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Comparisons Of Time To Task Failure And Muscle Activity For Two Different Submaximal Fatiguing Contractions

Sunggun Jeon
University of Mississippi

COMPARISONS OF TIME TO TASK FAILURE AND MUSCLE ACTIVITY FOR TWO DIFFERENT SUBMAXIMAL FATIGUING CONTRACTIONS

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Sunggun Jeon

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ABSTRACT

The aim of this study was to examine the time to task failure for two different fatiguing tasks (force vs. position task) on elbow flexion exercise, in order to explore potential mechanisms of muscle fatigue.

Twenty healthy and recreationally active individuals (10 men and 10 women) participated in this 3-visit investigation. At least 48 hours after the first visit as the familiarization, the subject returned for one of the experimental visits (order randomized). During the force task visit, the subject performed maximal voluntary contractions (MVCs), several submaximal trapezoid isometric contractions with different intensities (40% and 70% of MVC), and followed by ample rest and the time to failure task. For the position task visit, similar tests were conducted, but only with the position task setup. A minimum of 48 hours of rest was provided between visits. A paired samples *t*-test was used to compare the maximal force values. A two-way repeated measures (sex [Men vs. Women] × condition [Force task vs. Position task]) analysis of variance (ANOVA) was used to examine the time to task failure between two tasks. In addition, separate three-way mixed factorial (sex × condition × time) ANOVAs and three-way mixed factorial (sex × condition × intensity) ANOVAs were used to examine EMG parameters during the isometric fatiguing contractions and submaximal trapezoid contractions, respectively. There was no significant difference in time to task failure between two tasks, however, the time to task failure for men was significantly longer than women. In addition, the normalized EMG amplitude values of biceps brachii and triceps brachii for women were significantly higher than for men during the fatiguing contractions, and the normalized EMG median frequency value of triceps brachii for force task was significantly higher than the position task. In conclusion, during the fatiguing contractions, the muscle activities of women's angonist and antagonist increased quicker than those of men's, which led to a briefer time to task failure for women. Although no difference in time to task failure was found between tasks, motor control strategies for the antagonist muscle seem to be different.

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I would like to expess my deepest gratitude to my advisor, Dr. Xin Ye and my committee members, Dr. Mark Loftin and Dr. Ling Xin for continued support and encouragement. In addtion, I appreciate my colleagues, Miller William and Brittany Trahan for their help. I also want to thank my wife and family who always give me faith.

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CHAPTER I

INTRODUCTION

Many research studies have been conducted to examine muscle fatigue since the original work of Mosso (1903) and Reid (1928), however, the exact mechanisms for this phenomenon remain unclear. Muscle fatigue were defined through a number of studies. For example, Edward (1981) defined muscle fatigue as "failure to maintain the required or expected force" and fatigue may occur because the rate of energy supply does not meet the demand. In addition, Gandevia (2001) defined that muscle fatigue as the decreased ability to produce maximal muscle force caused by changes in the peripheral and central nervous systems. The reduction of force is not caused by a single factor, but more likely a combination of factors such as reflex function, motor unit recruitment, and motor unit firing rate (Weir et al., 2006). However, the reduced ability to produce force also depends on task-specific factors such as exercise intensity, type of muscle contraction, environment, and training status (Enoke & Stuart 1992; Weir et al., 2006).

Previous studies have used electrical stimulation of peripheral nerves (Bigland-Ritchie, Furbush, & Woods, 1986) and the interpolated twitch technique (Herbert & Gandevia, 1999) to determine the causes and mechanisms of muscle fatigue. Bigland-Ritchie et al. (1986) applied electrical stimulation to quadriceps and soleus muscles and compared the reduction of force during voluntary muscle contraction versus during electrical stimulation. The authors (Bigland-Ritchie, Furbush, & Woods, 1986) explained that the decrease in force during fatigue was not due to central factors, but a result of changes in the muscle contractile functions. On the other hand, Herbert and Gandevia (1999) reported that the increase in the myoelectrical amplitude during fatigue could be due to the decrement of the excitation of the motor neuron pool. These experiments have demonstrated that muscular fatigue can be affected by both muscular and neural mechanisms. However, as mentioned earlier, the mechanisms contributing to muscle fatigue depends on the task being performed.

One of the means to study muscle fatigue is by investigating the cause of task failure through two different types of submaximal isometric contraction (Maluf & Enoka, 2005; Hunter, Duchateau, & Enoka, 2004). One task is termed as the force task, during which the subject performs a pre-calculated constant submaximal isometric contraction against an immovable object until he/she cannot reach the designated force level. The other task is termed as the position task, where the subject performs submaximal isometric contraction by holding or supporting an external load, which is equvelant to the force produced in force task. Thereforce, these two tasks require the subject to exert the same amount of mechanical force. Many previous studies have examined time to task failure using these two different sustained isometric contraction tasks. For example, a shorter time to failure was found for the position task than for the force task with knee extension exercise in healthy adults (Poortvliet, Tucker, & Hodges, 2013). Furthermore, many other studies have examined these two tasks by investigating various factors such as exercise intensity (Rudroff et al., 2010), muscle group (Hunter et al., 2008; Mottram et al., 2005; Rudroff et al., 2010), and aging (Griffith et al., 2010). Hunter et al. (2002) also demonstrated that the time to failure of the elbow flexion exercise was twice as long for the force task compared to the position task, despite a similar net muscle torque for the two tasks. Generally speaking, the difference for time to failure between these two different tasks is related to motor unit activities (Rudroff et al., 2010), overall muscle activation and perceived effort (Hunter et al., 2008), and the spinal reflex activities (Klass et al., 2008).

The intensities of the submaximal isometric contractions of most previous studies have been performed at less than 30% maximal voluntary contraction (MVC), and most of these studies have showed a briefer time to task failure for the position task than the force task. However, Williams et al. (2014) compared two tasks with elbow flexion exercise with the load of 15% MVC in healthy adults, and reported a different finding: time to task failure was 42% shorter in force task than in the position task. In a different study (Maluf et al., 2005), at 60% MVC with the first dorsal interosseous (FDI) muscle performing index finger abductions, there was no difference in time to failure between the two tasks. However, at 20% MVC, briefer time was reported in the position task than that in the force task (Maluf et al., 2005). The authors believe that the different result of time to failure between 20% and 60% MVCs with FDI muscle might be related to the characteristic of motor unit recruitment of this specific muscle. Specifically, Maluf et al. (2005) explained that recruitment range of muscle would be likely to affect the difference of time to failure between the two tasks. Smaller muscles, such as the FDI muscle, recruit their motor units up to 55% MVC and mainly rely on the strategy of increasing the firing rate of the active motor units at higher force level (De Luca, 1985; Seki & Narusawa, 1996). On the other hand, larger muscles, such as biceps brachii muscle, recruit their motor units up to 100% MVC, and mainly rely on the strategy of recruiting high-threshold motor unit at high force level (Kukulka & Clamann, 1981; De Luca, 1985; Kamen, 2005).

In this study, since two different fatiguing tasks were performed at 50% MVC with elbow flexion exercise, the investigator expected to see a difference in time to failure between the two tasks. Therefore, the aim of this study was to compare two different tasks (force task vs. position task) to unveil the potential mechanisms of muscle fatigue. Specifially, time to task failure and sex difference were examined for both tasks. In addition, during both fatiguing tasks, surface electromyographic (EMG) signals were recorded so the muscle activation parameters were used to explain motor unit firing properties and motor control strategies during two different tasks.

