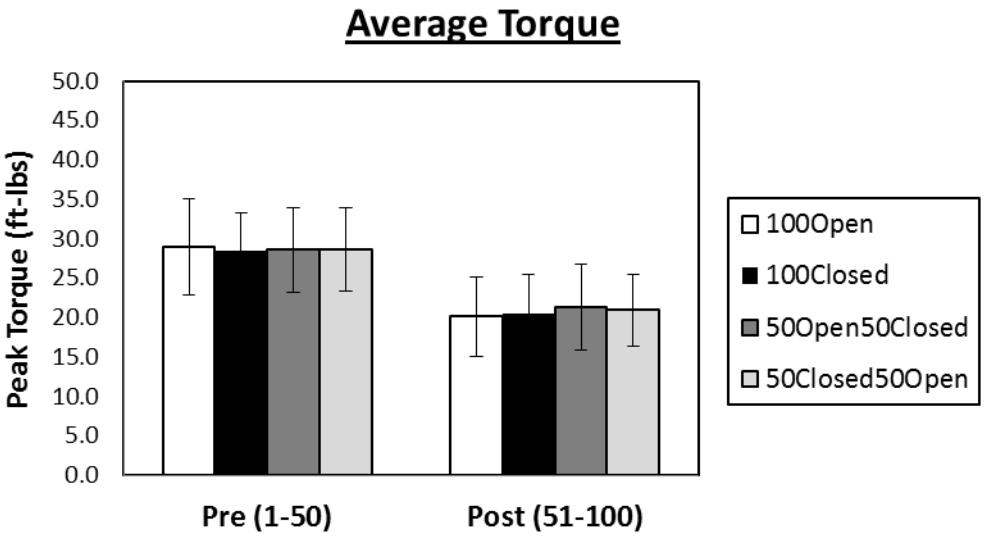


Figure 10. Mean ± SD linear slope coefficient values corresponding to the first (Pre) and second (Post) 50 maximal concentric isokinetic muscle actions with eyes open (100Open), eyes closed (100Closed), eyes open and closed for the first and last 50 muscle actions, respectively (50Open50Closed), and eyes closed and open for the first and last 50 muscle actions (50Closed50Open), respectively. For each condition, linear regression was performed on the torque values for Pre and Post to determine the linear slope coefficient for the decrease in isokinetic peak torque (ft.-lbs./repetition).

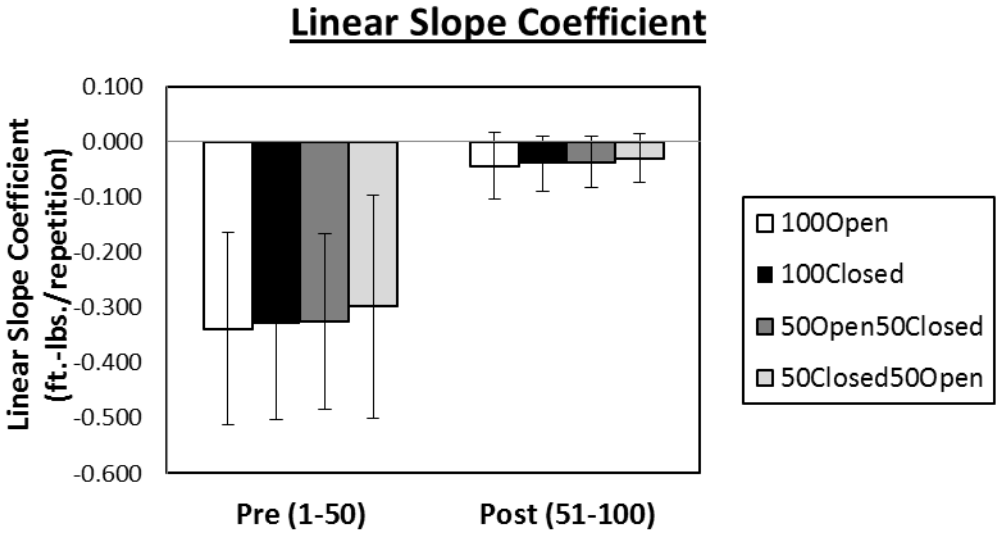


Figure 11. Mean ± SD normalized electromyographic (EMG) amplitude (RMS) values for the biceps brachii corresponding to the initial peak torque (three repetitions with the highest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All EMG amplitude values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

