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Original Article

Effect of sex on torque, recovery, EMG, and MMG responses to fatigue

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Abstract

Objective: The purpose of the present investigation was to examine the effect of sex on maximal voluntary isometric contraction (MVIC) torque and the EMG and MMG responses as a result of fatiguing, intermittent, submaximal (65% of MVIC), isometric elbow flexion muscle contractions. **Methods:** Eighteen men and women performed MVIC trials before (pretest), after (posttest), and 5-min after (5-min recovery) performing 50 intermittent, submaximal isometric muscle contractions. Surface electromyographic (EMG) and mechanomyographic (MMG) signals were simultaneously recorded from the biceps brachii muscle. **Results:** As a result of the fatiguing workbout torque decreased similarly from pretest to posttest for both the men (24.0%) and women (23.3%). After 5-min of recovery, torque had partially recovered for the men, while torque had returned to pretest levels for the women. For both sexes, from pretest to posttest EMG mean power frequency and MMG amplitude decreased, but returned to pretest levels after 5-min of recovery. **Conclusions:** In the present study, there were sex-related differences in muscle fatigue that were not associated with the EMG or MMG responses.

Keywords: Electromyography, Mechanomyography, Submaximal Fatigue, Motor Control, Isokinetic

Introduction

Time-dependent changes in electromyographic (EMG) and mechanomyographic (MMG) time and frequency domain parameters have been used to describe the patterns and time course of neuromuscular responses to fatigue and make inferences regarding the motor unit activation strategies that modulate torque production during fatiguing tasks[1-4]. Specifically, it has been suggested that the amplitude of the EMG signal reflects the level of muscle activation and the frequency content is associated with muscle fiber action potential conduction velocity[5-7]. The amplitude of the MMG signal, however, can provide information regarding motor unit recruitment and the frequency content is qualitatively related to the global firing rate of the activated motor units[8-10]. Thus, simultaneous assessments of timing and patterns of responses for the amplitude and frequency characteristics of EMG and MMG signals may provide insight regarding fatigue-related changes in motor unit activation strategies.

Fatigue has been defined as "... any reduction in the force generating capacity of the total neuromuscular system regardless of the force required in any given situation" (p. 691)[11] and described as a multifaceted, task dependent process that may be manifested by reductions in torque, decreased time to exhaustion, and/or increases in perceived effort[12]. In addition, it has been demonstrated that the performance and neuromuscular responses to fatigue are intensity-specific[12,13]. For example, Orizio[8] reported that for the biceps brachii MMG amplitude (AMP) increased, remained unchanged, or decreased during sustained, isometric elbow flexion muscle contractions at submaximal intensities of 20 to 80% of maximal voluntary isometric contraction (MVIC). Furthermore, Seghers and Spaepen[2] reported that for the biceps brachii EMG median power frequency decreased at 25% of MVIC, but remained unchanged at 50% of MVIC during intermittent, isometric elbow flexion muscle contractions. Like the neuromuscular responses during submaximal mus-

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Table 1. Height, bodyweight, and age (means ± SD) for the men and women.

	Height (cm)*	Bodyweight (kg)*	Age
Men	179.8 ± 8.0	85.5 ± 7.1	23.3 ± 2.0
Women	167.1 ± 6.6	60.7 ± 5.8	22.4 ± 3.0

**p<0.05, men versus women: Men > women for height and bodyweight.*

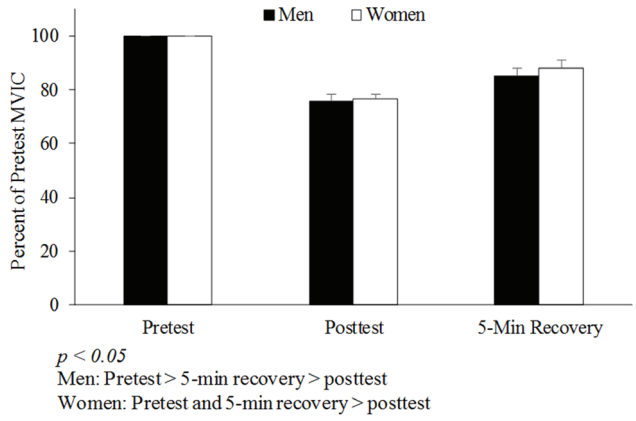

Figure 1. Pretest, posttest, and 5-min recovery mean (± standard error) torque responses for the men and women during the maximal voluntary isometric contractions (MVIC).