CHAPTER II

LITERATURE REVIEW

Muscle fatigue has been defined in several studies, and the responsible mechanism for reducing force capacity depends on the details of the task being performed (Bigland-Ritchie et al., 1995). Because of the task-dependent changes in these mechanisms, it is not possible to identify the single cause of muscle fatigue (Maluf & Enoka, 2005). Many studies have investigated the cause of failure of particular tasks. Hunter et al. (2002) investigated endurance time (time to task failure) and cardiovascular responses (Heart rate and mean arterial pressure) during two type of submaximal isometric contractions: force task which the subjects contracted their arm against an immovable object, and position task which the subjects performed submaximal isometric contractions by supporting an inertial load with elbow flexor which was equivalent to the force produced during the force task. Sixteen health adults (8 men and 8 women) performed maximal force contractions followed by the fatiguing contractions at 15% of their maximal voluntary contraction (MVC) until task failure. During the fatigue task, heart rate, mean arterial pressure (MAP), and subjects' perceived effort level (RPE) (Borg, 1982) were recorded every 1-2 minutes. The maximal force was similar between force task visit (308 ± 151 N) and position task visit (307 ± 152 N). Despite a similar net muscle torque for the two tasks, the time to failure of elbow flexion exercise lasted twice as long as the force task (1402 ± 728 s), compared to the position task (702 ± 582 s). The amplitude of electromyographic (EMG) increased progressively in all of elbow flexor muscles during fatiguing contractions but the average EMG amplitude was greater at exhaustion during force task than that during position task. In contrast, the rate of bursts of

EMG activity and the increase in the force fluctuations, MAP, heart rate, RPE were greater for position task compared with force task. This results indicated that there is a difference in the excitation and inhibition inputs of the motor neuron pool between the two tasks. Similar experimental design was done in Hunter et al. (2008). However, unlike the previous study, participants performed a fatiguing contraction (force task vs. position task) of 20% MVC using dorsiflexor muscle (tibialis anterior). The researchers (Hunter et al., 2008) also measured antagonist (medial head of gastrocnemius), and stabilizer (vastus lateralis and rectus femoris) muscles. The time to task failure was twice as long for the force task, compared to the position task. During the position task, there were rapid rate of increase in EMG activity of tibialis anterior and gastrocnemius, EMG bursting, RPE, force fluctuation, MAP, and heart rate. Based on the findings, the difference in time to failure may be attributed to the activity of the stabilizer muscles (vastus lateralis and rectus femoris). The authors (Hunter et al., 2008) also explained that recruitment range of muscle and increased rate of central neural activity and descending drive were likely to induce the differential result of time to failure between the force task and the position task.

In addition to the possible contributions from antagonist muscle and stabilizing muscles, the distinct neural control of force production in specific muscles may also play an important role influencing muscle fatigability. For example, the investigation by Maluf et al. (2005) was designed to examine the differences in time to task failure within and beyond the motor unit recruitment maximal range during submaximal isometric contraction (force task and position task) with the first dorsal interosseus (FDI) and second palmar interosseus (SPI). Twenty healthy adults were divided into two groups (low intensity and high intensity) and performed force task and position task at 20% and 60% MVC respectively, followed by a secondary fatigue task (force task). During the tasks researchers measured heart rate, MAP, and modified Borg 10-point scale (RPE). Although muscle force was similar during the primary or secondary fatiguing contractions in low and high intensity groups, the coefficient of variation (variability in motor output) of muscle force was smaller for position task in primary contraction compared to primary force task for both groups. The endurance time was greater for the primary force task for the FDI when compared with the task performed by the low intensity groups. However, for secondary fatiguing contraction, there was no difference both groups. In addition, EMG activity and RPE increased sharply in primary position task with FDI in the low intensity group. These results suggest that shorter time to failure is caused by early motor unit recruitment of motor neuron pool. In addition, Klass et al. (2008) compared motor-evoked potentials (MEPs) using transcranial magnetic stimulation (TMS) and Hoffmann reflexes (H-reflex) in the brachial plexus during force task and position task of 20% elbow flexion MVC. Eleven subjects (6 male, 5 female) participated in two experimental protocols. One of protocols was that TMS stimulation and electrical stimulation for motor-evoked potential (MEP) and maximal M-wave (Mmax), respectively. These stimulations were delivered at 30-second intervals during each fatiguing contraction tasks, followed by the MVCs of elbow flexion and elbow extension. The other protocol was similar but added train of 60 stimuli (3 Hz) before maximal stimulation of the brachial plexus (Mmax) and delivered at 1-min intervals during each fatiguing contraction tasks. Similar to previous research, time to failure is greater in the force task than in the position task. In addition, the average EMG and the size of the MEP were also greater in the force task, whereas the H-reflex showed a sharp reduction and a further decrease for the position task. In conclusion, the authors suggested that the difference in time to failure would not be attributed to the descending drive or coactivation (antagonist muscle), but possibly by the spinal mechanism due to a reduction in peripheral excitation input.

In addition, several studies have reviewed the causes of muscle fatigue, the mechanism of task failure, and the affects the neuromuscular system in two different tasks.

Hunter, Duchateau, & Enoka (2004) examined the mechanisms of two different tasks and the causes of task failure. The authors (Hunter, Duchateau, & Enoka, 2004) described the muscle fatigue as "exercise-induced reduction in the maximal force capacity of the muscle" and introduced a classic approach to identify the causes of muscle fatigue, and further explained that the muscular and neurological mechanisms are impaired during fatiguing muscle contractions. However, the exact causes of muscle fatigue are still unknown, and the mechanisms contributing to muscle fatigue are dependent on the task being performed. They also introduced two tasks (force task and position task) to investigate muscle fatigue. During the position task, the rates of increase in the MAP, heart rate, RPE, and the fluctuations of the motors output were high, suggesting that the rate of increase for the descending drive of the spinal neurons was greater than that for the force task. Differential inputs from these motor neuron pools can be the main explanation for the different time to task failure. The difference in firing rates of the same motor units is accompanied by an additional motor unit recruitment during the position task, and this increased motor unit activity is also associated with changes in motor output, cardiovascular responses, and RPE in the position task. EMG bursting occurs during fatiguing contraction, presumably indicating the recruitment of the additional motor unit to compensate for the reduction in force capacity.

Enoka and Duchateau (2008) discussed in their review regarding what fatigue is, why, and how it affects the neuromuscular system. In addition, the authors (Enoka and Duchateau, 2008) tried to identify the mechanisms of task failure. For example, when performing maximal eccentric and concentric contractions, older adults exhibit more fatigability compared to younger adults; whereas for submaximal isometric contraction, older adults are more fatigue-resistant than younger adults. The mechanisms of task failure and muscle fatigue are explained by several factors. Specifically, the briefer duration of the position task is related to a more rapid increase in the amplitude of the surface EMG, which suggests a rapid recruitment of the motor unit during the position task. It also shows a greater decrease in the motor unit discharging rate and a greater increase in the coefficient of variation for the motor unit discharging time during the position task, indicating a rapid increase in synaptic noise. At the same relative intensity of force and position task, the time to failure duration varies from person to person and can also be changed depending on the task posture. Furthermore, the amplitude of the Hoffman reflexes in the biceps brachia was reduced more rapidly during the position task compared to the force task. This suggests that the difference in synaptic input received by the motor neuron pool is related to presynaptic inputs. In conclusion, the endurance time of the position task may be limited by the spinal cord mechanism. Therefore, failure of two different tasks is associated with the excitation and inhibition inputs of the motor neuron pool, the motor unit recruitment strategy, the rate of increase for the descending drive, and the spinal mechanism.