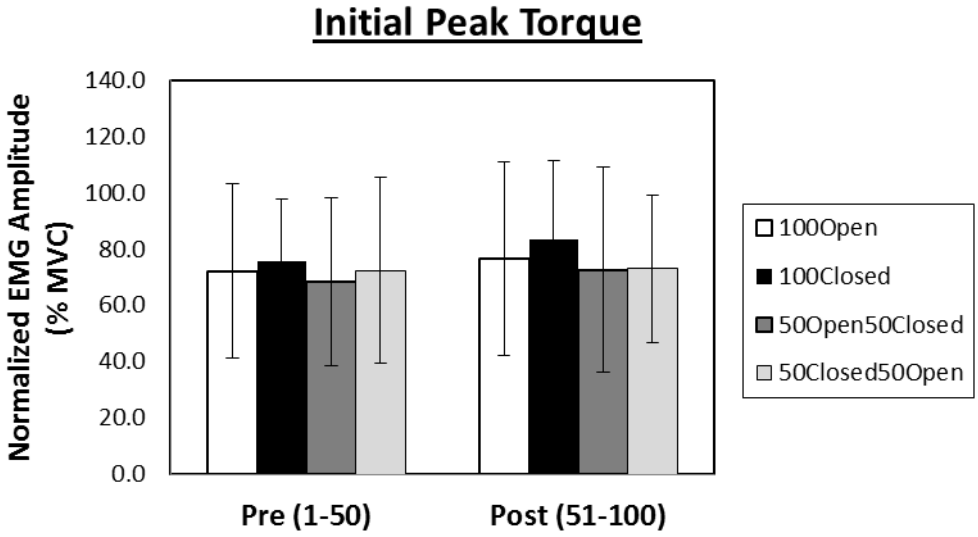


Figure 12. Mean ± SD normalized electromyographic (EMG) amplitude (RMS) values for the biceps brachii corresponding to the final peak torque (three repetitions with the lowest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All EMG amplitude values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

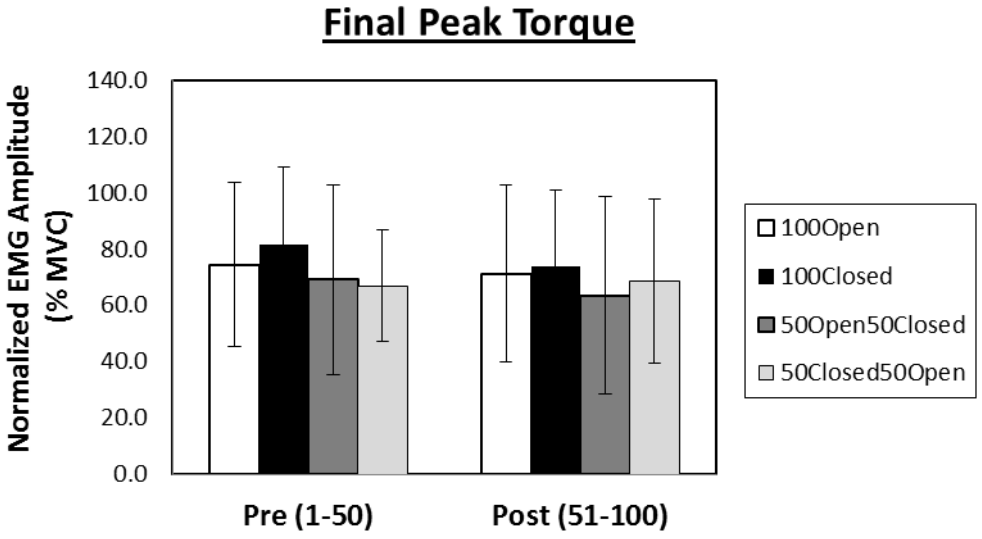


Figure 13. Mean ± SD normalized electromyographic (EMG) mean frequency (MNF) values for the biceps brachii corresponding to the initial peak torque (three repetitions with the highest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All EMG MNF values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