cle contractions, there are also intensity-specific effects on MVIC torque and the neuromuscular responses following fatiguing workbouts. Specifically, Sogaard et al[1] reported that for the biceps brachii EMG mean power frequency (MPF) decreased and remained unchanged as a result of intermittent, isometric elbow flexion muscle contractions at 10 and 30% of MVIC, respectively. There exists a need, however, to further examine MVIC torque and the EMG and MMG responses following submaximal, intermittent, isometric muscle contractions at other intensities (i.e. greater than 30% of MVIC).

It has been suggested that the mechanisms of muscle fatigue are sex-specific. Specifically, women can perform sustained muscle contractions for a longer duration of time and perform a greater number of intermittent muscle contractions than men at the same relative intensity[14-17]. The sex-related differences in muscle fatigue have been associated with differences in muscle morphology, muscle size, muscle strength, muscle blood flow, metabolic substrate utilization (i.e. greater glycolytic rates in men), and voluntary activation[15-21]. For example, it has been hypothesized[14,19] that greater glycolytic rates in men may be associated with the buildup of metabolic byproducts and, consequently, increased activity of group III and IV nerve afferents which may adversely affect muscle activation. Consistent with this hypothesis, Hakkinen[22] reported that voluntary activation decreased to a greater extent in men than women following fatiguing exercise. Contrary to these findings, however, Hunter et al[23] reported that there were no sex-related differences in voluntary activation, despite sex-related differences in MVIC torque following a fatiguing workbout. Thus, there is conflicting evidence regarding sex-related differences in voluntary activation (EMG) and motor unit activation strategies as a result of fatiguing exercise. No previous investigations, however, have examined potential sex-specific MMG responses. Thus, it is possible that the simultaneous examination of EMG and MMG may provide unique insight regarding the underlying mechanisms of sex-specific muscle fatigue. Therefore, the purpose of the present investigation was to examine the effect of sex on MVIC torque and the EMG and MMG responses as a result of fatiguing, intermittent, submaximal (65% of MVIC), isometric elbow flexion muscle contractions. Based on previous investigations[14-17], we hypothesized that men would experience greater reductions in MVIC torque and would require more time to recover following the fatiguing workbout. In addition, we hypothesized that the EMG and MMG responses would not be sex-specific[23].

Methods

Subjects

Eighteen men and women volunteered to participate in this investigation (Table 1). The subjects regularly participated in resistance training and had no known cardiovascular, pulmonary, metabolic, muscular and/or coronary heart disease, or regularly used prescription medication or nutritional supplements. The subjects visited the laboratory on 2 occasions separated by at least 48-h and were instructed not to perform upper body exercise 48-h prior to each visit. The study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

Procedures

Familiarization (Visit 1). The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, the subjects practiced MVICs and submaximal (65% of MVIC) isometric muscle contractions of the elbow flexors. The subjects visually tracked torque production using real-time torque displayed on a computer monitor programmed using LabVIEW 13.0 software (National Instruments, Austin, TX).

Determination of MVIC. During visit 2, the subjects performed a warm-up consisting of 10-15 submaximal (50-75% max) isometric muscle contractions of the dominant (based on throwing preference) elbow flexors on a calibrated Cybex II dynamometer. After 2-min of rest, the subjects performed 2, 4-s pretest MVIC trials separated by 4-s of rest at

an elbow joint angle of 115° where 180° corresponded to full extension. The highest isometric torque from the 2 trials was selected as the pretest MVIC.