Regarding the neural control of force production, De Luca and his colleagues have established motor unit firing behavior-related research through their EMG decomposition algorithmic techniques. De Luca et al. (1982a) examined the behavior of the motor unit firing by using the decomposition method to investigate motor unit firing behavior in voluntary contractions. A total of 13 subjects participated in the study, including four normal healthy individuals, three swimmers, three power lifters, and three pianists. A single bipolar needle electrode was used to record EMG signals from 2 to 8 individual motor units in FDI and deltoid muscles during 40% and 80% MVC isometric contractions. Subject also performed three different force rate (10, 20, and 40%) contractions. As a results, lower threshold motor units tended to be recruited at lower force levels whereas higher threshold motor units tended to be recruited at higher force levels. In addition, motor units tended to decruit at a slightly higher level than the force level at which they were recruited. De Luca and colleagues described this phenomenon as mechanical and neural adaptation and suggested that the potentiation of motor-unit twitch tension could occur after repetitive stimulation. In addition, the mechanisms for force generation of FDI and deltoid muscle are different. FDI highly relies on the coding of the firing rate of the motor units, producing an accurate and smooth force. On the other hand, deltoid muscles have about 1000 motor units, and mainly relies on the recruitment of motor units to high force level generation.

In terms of the relationship between motor unit recruitment threshold and firing rate, the author explained that lower threshold motor units have a higher discharge rate and higher threshold motor units have a lower frequency of discharging. Specifically, De Luca and Hostage (2010) examined the relationship between recruitment and mean firing rate of motor unit by using the surface EMG decomposition technique. Six subjects participated in this study and performed isometric contractions of 20, 50, 80, and 100% MVC at the vastus lateralis (VL), first dorsal interosseous (FDI), and tibialis anterior (TA) muscles. They found that the relationship between recruitment threshold and the mean firing rate of motor units in all muscles and during all force levels are inversely related: as the force level increases, the regression line becomes progressively flatter. In addition, the author described this phenomenon as "the firing rate versus recruitment threshold line describes an “operating point” of the motoneuron pool that shifts in response to excitation".

Lastly, the entire population motor units are controlled by a common synaptic neural drive, which interacts with the other two properties of motor unit firing (recruitment and firing rate) (De Luca 1985). The common drive indicates that the nervous system does not individually control the firing of each individual motor unit, instead, each motor unit is regulated in a uniform fashion with the motoneuron pool. Thus, muscle force is modulated by the excitation or inhibition of the motorneuron pool. In addition, it has been shown that as the firing rates of the newly activated motor units increase and as the force output of the muscles increases, the firing rates of previously activated motor units decrease. This interaction between recruitment and firing rates can be explained by the behavior of stretch reflexes and Renshaw inhibition, which appears to be configured to 'balance' their contribution so that the muscle produces a relative smooth force output. Therefore, the interaction between the recruitment of a new motor units and the motor unit firing rates can be described as an "onion-skin" phenomenon. The firing rates of earlier recruited motor units during isometric contraction are greater than later recruited motor units. In addition, the central nervous system (CNS) does not control motor unit firing separately, but uses a common strategy for the active motor units.

CHAPTER III

METHODOLOGY

The purpose of this investigation was to examine the time to task failure between two different fatiguing tasks (force task and position task) in order to examine the potential mechanisms of muscle fatigue. The target population was healthy and recreationally active male and female between the ages of 18-35, and the sample size was 20 (10 men and 10 women). At the time of the recruitment, all subjects did not have neuromuscular and cardiovascular diseases for a year leading to this investigation. In addition, other exclusion criteria included the history of shoulder, elbow, and wrist injuries, which could interfere the elbow flexion exercises. Before participation, each subject provided the informed consent and the laboratory questionnaire.

Experimental Design

This investigation used a within-subject crossover design. There were three laboratory visits required for this investigation. A minimum of 48 hours of rest was provided between visits. At the 1st visit, the subject was familiarized with all the expermental testing and the fatiguing tasks. The investigator first measured participants' height and weight. Then, by asking which hand the subject would throw a football, the arm dominance was determined. All testing and interventions in this investigation were performed with the dominant arm. The subject then was familiarized with the procedures. The first task was to practice isometric strength testing for the elbow extension and flexion exercises. The next task was to familiarize submaixmal trapezoid isometric contraction tasks. For these tasks, participants practiced submaximal isometric contractions with 40% and 70% of the pre-determined MVC with visual feedback. The last familiarization session was both fatiguing tasks (force vs. position). During the force task, the subject practiced to perform the isometric contraction at the intensity of 50% of MVC. A visual feedback was provided to indicate if the subject's force matches the target force. Practices were made until the subject was able to match his/her own force with the target force with minimal errors. During the position task, a pre-calculated external load (equivelant to the force of 50% MVC) was applied on the subject's elbow, and the subject was asked to hold the external load for 10 seconds. For both fatiguing tasks, the subjects were told and encouraged to main a sitted upright position.

The 2nd and 3rd visits were experimental visits, during which different fatiguing task protocols (force task vs. position task) were randomly sequenced. At the force task visit, the investigator started by measuring the maximal strength of the subject's elbow extensors for 3sets of 3-s maximal voluntary contractions (MVCs). Then, the subject performed the maximal strength of the subject's elbow flexors by by having him/her perform 3 sets of 5-s MVCs of the elbow flexion exercise. The highest MVC of all 3 contractions was recored as the subject's maximal isometric strength. After the strength measurements, subject was asked to perform several submaximal isometric exercise at the intensity of 40% and 70% MVC with visual feedback, followed by ample rest, and lastly concluded by performing the fatiguing contraction task of 50% of MVC time to failure. At the positon task visit, participants performed 3 sets of 3-s MVCs for triceps brachii, 3 sets of 5-s MVCs for biceps brachii, trapezoid submaximal isometric contraction at 40% and 70% MVC, and then finished with 50% of time to failure with position task. The subject was verbally encouraged during the isometric strength testing and the fatiguing tasks.

Testing and Interventions

Isometric Strength Testing

During this test, the subject was asked to sit in an adjustable chair with an upright posture. The elbow was placed on the padded v-shape foam support, and the upper arm was fixed to minimize the movement of the shoulder, which could affect the strength testing of the elbow extension. The participants first performed an elbow extension with maximal efforts for 3 sets of three seconds against an immovable object. After the isometric strength testing of the elbow extensors, the investigator placed the participant's wrist into a cuff, which was connected to a force transducer (Model SM-500; Interface, Scottsdale, Arizona, USA), with the other end connecting to an immovable board mounted to the floor. The investigator made adjuetments for the subject's sitting position, so the upper arm and forearm of the subject's were at the angle of 135 degrees. After a few submaximal elbow flexions as warm-up, the subject was asked to flex the elbow as much as he/she can for 3 sets of five seconds to measure maximal voluntary isometric contractions (MVCs). At least a one-minute break was provided for between consecutive sets.

Submaximal Trapezoid Isometric Contractions (during force task visit)

Following the isometric strength testing with at least 5 minutes of rest, the subject sat in same posture as the he/she did for the isometric strength testing. This type of contraction required the subject to start producing force gradually from rest to 40% of the pre-determined MVC for 4 seconds (10% MVC per second), to hold it for 10 seconds, and then to gradually decrease force output to the relaxed state for 4 seconds. The total time for 40% MVC was 24 seconds (3 seconds pre-rest + 4 seconds force increase + 10 seconds holding at 40% MVC + 4 seconds force decrease + 3 seocnds post-rest). During this type of isometric contraction, a monitor showed target force template and the subject's real time force. With the same force increasing/decreaing rate, the subject performed 70% MVC trapezoid isometric contraction with 30 seconds. The order of 40% and 70% MVC trapezoid isometric contractions were randomized.