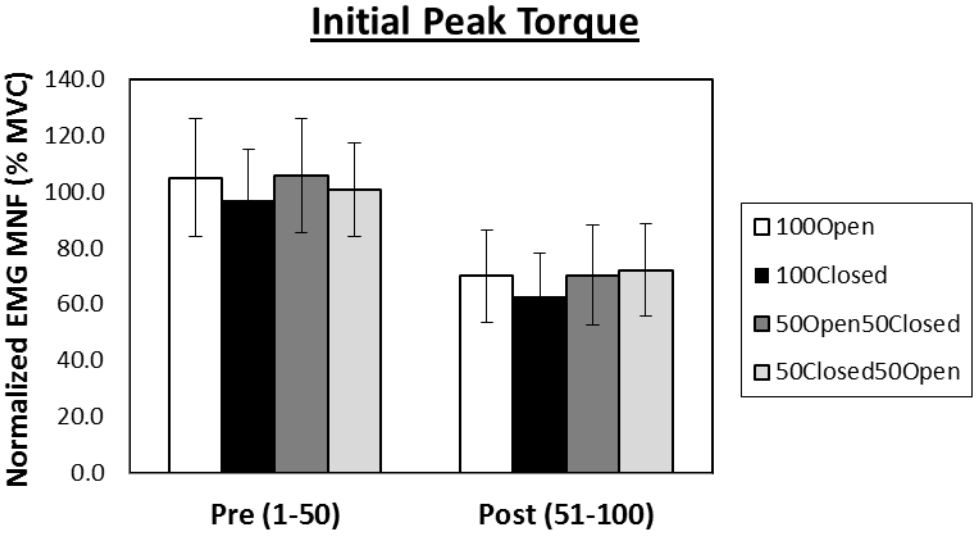


Figure 14. Mean ± SD normalized electromyographic (EMG) mean frequency (MNF) values for the biceps brachii corresponding to the final peak torque (three repetitions with the lowest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All EMG MNF values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

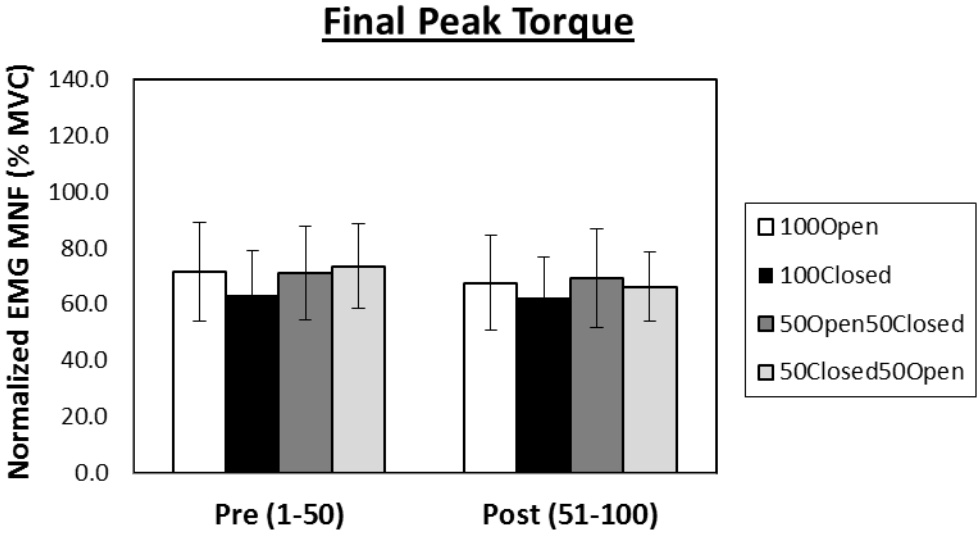


Figure 15. Mean ± SD normalized mechanomyographic (MMG) amplitude (RMS) values for the biceps brachii corresponding to the initial peak torque (three repetitions with the highest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All MMG amplitude values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