Fatiguing protocol. Following the determination of the pretest MVIC, the subjects performed 50 submaximal isometric muscle contractions at 65% of their pretest MVIC. Each submaximal isometric muscle contraction was performed for 4-s followed by 4-s of rest. Like the familiarization visit, real-time torque was displayed on a computer monitor. In addition, a light bulb indicated the start and end of each repetition which was displayed on the same computer monitor as the real-time torque. Immediately after (posttest) and 5-min after (5-min recovery) completing the 50 submaximal isometric muscle contractions, the subjects performed MVIC trials using the same procedures as the pretest.

Electrode and accelerometer placements. During visit 2, a bipolar (30 mm center-to-center) surface EMG electrode (circular 4 mm diameter silver/silver chloride, BIOPAC Systems, Inc., Santa Barbara, CA) arrangement was placed on the dominant arm over the biceps brachii muscle according to the recommendations of Barbero et al[24]. A reference electrode was placed over the acromion process. Prior to each electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The MMG signal from the biceps brachii was detected using an accelerometer (Entran EGAS FT 10, dimensions: 1.0 x 1.0 x 0.5 cm, mass 1.0 g) that was placed between the proximal and distal EMG electrodes of the bipolar arrangement using double-sided adhesive tape.

Signal processing. The raw EMG and MMG signals were digitized at 1000 Hz with a 32-bit analog-to-digital converter (Model MP100, Biopac Systems, Inc.) and stored in a personal computer (ATIV Book 9 Intel Core i7 Samsung Inc., Dallas, TX) for subsequent analyses. The EMG signals were amplified (gain: x 1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA). The EMG and MMG signals were digitally bandpass filtered (zero-phase shift, fourth-order Butterworth) at 10-500 Hz and 5-100 Hz, respectively. All signal processing was performed using custom programs written with LabVIEW programming software. The EMG (μV root-mean-square, μVrms) and MMG ($m \cdot s^{-2}$) AMP and MPF (Hz) values for the MVIC muscle contractions were calculated for the middle third of each contraction. Thus, signal epochs of 1.33-s were used to calculate the AMP and MPF values of the EMG and MMG signals. This portion of the signal was selected to avoid initial gross lateral movement of the muscle at the onset of muscle contraction[8]. For the MPF analyses, each data segment was processed with a Hamming window and the Discrete Fourier transform algorithm[25,26]. The MPF was selected to represent the power spectrum in accordance with the recommendations of Hermens et al[27].

Statistical analyses

Separate 2 (Sex [men, women]) X 3 (Time [pretest, posttest, 5-min recovery]) mixed factorial ANOVAs were used to analyze the absolute MVIC torque values as well as the normalized (to pretest MVIC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF values assessed during the MVIC muscle contractions. Significant interactions were decomposed with follow-up repeated measures ANOVAs and Bonferonni-corrected independent samples t-tests. In addition, Greenhouse-Geisser corrections were applied when sphericity was not met according to Maulchy's Test of Sphericity and partial eta effect sizes (η_p^2) were calculated for each ANOVA. Independent samples t-tests were also used to compare men's versus women's height and bodyweight. All statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p<0.05$ was considered statistically significant.

Results

Torque

There was a significant ($p<0.001$, $\eta_p^2=0.623$) Time X Sex interaction for torque. In addition, there were significant ($p<0.001$, $\eta_p^2=0.869$ and $p<0.001$, $\eta_p^2=0.675$) one-way repeated measures ANOVAs for Time for both sexes. Analyses of the simple main effects for torque across Time indicated that for the men, pretest > 5-min recovery > posttest and for the women, pretest and 5-min recovery > posttest (Figure 1). The results of the independent t-tests between sexes indicated that MVIC torque was greater for the men than the women at pretest, posttest, and 5-min recovery (Figure 1). Collectively, these results indicated that men and women had similar reductions in torque (24.0% and 23.3%, respectively) from pretest to posttest, but men recovered more slowly than women (8.3% vs. 11.2%, respectively) when measured at 5-min recovery.