Submaximal Trapezoid Isometric Contractions (during position task visit)

During the position task visit. The subject performed the submaximal trapezoid isometric contractions with a different manner as they did during the force task visit. Specifially, instead of actively flexing the elbow agianst the force transducer, the subject was told to hold the forearm position, and to resist against the pulling force from the other side of the force transducer, created by the investigator. Therefore, during this task of this visit, the monitor showed the force template and the subject's reali-time force were manipulated by the skilled investigator. The durations of both 40% and 70% MVC trapezoid contractions were exactly the same as the ones from force task visit.

Fatiguing Force Task

Following the trapezoid submaximal isometric contractions with at least 5 minutes of rest. The subject performed a fatiguing isometric contraction until task failure. Specifically, he/she was asked to actively contracting against the force transducer at the intensity of 50% MVC. With the computer monitor showing both target force and the real-time force, the subject was required to sustain the contraction at this force level as long as he/she could. Once the exerted force was dropped below 50% MVC for 3 seconds, the task was determined as failure.

Fatiguing Position Task

With the similar setup as the force task, the subject's wrist was attached an external load which is equevalent to the force level of 50% MVC. And the subject was asked to maintain the elbow position as along as he/she can. Failing to maintian the position leaded to the task failure.

Measurements

Force

During all the maximal and submaximal isometric contraction tasks for the elbow flexors, force was detected by the tension applied to the load cell (Model SM-500; Interface, Scottsdale, Arizona, USA). The maximal force output was selected from the highest 1-s portion of the 5-s isometric MVC. The force signal was digitized with a 12-bit analog to digital converter (National Instruments, Austin, TX) and stored in a lab computer for further analysis.

Surface EMG Acquasition and Signal Processing

The biceps brachii and the long head of the triceps brachii muscle activities were recorded through bipolor surface EMG sensors. Based on the electrode locations from SENIAM (Hermens et al., 1999), the investigator shaved and cleaned the skin surface with rubbing alcohol before placing electrodes. Then, two bipolar surface EMG sensors (DE 2.1 Single Differential Surface EMG sensor, Delsys, Inc., Natick, MA; 10-mm interelectrode distance) were placed onto the target muscle bellies. Lastly, the reference electrode (Model

USX2000; Axelgaard, Fallbrook, CA, USA) placed on the seventh cervical vertebrae (C7).

All analog bipolar EMG signals were collected and amplified (gain = 1,000) with a modified Bagnoli 16-channel EMG system (Delsys, Inc., Natick, MA, USA) and filtered with high and low pass filters set at 20 Hz and 450 Hz, respectively. The filtered signals were then digitized at a sampling rate of 20000 Hz with a 12-bit analog-to-digital converter (National Instruments, Austin, TX) and stored in a lab computer for subsequent analyses. The amplitude of each selected EMG signal was calculated as the root mean square (RMS). The Discrete Fourier Transform (DFT) algorithm was used to derive the EMG signal into power spectrum, and the median frequency (MF) of the spectrum was then calculated based on the equation described by Kwatny et al. (1970). Furthermore, all RMS and MF values were normalized as percentages against the values from the EMG raw values obtained during that muscle's highest MVC.

Statistical Analyses

A priori power analyses (G*Power 3.1) indicated that a sample size of approximately 18 participants (9 men and 9 women) would be appropriate for a power level of 0.80. Dependent variables were reported as mean ± SD. The paired samples *t*-test was used to compare the maximal force values. To compare the time to task failure between two tasks, a two-way mixed factorial (sex [Men vs. Women] × condition [Force task vs. Position task]) analysis of variance (ANOVA) was used. To examine the changes of EMG parameters (amplitude and MF) within the fatiguing contractions, we equally separated each fatiguing contraction into three phases: the beginning (Begin), the middle (Mid), and the end (End). Thus, separate three-way mixed factorial (sex [Men vs. Women] × condition [Force task vs. Position task] × time[Begin vs. Mid vs. End]) ANOVAs were used to examine dependent variables (normalized EMG amplitude and normalized EMG MF) through the entire fatiguing contraction between different tasks for both sexes. In addition, different three-way mixed factorial (sex [Men vs. Women] × condition [Force task vs. Position task] × intensity [40% vs. 70% MVC]) ANOVAs were used to examine the normalized EMG amplitude and normalized EMG MF during the trapezoid submaximal contractions. When appropriate, the follow-up test included one-way repeated ANOVA, independent samples *t*-tests, and paired samples *t*-tests with Bonferroni adjustments. All statistical tests was conducted using statistical software (IBM SPSS Statistics 22.0, IBM, Armonk, NY) with alpha set at 0.05. In addition, effect sizes were calculated using Cohen's *d*, with 0.20, 0.50, and 0.80 as small, medium, and large effect sizes, respectively (Cohen, 1992).

CHAPTER IV

RESULTS

This study was conducted to examine the mechanisms of muscle fatigue by comparing two different fatiguing tasks (force task and position task) in healthy active men and women between ages of 18-35. Twenty subjects participated in this study and the data of all subjects was analyzed. Of these 20 subjects, 10 were males (mean ± SD: age = 23.9 ± 4.3 years, height = 172.4 ± 6.0 cm, weight = 82.5 ± 11.7 kg) and 10 were female (mean ± SD: age = 22.1 ± 3.1 years, height = 164.9 ± 3.9 cm, weight = 72.6 ± 12.8 kg).

Test- retest Reliability

The maximal isometric strength values for the dominant elbow flexors among three visits (Familiarization vs. Force task vs. Position task) were reliable, with r = 0.97 for the intraclass correlation coefficient model (3, 1) ($ICC_{3,1}$) (Weir, 2005). In addition, the isometric strength values were not significantly different among three visits ($p = 0.843$). The ICCs for the absolute EMG amplitudes and EMG median frequencies during Visits 2 and 3 were at least 0.74 and 0.88, respectively, with no significant differences between experimental visits.

Isometric strength

For the isometric strength of the elbow flexors between two experimental testing visits (Visits 2 and 3), the paired samples *t*-test showed no significant difference between the force task visit and position task visit (mean ± SD: Force task visit vs. Position task visit = 274.4 ± 124.3 N vs. 270.2 ± 124.4 N, $p = 0.541$; $d = 0.03$).

Time to Task Failure

For the time to task failure for force task and position task, the result from the two-way (sex [Men vs. Women] × condition [Force vs. Position]) ANOVA indicated that there was no significant two-way interactions. However, there was a main effect for sex ($p = 0.029$). After collapsing across the condition, the follow-up independent samples *t*-test showed that the time to task failure for men was significantly longer than that for women (Male vs. Female = 42.4 ± 16.1 s vs. 28.5 ± 9.2 s, $p = 0.015$; $d = 1.06$) (Figure 1).