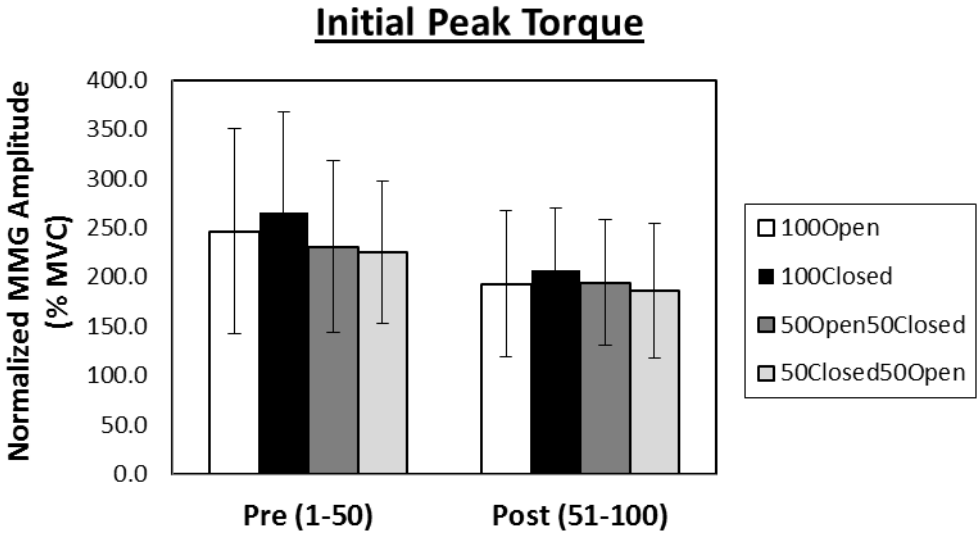


Figure 16. Mean ± SD normalized mechanomyographic (MMG) amplitude (RMS) values for the biceps brachii corresponding to the final peak torque (three repetitions with the lowest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All MMG amplitude values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

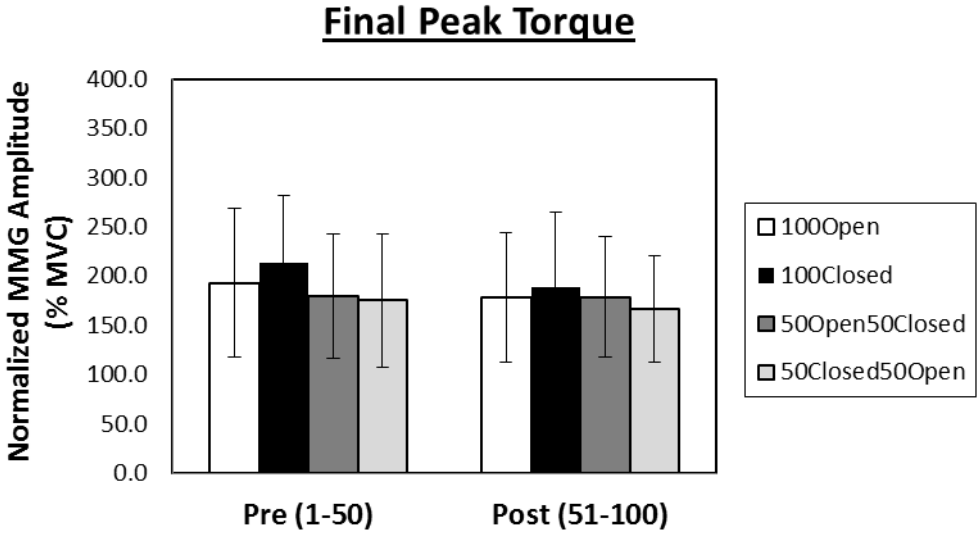


Figure 17. Mean ± SD normalized mechanomyographic (MMG) mean frequency (MNF) values for the biceps brachii corresponding to the initial peak torque (three repetitions with the highest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All MMG MNF values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).