EMG AMP and EMG MPF

There were no significant Time X Sex interactions for EMG AMP ($p=0.468$, $\eta_p^2=0.091$), or EMG MPF ($p=0.416$, $\eta_p^2=0.104$). There were, however, significant ($p<0.001$, $\eta_p^2=0.753$) main effects for Time (collapsed across Sex) for EMG MPF (posttest and 5-min recovery > posttest) (Figure 2). Thus, there were no sex-related differences in the EMG AMP or EMG MPF responses at any of the time points. EMG MPF, however, decreased from pretest to posttest, but returned to pretest levels at 5-min of recovery.

MMG AMP and MMG MPF

There were no significant Time X Sex interactions for MMG AMP ($p=0.903$, $\eta_p^2=0.013$), or MMG MPF ($p\geq0.999$, $\eta_p^2=0.001$). There were, however, significant ($p<0.001$, $\eta_p^2=0.313$) main effects for Time collapsed across Sex) for MMG AMP (posttest > pretest) (Figure 2). Thus, there were no sex-related differences in the MMG AMP or MMG MPF responses at any of the time points. MMG AMP, however, increased from pretest to posttest, but returned to pretest levels at 5-min of recovery.

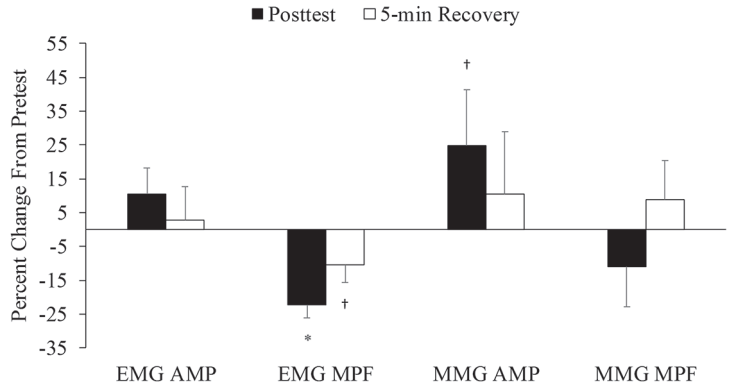

Figure 2. Posttest and 5-min recovery marginal means (± standard error), collapsed across Gender, expressed as a percent change from pretest for electromyographic amplitude (EMG AMP), EMG mean power frequency (EMG MPF), mechanomyographic (MMG) AMP, and MMG MPF assessed during the maximal voluntary isometric contractions (MVIC).
† Significant ($p < 0.05$) increase (main effect for Time). * Significant ($p < 0.05$) decrease (main effect for Time).

Table 2. MVIC torque and neuromuscular responses (mean ± SD) for pretest, posttest,and 5-min recovery.

Men	Pretest	Posttest	5-min Recovery
MVIC Torque (Nm)	86.5 ± 8.6	65.7 ± 6.3	73.6 ± 7.6
EMG AMP (μV)	975.8 ± 383.1	1128.3 ± 554.3	1060.7 ± 478.7
EMG MPF (Hz)	82.1 ± 29.0	65.7 ± 24.7	74.1 ± 21.5
MMG AMP ($m \cdot s^{-2}$)	0.71 ± 0.22	0.87 ± 0.35	0.80 ± 0.52
MMG MPF (Hz)	30.2 ± 6.6	25.2 ± 7.8	32.1 ± 7.8
Women	**Pretest**	**Posttest**	**5-min Recovery**
MVIC Torque (Nm)	40.8 ± 3.6	31.3 ± 2.1	35.9 ± 3.9
EMG AMP (μV)	678.7 ± 303.5	744.6 ± 372.3	607.1 ± 293.7
EMG MPF (Hz)	93.6 ± 12.5	69.9 ± 10.8	80.6 ± 13.0
MMG AMP ($m \cdot s^{-2}$)	0.40 ± 0.17	0.47 ± 0.21	0.39 ± 0.11
MMG MPF (Hz)	26.9 ± 7.1	23.4 ± 8.5	27.0 ± 5.2

Maximal voluntary isometric contraction (MVIC), electromyographic amplitude (EMG AMP), EMG mean power frequency (EMG MPF), mechanomyographic (MMG) AMP, and MMG MPF.