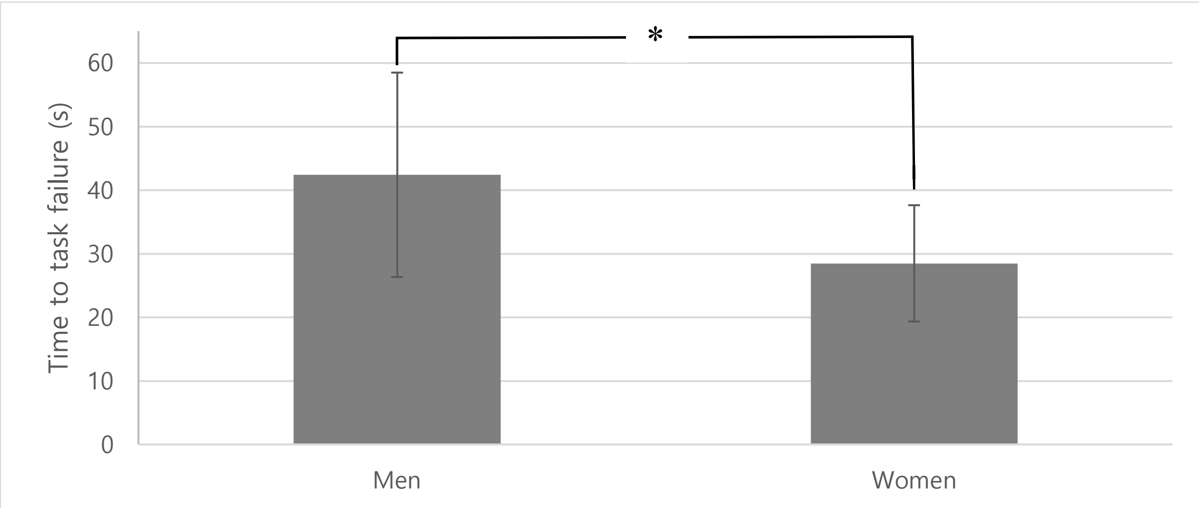

Figure 1. Time to task failure (mean ± SD) for men and women. * $p > .05$ between men and women.

Normalized EMG amplitude

Time to task failure (begin vs. mid vs. end) for the biceps brachii

The results from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × time [Begin vs. Mid vs. End]) mixed factorial ANOVA indicated that there was no significant three-way interaction, but there was a significant sex × time two-way interaction ($F = 3.928$, $p = 0.029$). When collapsed across condition, the follow-up one-way repeated ANOVA showed that there was significant difference for normalized EMG amplitude (begin vs. mid vs. end) for women ($p < 0.001$), but not for men ($p = 0.093$). In addition, separate independent samples *t*-tests showed that the normalized EMG amplitude was significantly higher in both mid (Male vs. Female = 79.4 ± 19.6 % vs. 101.0 ± 19.9 %, $p = 0.013$; $d = 1.10$) and end (Male vs. Female = 81.0 ± 21.0 % vs. 113.1 ± 23.1 %, $p = 0.002$; $d = 1.45$) of the fatiguing contractions for women than those for men (Figure 2).

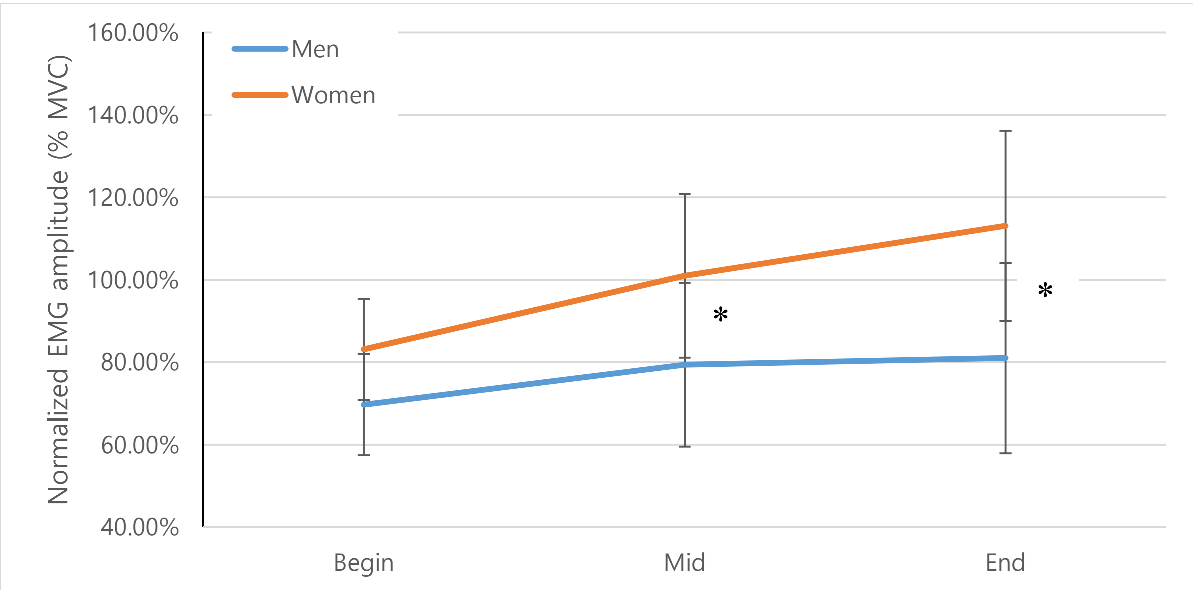

Figure 2. Normalized EMG amplitude (% MVC) of time to task failure (begin vs. mid vs. end) for the biceps brachii between men and women. * $p > .05$ between men and women.

Time to task failure (begin vs. mid vs. end) for the triceps brachii

The results from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] ×

time [Begin vs. Mid vs. End]) mixed factorial ANOVA indicated that there was no significant three-way interaction, but there was a significant sex × time two-way interaction ($F = 10.065$, $p < 0.001$). When collapsed across condition, the follow-up one-way repeated ANOVA showed that there was significant difference for normalized EMG amplitude (begin vs. mid vs. end) for men ($p = 0.001$) and for women ($p < 0.001$). In addition, separate independent samples *t*-tests showed that the normalized EMG amplitude was significantly higher at the beginning (Male vs. Female = 14.6 ± 10.2 % vs. 27.7 ± 14.4 %, $p = 0.015$; $d = 1.05$), mid (Male vs. Female = 16.8 ± 12.3 % vs. 35.0 ± 16.0 %, $p = 0.006$; $d = 1.27$) and end (Male vs. Female = 18.3 ± 12.4 % vs. 40.1 ± 18.9 %, $p = 0.004$; $d = 1.37$) of the fatiguing contractions for women than those for men (Figure 3).

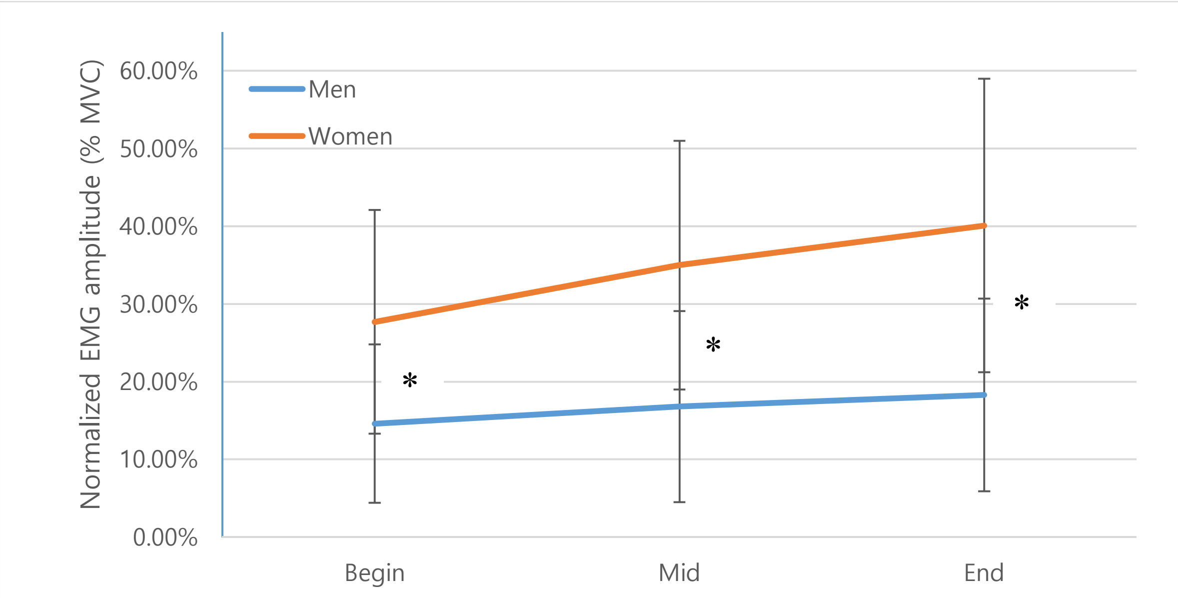

Figure 3. Normalized EMG amplitude (% MVC) of time to task failure (begin vs. mid vs. end) for the triceps brachii between men and women. * $p > .05$ between men and women.