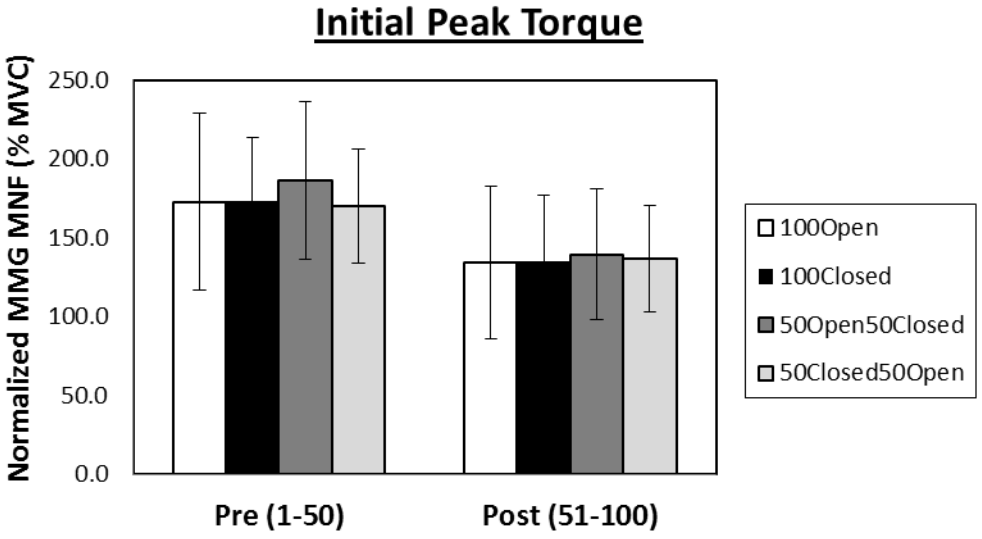
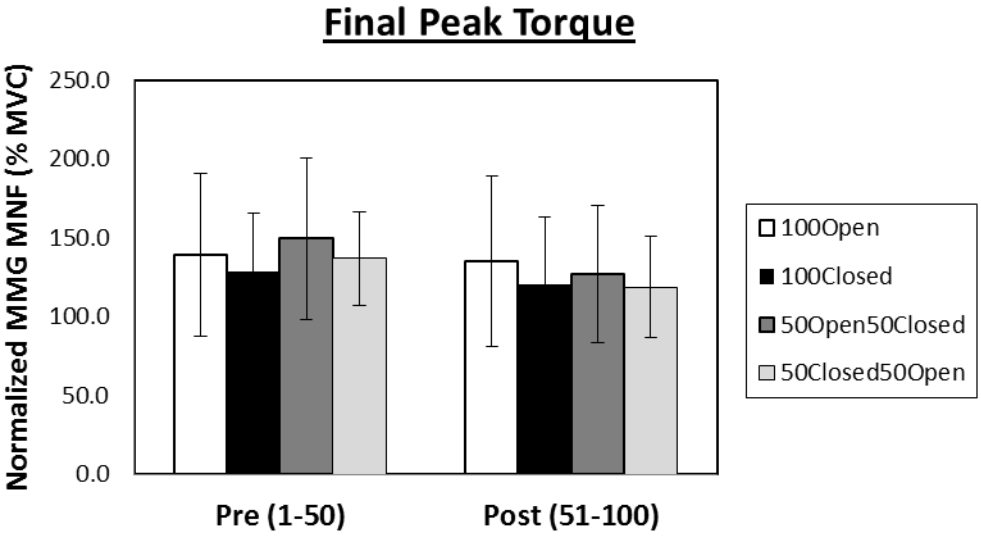


Figure 18. Mean ± SD normalized mechanomyographic (MMG) mean frequency (MNF) values for the biceps brachii corresponding to the final peak torque (three repetitions with the lowest peak torque) for each of the conditions (100Open, 100Closed, 50Open50Closed, and 50Closed50Open). For each fatigue test, the data for the first 50 muscle actions served as the pre-test (Pre) and the data for the second 50 muscle actions served as the post-test (Post). All MMG MNF values were normalized to those for a non-fatigued isometric maximum voluntary contraction (MVC).