Submaximal trapezoid contractions (40% vs 70% MVC) for the biceps brachii

For the trapezoid contractions during the force task and position task visits, the result from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × intensity [40% vs. 70% MVC]) mixed factorial ANOVA indicated that there was no significant three-way or two-way interactions. However, there was a main effect for intensity ($p < 0.001$). After collapsing across the sex and condition, the follow-up paired samples *t*-test showed that the normalized EMG amplitude was significantly higher at 70% MVC (40% vs. 70% = 59.5 ± 18.8 % vs. 107.2 ± 22.7 %, $p < 0.001$; $d = 2.29$) than that at 40% MVC.

Submaximal trapezoid contractions (40% vs 70% MVC) for the triceps brachii

For the trapezoid contractions during the force task and position task visits, the result from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × intensity [40% vs. 70% MVC]) mixed factorial ANOVA indicated that there was no significant three-way or two-way interaction. However, there were main effects for intensity ($p < 0.001$) and sex ($p = 0.047$). After collapsing across the sex and condition, the follow-up paired samples *t*-test showed that the normalized EMG amplitude was significantly higher at 70% MVC (40% vs. 70% = 15.3 ± 11.0 % vs. 28.7 ± 19.2 %, $p < 0.001$; $d = 0.85$) than that at 40% MVC. In addition, After collapsing across the condition and intensity, the follow-up independent samples *t*-test showed that the normalized EMG amplitude for women was significantly higher than that for men (Male vs. Female = 15.5 ± 10.4 % vs. 28.6 ± 16.4 %, $p = 0.024$; $d = 0.95$) (Figure 4).

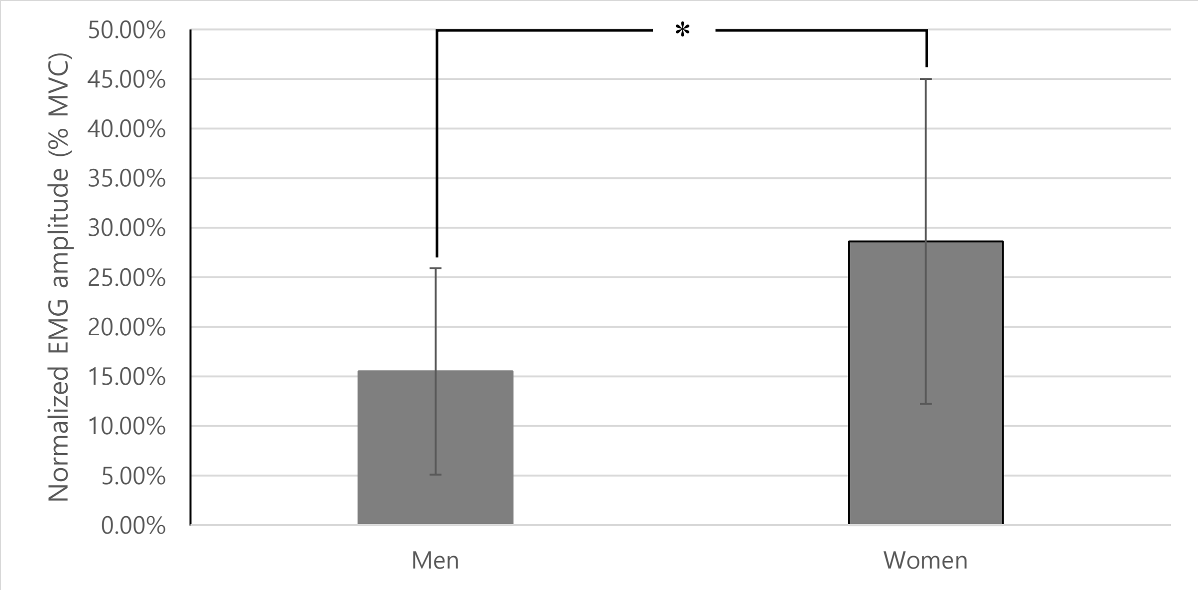

Figure 4. Normalized EMG amplitude (% MVC) of submaximal trapezoid contractions for the triceps brachii between men and women. * $p > .05$ between men and women.

Normalized EMG median frequency (MF)

Time to task failure (begin vs. mid vs. end) for the biceps brachii

The results from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × time [Begin vs. Mid vs. End]) mixed factorial ANOVA indicated that there was no significant three-way or two-way interaction, but there was a main effect for time ($p < 0.001$). After collapsing across the sex and condition, the follow-up one-way repeated measures ANOVA showed that there was a significant difference for normalized EMG MF (begin vs. mid vs. end) of the fatiguing contractions ($p < 0.001$). In addition, separate paired samples *t*-tests showed that the normalized EMG MF was significantly higher in begin compared with mid (Begin vs. Mid = 101.0 ± 11.9 % vs. 91.8 ± 9.1 %, $p < 0.001$; $d = 0.87$), significantly higher in begin compared with end (Begin vs. End = 101.0 ± 11.9 % vs. 82.1 ± 8.9 %, $p < 0.001$; $d =$

1.80), and significantly higher in mid compared with end (Mid vs. End = 91.8 ± 9.1 % vs. 82.1 ± 8.9 %, $p < 0.001$; $d = 1.08$) of the fatiguing contractions.

Time to task failure (begin vs. mid vs. end) for the triceps brachii

The results from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × time [Begin vs. Mid vs. End]) mixed factorial ANOVA indicated that there was no significant three-way or two-way interaction, but there were main effects for time ($p < 0.001$) and condition ($p = 0.015$). After collapsing across the sex and condition, the follow-up one-way repeated measures ANOVA showed that there was a significant difference for normalized EMG MF (begin vs. mid vs. end) of the fatiguing contractions ($P < 0.001$). In addition, separate paired samples *t*-tests showed the normalized EMG MF was significantly higher in begin compared with mid (Begin vs. Mid = 41.8 ± 27.3 % vs. 38.0 ± 25.6 %, $p < 0.001$; $d = 0.15$), significantly higher in begin compared with end (Begin vs. End = 41.8 ± 27.3 % vs. 34.3 ± 23.4 %, $p < 0.001$; $d = 0.30$), and significantly higher in mid compared with end (Mid vs. End = 38.0 ± 25.6 % vs. 34.3 ± 23.4 %, $p < 0.001$; $d = 0.15$) of the fatiguing contractions. When collapsed across the time and sex, the follow-up paired samples *t*-test showed that the normalized EMG MF for force task was significantly higher than that for position task (Force task vs. Position task = 41.9 ± 28.5 % vs. 34.2 ± 23.6 %, $p = 0.008$; $d = 0.29$) (Figure 5).