Appendix C: Institutional Review Board Approval Letter

The University of Oklahoma

OFFICE OF HUMAN RESEARCH PARTICIPANT PROTECTION - IRB

IRB Number: 13557
Approval Date: September 13, 2011

September 15, 2011

Matthew Stock
Health & Exercise Science
1401 Asp Avenue, HHC 106
Norman, OK 73019

RE: Strength Responses During Concentric Exercise with Eyes-Open Versus Eyes-Closed

Dear Mr. Stock:

On behalf of the Institutional Review Board (IRB), I have reviewed and granted expedited approval of the above-referenced research study. This study meets the criteria for expedited approval category 4. It is my judgment as Chairperson of the IRB that the rights and welfare of individuals who may be asked to participate in this study will be respected; that the proposed research, including the process of obtaining informed consent, will be conducted in a manner consistent with the requirements of 45 CFR 46 as amended; and that the research involves no more than minimal risk to participants.

This letter documents approval to conduct the research as described:

IRB Application Dated: September 12, 2011
Protocol Dated: September 12, 2011
Consent form - Subject Dated: September 12, 2011
Other Dated: September 12, 2011 Classroom recruitment script
Recruitment flyer Dated: September 12, 2011
IRB Application Dated: September 12, 2011
Survey Instrument Dated: August 26, 2011 Decision making criteria
Survey Instrument Dated: August 26, 2011 Pre-Exercise Health Questionnaire
Priv - Research Auth 1 Dated: August 26, 2011

As principal investigator of this protocol, it is your responsibility to make sure that this study is conducted as approved. Any modifications to the protocol or consent form, initiated by you or by the sponsor, will require prior approval, which you may request by completing a protocol modification form. All study records, including copies of signed consent forms, must be retained for three (3) years after termination of the study.

The approval granted expires on September 12, 2012. Should you wish to maintain this protocol in an active status beyond that date, you will need to provide the IRB with an IRB Application for Continuing Review (Progress Report) summarizing study results to date. The IRB will request an IRB Application for Continuing Review from you approximately two months before the anniversary date of your current approval.

If you have questions about these procedures, or need any additional assistance from the IRB, please call the IRB office at (405) 325-8110 or send an email to irb@ou.edu.

Cordially,

E. Laurette Taylor, Ph.D
Chair, Institutional Review Board

1816 West Lindsey, Suite 150 Norman, Oklahoma 73069 PHONE: (405) 325-8110

Ltr_Prot_Fappv_Exp

Appendix D: Informed Consent

701-A-1

University of Oklahoma
Institutional Review Board
Informed Consent to Participate in a Research Study

Project Title: Strength responses during concentric exercise with eyes-open versus eyes-closed
Principal Investigator: Matt S. Stock
Department: Health and Exercise Science

You are being asked to volunteer for this research study. This study is being conducted at the Collums Building (Department of Health and Exercise Science, Norman campus). You were selected as a possible participant because you are a healthy male between the ages of 18-35 and you are experienced in upper-body strength training.

Please read this form and ask any questions that you may have before agreeing to take part in this study.

Purpose of the Research Study

The purpose of this study is to examine the effects of opening or closing your eyes during exercise on muscle activation and fatigue.

Number of Participants

About 30 men will take part in this study.

Procedures

If you agree to be in this study, you will be asked to make five separate visits to the Collums building of the Department of Health and Exercise Science. During each visit, you will be required to perform 100 repeated dynamic muscle actions with your dominant arm while wearing earplugs. Specifically, you will be required to flex and extend your arm at the elbow joint while you are positioned in an isokinetic dynamometer. For some of these visits, you will be asked to open or close your eyes during the exercise. Electrodes and sensors will be placed on your arm to record the electrical and mechanical activity of your muscles during testing. Prior to each test, your skin will have to be shaved and cleansed with alcohol for the electrode and sensor placements. You will not be able to feel the electrodes and sensors that are placed over your muscles. They are similar to placing a sticker on the surface of your skin.

Length of Participation

Participation in this study requires a total of five visits to the laboratory. These visits must each be separated by at least 48 hours. Each visit will take approximately 30 minutes.

This study has the following risks:

There is an extremely minimal risk for muscle injury during strength testing. A series of warm-ups will be administered to help avoid such injuries.

APPROVED SEP 13 2011 OU NC IRB

APPROVAL SEP 12 2012 EXPIRES

Benefits of being in the study are

None

Injury

In case of injury or illness resulting from this study, 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.

Confidentiality

In published reports, there will be no information included that will make it possible to identify you. Research records will be stored securely and only approved researchers will have access to the records.

Compensation

You will not be reimbursed for you time and participation in this study.

Voluntary Nature of the Study

Participation in this study is voluntary. If you withdraw or decline participation, you will not be penalized or lose benefits or services unrelated to the study. If you decide to participate, you may decline to answer any question and may choose to withdraw at any time.

Contacts and Questions

If you have concerns or complaints about the research, the researcher(s) conducting this study can be contacted at

Primary Investigator: Matt S. Stock
Email: mattstock@ou.edu
Phone: (954) 801-7308

Faculty Sponsor: Dr. Travis W. Beck
Email: tbeck@ou.edu
Phone: (405) 325-1378

Contact the researcher(s) if you have questions or if you have experienced a research-related injury.

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

You will be given a copy of this information to keep for your records. If you are not given a copy of this consent form, please request one.

APPROVED
SEP 13 2011
OU NC IRB

APPROVAL
SEP 12 2012
EXPIRES

Statement of Consent

I have read the above information. I have asked questions and have received satisfactory answers. I consent to participate in the study.

Signature Date

Appendix E: Authorization to Use or Disclose Protected Health Information for Research

UNIVERSITY OF OKLAHOMA – NORMAN CAMPUS
INSTITUTIONAL REVIEW BOARD

AUTHORIZATION TO USE or DISCLOSE PROTECTED HEALTH INFORMATION FOR RESEARCH

An additional Informed Consent Document for Research Participation may also be required.

Title or Research Project: Strength responses during concentric exercise with eyes-open versus eyes-closed

Principal Investigator: Matt S. Stock

IRB Number: n/a

Address: Department of Health and Exercise Science, 1401 Asp Ave., Norman, OK 73019

Phone Number: (954) 801-7308

If you decide to join this research project, University of Oklahoma (OU) researchers may use or share (disclose) information about you that is considered to be protected health information for their research. Protected health information will be called private information in this Authorization.

Private information To be Used or Shared. Federal law requires that researchers get your permission (authorization) to use or share your private information. If you give permission, the researchers may use or share with the people identified in this Authorization any private information related to this research from your medical records and from any test results. Information, used or shared, may include all information relating to any tests, procedures, surveys, or interviews as outlined in the consent form, medical records and charts, name, address, telephone number, date of birth, race, and government-issued identification number.

Purposes for Using or Sharing Private Information. If you give permission, the researchers may use your private information to determine whether or not you meet the inclusion and exclusion criteria for the study.

Other Use and Sharing of Private Information. If you give permission, the researchers may also use your private information to develop new procedures or

commercial products. They may share your private information with the research sponsor, the OU Institutional Review Board, auditors and inspectors who check the research, and government agencies such as the Department of Health and Human Services (HHS). The researchers may also share your private information with the purpose of creating descriptive data of the subjects that participate in the study. This descriptive data is only for the purpose of describing the subject pool, and will not be used to identify any individual subject.

Confidentiality. Although the research may report their findings in scientific journals or meetings, they will not identify you in their reports. The researchers will try to keep your information confidential, but confidentiality is not guaranteed. Any person or organization receiving the information based on this authorization could re-release the information to others and federal law would no longer protect it.

YOU MUST UNDERSTAND THAT YOUR PROTECTED HEALTH INFORMATION MAY INCLUDE INFORMATION REGARDING ANY CONDITIONS CONSIDERED AS A COMMUNICABLE OR VENEREAL DISEASE WHICH MAY INCLUDE, BUT ARE NOT LIMITED TO, DISEASES SUCH AS HEPATITIS, SYPHILIS, GONORRHEA, AND HUMAN IMMUNODEFICIENCY VIRUS ALSO KNOWN AS ACQUIRED IMMUNE DEFICIENCY SYNDROME (AIDS).