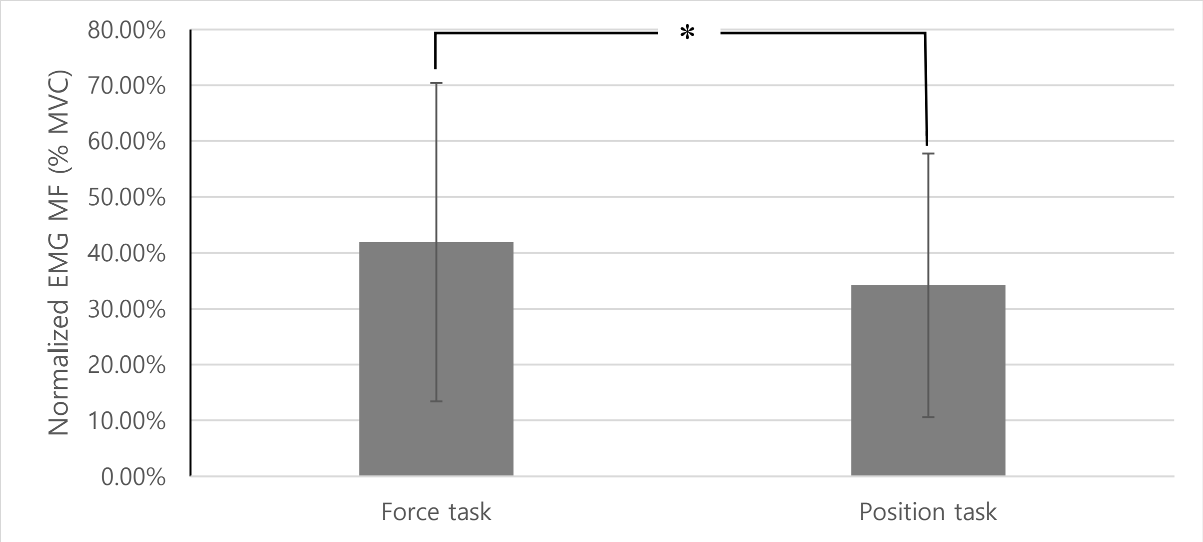

Figure 5. Normalized EMG median frequency (% MVC) for the triceps between force task and position task. * $p > .05$ between force task and position task.

Submaximal trapezoid contractions (40% vs 70% MVC) for the biceps brachii

For the trapezoid contractions during the force task and position task visits, the result from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × intensity [40% vs. 70% MVC]) mixed factorial ANOVA indicated that there was no significant three-way intractions, but there was a significant intensity × condition two-way interaction (F = 7.013, p = 0.016). When collapsed across sex, the follow-up separate paired samples t-tests showed that the normalized EMG MF for force task was significantly higher at 40% MVC (40 % vs. 70 % MVC = 100.1 ± 12.1 % vs. 92.2 ± 11.5 %, $p < 0.001$; $d = 0.67$) than that at 70% MVC. In addtion, the normalized EMG MF for position task was significantly higher at 40% MVC (40 % vs. 70 % MVC = 102.9 ± 15.1 % vs. 89.4 ± 12.1 %, $p < 0.001$; $d = 0.99$) than that at 70% MVC. However, there were no significant difference at 40 % MVC between the force task and position task ($p = 0.282$), as well as at 70% MVC ($p = 0.217$).

Submaximal trapezoid contractions (40% vs 70% MVC) for the triceps brachii

For the trapezoid contractions during the force task and position task visits, the result from the 3-way (sex [Men vs. Women] × condition [Force vs. Position] × intensity [40% vs. 70% MVC]) mixed factorial ANOVA indicated that there was no significant three-way or two-way interaction. However, there were main effects for intensity ($p = 0.007$) and condition ($p = 0.005$). When collapsed across the condition and sex, the follow-up paired samples *t*-test showed that the normalized EMG MF was significantly higher at 40% MVC (40% vs. 70% = 42.4 ± 28.3 % vs. 38.8 ± 24.7 %, $p = 0.003$; $d = 0.14$) than that at 70% MVC. In addition, after collapsing across the intensity and sex, the follow-up paired samples *t*-test showed that the normalized EMG MF for force task was significantly higher than that for position task (Force task vs. Position task = 45.2 ± 29.8 % vs. 36.0 ± 24.4 %, $p = 0.003$; $d = 0.34$) (Figure 6).

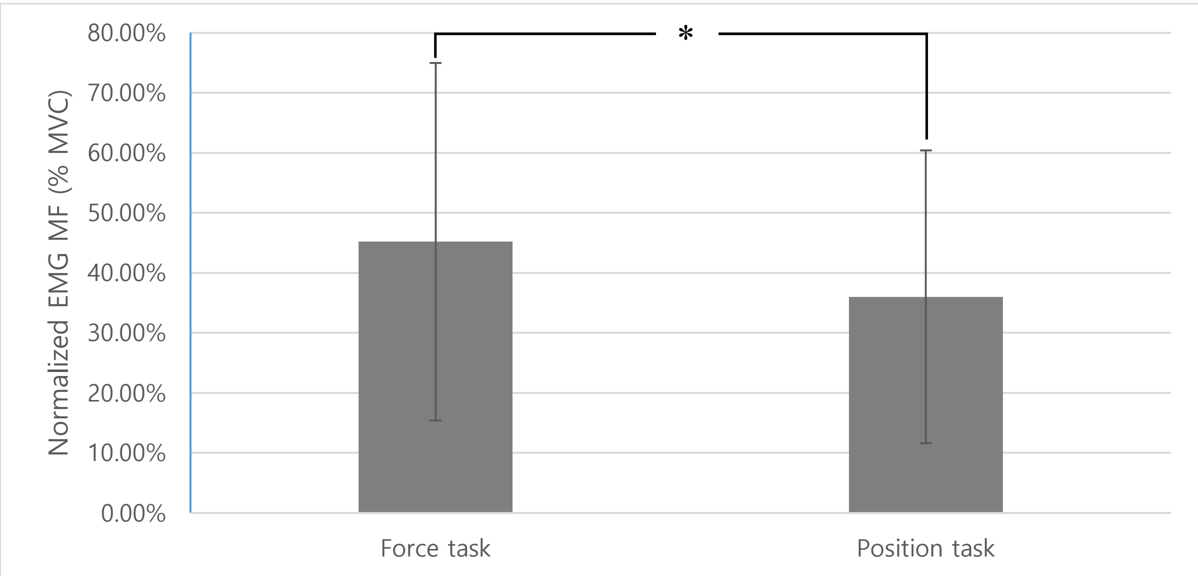

Figure 6. Normalized EMG median frequency (% MVC) for the triceps during submaximal trapezoid contractions between forcc task and position task. * $p > .05$ between force task and position task.

CHAPTER V

DISCUSSION

The purpose of this study was to investigate the time to task failure of two different submaximal isometric fatiguing tasks (force task and position task) performed with the elbow flexor muscles in healthy men and women. In addition, the surface EMG technique was used in order to explore the potential mechanisms of muscle fatigue. First, the subjects' elbow flexion isometric strength between two experimental testing visits (Force task visit and Position task visit) were not significantly different. Second, the main finding of this study is that there was no significant difference in time to task failure between the force task and position task. In addition, our results also showed that in general, men sustained a longer time than women did during the fatiguing tasks.

Time to task failure for two different submaximal isometric fatiguing tasks

Different from the majority of the previous studies that reported a longer time to task failure for the force task than for the position task (Hunter et al., 2002; Griffith, Yoon, & Hunter, 2010; Baudry et al., 2011; Lauber et al., 2012), the results of the current study showed no difference in time to task failure for the two different fatiguing tasks. Based on our effect size calculation, comparing to the force task, the position task imposed a small treatment effect (*d* = 0.34) towards a shorter time to task failure. In addition to the obvious different experimental setup, an important factor that might have influenced our results is the intensity used during the submaximal fatiguing tasks. In some studies where the relatively low contraction intensities (e.g., less than 30% MVC) were used, the time to task failure during the position task was usually shorter than that during the force task. However, at the relatively high intensities (e.g., greater than 45% MVC), some experiments showed no difference in time to task failure between the two tasks (Maluf et al., 2005; Rudroff et al., 2010; Booghs 2012). Based on previous studies, a potential explanation for this phenomenon is due the differences in the motor control strategies of the fatigued muscle. Specifically, when the target force (the force that the subjects have to sustain) exceeds the maximal range of motor unit recruitment during sustained fatiguing contractions, all motor units are recruited and activated at the beginning of the tasks and the EMG amplitude increases at a similar manner during two fatiguing tasks (Maluf et al., 2005). Consequently, the difference in endurance time between the two tasks should be absent due to the maximal range of the motor unit recruitment. However, this explanation seems impossible because the biceps brachii used in this study has a very high motor unit recruitment range (over 88% MVC) (Kukulka & Clamann, 1981). Another possible explanation may be due to muscle perfusion in the fatigued muscle. Specifically, during an isometric contraction, the intramuscular pressure directly influences the rate of blood flowing out of the muscle. At a relatively high intensity (greater than 30% MVC) (De Luca, 1997), the blood flow can be obstructed at the beginning of contractions, and the occluded blood flow may limit oxygenation and metabolic removal in the target muscle. With the accumulation of the metabolites, the Group III and Group IV muscle afferent can be activated, inhibiting the nerve drive from the central nervous system (Amann, 2012), thus to contribute to the muscle fatigue (Rudoff et al., 2010; Booghs et al., 2012). Therefore, the absence of a difference in time to task failure between tasks at the 50% MVC may be partly due to the relative high intensity muscle contraction-induced blood flow occlusion.

Although no difference in time to task failure was found, our results on EMG parameters did indicate a novel finding regarding the different motor control strategies between two tasks. Specifically, the frequency information of EMG signal is commonly used to assess muscle fatigue and to analyze the recruitment of motor units (Cifrek et al., 2009). The central (median and mean) frequency decreases during a fatiguing contraction due to the shifting of the power spectrum from a high to a low frequency domain (Thongpanja et al., 2015). This change is generally thought to be due to the changes of the muscle fiber conduction velocity and the firing frequencies of the active motor units as the sustained contractions proceeds (De Luca, 1997; Farina, Merletti, & Enoka, 2004). In current investigation, the EMG MF for biceps brachii gradually decreased during the fatiguing contractions, which is within our expectation and consistent with previous studies (Krogh-Lund & Jørgensen, 1991; McManus et al., 2015). Interestingly, during both fatiguing contractions and submaximal trapezoid contractions, the position task demonstrated an overall lower EMG MF for triceps brachii than the force task. These results suggested that comparing to the force task, the position task seemed to rely more on the slow twitch muscle fibers. Thus, the different motor control strategies for the antagonist muscle between two tasks might have contributed to the small treatment effect toward a shorter time to task failure during the position task. However, at this time we are not able to further distinguish factors such as motor unit recruitment and firing properties of the muscle involved.

Sex difference in fatigability

In addition to the results of the time to task failure between two different fatiguing tasks, another novel finding is the sex differences in fatigability. Specifically, the time to task failure was short for women than for men. This result was in contrast to previous studies which reported that time to failure was longer for women than for men in fatiguing contractions with the intensity of 20% MVC (Hunter, Critchlow, & Enoka, 2004). Hunter and colleagues (2004) suggested that sex difference in time to failure could at least partly explained by the intensity of target force. It is also worth mentioning that the majority of the previous studies have used relatively low intensity fatiguing exercise, where the blood occlusion was not necessarily complete. However, for the current investigation, it is important to point out that at relatively high intensity (50% MVC) contraction, this mechanism may not be used to explain the sex differences found from previous experiments. Based on our findings, the normalized biceps brachii EMG amplitude for women increased more rapidly than that for men during the fatiguing contractions. During a submaximal isometric fatiguing contraction, the EMG amplitude is expected to increase mainly due to the increased demand of neural drive to maintain the target force. Thus, an increased in the EMG amplitude can be caused by the recruitment of additional motor units as well as the increase of firing rate of active motor units (McManus et al., 2015). In the current study, therefore, women's less fatigue resistant is likely due to their higher demand for increased neural drive to sustain the isometric contractions.

Besides the muscle activation of the agonist muscle (biceps brachii), women also demonstrated higher EMG amplitude for antagonist muscle (triceps brachhii) than men during the fatiguing contractions. The activation of the antagonist muscles (co-activation) may contribute to time to task failure of the fatiguing contractions (Hunter et al., 2008), because the antagonist muscles help maintain the posture and joint stability, and contribute to stabilize the target joint angle during the sustained contraction (Griffith et al., 2009). According to Booghs et al. (2012), the activation of the antagonist muscle for stability in sustained fatiguing contractions may also be accompanied by a higher metabolic energy expenditure, which may cause the target muscle to become fatigued more rapidly. In addition, the net force produced by a certain joint is the amount of force generated by the agonist subtracting the amount force generated by the antagonist (Van Dyke, 2015), meaning that a more activated antagonist muscles can reduce the net force of the overall arm muscles. Based on the results of the current study, the greater EMG amplitude for triceps brachii in women possibly suggested that women's elbow joint during a sustained contraction was less stable than men, thus, greater activity of the triceps brachii was needed to improve the stability of the elbow joint. As a consequence, to maintain a certain level of net force produce by the elbow joint, a greater agonist (biceps brachii) muscle activity was required for women than for men. Therefore, the shorter time to task failure for women in this current investigation was likely due to an overall decrease in net force of the elbow joint with an increase in metabolic energy expenditure.

Conclusions

In conclusion, during submaximal isometric fatiguing contractions, the muscle activities of the women's agonist and antagonist increased quicker than those of the men's, which led to a briefer time to task failure for women. In addition, although no difference in time to task failure was found during the force task and the position task, motor control strategies for the antagonist muscles motor seems to be different. Future research should be directed to the examinations of potential different neuromuscular properties of the antagonist muscle between different fatiguing tasks.

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VITA

SUNGGUN JEON

1022 Oxford way • Oxford, MS 38655 • (662) 202-7321 • sjeon3@go.olemiss.edu

EDUCATION

M.S., Exercise science, University of Mississippi, May 2018
Thesis: Comparisons of Time to Task Failure and Muscle Activity for Two Different Submaximal Fatiguing Contractions

M.S., Physical Education, Yonsei University, February 2015
Thesis: The Effects of 8 Weeks Complex Training on Blood Vascular Endothelial Growth Factor and Angiopoietin Levels in Obese Middle Aged Women

B.A, Exercise and Health Management, Ulsan University, February 2012

TEACHING EXPERIENCE

Instructor, 2018 – present
University of Mississippi
Course: EL 156 Jogging

Teaching Assistant, 2013 – 2014
Yonsei University
Course: Exercise Physiology, Health and Exercise, Physical Fitness

Research Assistant, 2013 – 2015
Yonsei University
Frontier Research Institute of Convergence Sports Science

HONER and FELLOWSHIPS

Teaching Fellowship, 2013 – 2014
Yonsei University
Grade Enhancement Scholarship, 2009, 2011
Ulsan Univisersity
Grade Scholarship of Excellence, 2009 – 2011
Ulsan University
Academic Grade Honors, 2009, 2011
Ulsan University

PUBLICATIONS and PRESENTATIONS

Jeon, Sunggun., Jin, Chanho., & Paik, Ilyoung. (2015). The Effects of Combined Training and Dietary Control on Blood Vascular Endothelial Growth Factor and Angiopoietin Levels and PWV in Obese Middle Aged Women. The Korea Journal of Physical Education, 54(5), 791 - 801.