Voluntary Choice. The choice to give OU researchers permission to use or share your private information for their research is voluntary. It is completely up to you. No one can force you to give permission. However, you must give permission for OU researchers to use or share your private health information if you want to participate in the research and if you revoke your authorization, you can no longer participate in this study.

Refusing to give permission will not affect your ability to get routine treatment or health care from OU.

Revoking Permission. If you give OU researchers permission to use or share your private information, you have a right to revoke your permission whenever you want. However, revoking your permission will not apply to information that the researchers have already used, relied on, or shared.

End of Permission. Unless you revoke it, permission for OU researchers to use or share your private information for their research will be granted. You may revoke your permission at any time by writing to:

Privacy Official
University of Oklahoma
1000 Stanton L. Young Blvd., STE 221,
Oklahoma City, OK 73117
If you have questions, call: (405) 271-2511

Giving Permission. By signing this form, you give OU and OU's researchers led by Matt S. Stock + Dr. Travis W. Beck, permission to share your private information for the research project called "Strength responses during concentric exercise with eyes-open versus eyes-closed".

Subject Name:

_____ _____

Signature of Subject Date
Or parent if Subject is a Child

Or

_____ _____

Signature of Legal Representative** Date

**If signed by a legal Representative of the Subject, provide a description of the relationship to the Subject and the Authority to Act as Legal Representative:

_____

OU may ask you to produce evidence of your relationship.

A signed copy of this form must be given to the Subject or the Legal Representative at the time this signed form is provided to the researcher or his representative.

Appendix F: Pre-exercise Testing Health & Exercise Status Questionnaire

PRE-EXERCISE TESTING HEALTH & EXERCISE STATUS QUESTIONNAIRE

The University of Oklahoma
DEPARTMENT OF HEALTH AND EXERCISE SCIENCE

Name _____ Date_____

Home Address_____

Work Phone _____ Home Phone _____

Person to contact in case of emergency _____

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

Personal Physician _____ Physician's Phone_____

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.*

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. FAMILY HISTORY (✓Check if any of your blood relatives . . . parents, brothers, sisters, aunts, uncles, and/or grandparents . . . have or had any of the following)

( ) Heart Disease
( ) Heart Attacks or Strokes (prior to age 50)
( ) Elevated Blood Cholesterol or Triglyceride Levels
( ) High Blood Pressure
( ) Diabetes
( ) Sudden Death (other than accidental)

G. 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**

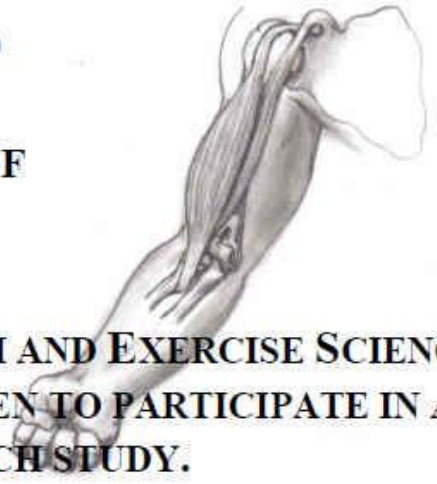
How long have you engaged in this form of exercise? _____ years _____ months

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

Appendix G: Recruitment Flyer

HES RESEARCH STUDY

FIVE VISITS REQUIRED (EACH WILL REQUIRE ROUGHLY 30 MINUTES OF YOUR TIME)



THE DEPARTMENT OF HEALTH AND EXERCISE SCIENCE IS LOOKING FOR HEALTHY MEN TO PARTICIPATE IN A SHORT RESEARCH STUDY.

Healthy men that are experienced in upper-body strength training and between the ages of 18 and 35 are encouraged to inquire.

IRB #: 13557

HES Study mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu	**HES Study** mattstock@ou.edu