Discussion

MVIC torque responses

In the present investigation, the magnitude of the decreases in MVIC torque from pretest to posttest were the same for the men (24.0%) and women (23.3%). These findings were in agreement with those of Yoon et al[28], but were not consistent with those of Hunter and Enoka[15]. Yoon et al[28] reported that men and women fatigued equally (15.4 and 16.1%, respectively) following submaximal (80% of MVIC) intermittent isometric elbow flexion muscles contractions. Hunter and Enoka[15], however, reported small, but significant differences in the decreases in MVIC torque for men (38.7%) versus women (34.5%) following a fatiguing bout of submaximal (20% of MVIC) intermittent isometric elbow flexion muscle contractions. Sex-related differences in muscle fatigue have been attributed to differences in absolute strength between men and women, as well as the intensity at which the submaximal muscle contractions were performed[14-16]. Hunter and Enoka[15] found that individuals with greater absolute strength fatigued more rapidly than their weaker counterparts during submaximal intermittent elbow flexion muscle contractions. The sex-related differences in fatigue responses reported by Hunter and Enoka[15], however, were eliminated when the differences in MVIC torque responses were covaried for absolute muscle strength. Consistent with these findings,

2 previous investigations[29,30] reported no sex differences in the MVIC torque responses for strength-matched men and women following submaximal elbow flexion muscle contractions. Thus, fatigue-related differences may not be a function of sex, but instead due to differences in absolute strength.

It has been hypothesized[14-16] that the mechanism underlying the strength-related effect on muscle fatigue is related to muscle blood flow. Theoretically, greater absolute muscle strength increases mechanical compression of vascular beds and results in greater occlusion of blood flow and increased accumulation of metabolic byproducts[14-16]. Consistent with this hypothesis, Russ and Kent-Braun[18] demonstrated that during maximal intermittent dorsi-flexion muscle contractions, MVIC torque decreased to a greater extent in men than women, but this difference was eliminated when blood flow was occluded. In the present study, however, despite sex-related differences in absolute muscle strength, the fatigue-related decreases in MVIC torque from pretest to posttest were equal for the men and women. Therefore, it is possible that the lack of a sex-related difference in the decreases in MVIC torque in the present study was related to the intensity of the submaximal muscle contractions. For example, like the present study, Yoon et al[28] reported that MVIC torque decreased equally (15.4 and 16.1% for men and women, respectively) at a high intensity (80% of MVIC), but unlike the present study, MVIC torque decreased to a greater extent in men than women (31.6 vs. 16.7%) at a low intensity (20% of MVIC). Thus, it is likely that at 65% of MVIC, the intermittent muscle contractions in the present study were of sufficient intensity to elicit a comparable level of fatigue in both the men and women. Future studies should examine the intensity that demarcates sex-related differences in muscle fatigue during intermittent muscle contractions and the mechanism underlying this intensity-related sex difference.

After 5-min of recovery, MVIC torque returned to the pretest levels for the women (pretest = 5-min recovery), but only partially recovered for the men (5-min recovery > posttest). These findings were consistent with those of Russ and Kent-Braun[18] and Hunter et al[23] who also reported that MVIC torque recovered more fully in women than men when measured at 5- and 10-min following fatiguing exercise. It has been suggested[18-20,23] that the sex-related differences in MVIC torque recovery may be related to differences in metabolic substrate utilization between men and women. Russ et al[19] reported that men exhibited greater glycolytic activity (as evidenced by greater decreases in muscle pH) and Maughan et al[20] suggested that women rely more on oxidative metabolism for energy production during fatiguing exercise. Consistent with these findings[19,20], Hunter et al[23] found that men experienced a greater fatigue-induced reduction in resting twitch amplitude which was attributed to a greater buildup of metabolic byproducts from higher glycolytic rates. In addition, it has been reported that larger muscles require more energy and time to recover than smaller muscles[21]. Furthermore, Wust et al[31] stated that sex-related differences in fatigability "... must reside in the rate at which energy is used by the muscle fibers..." (p. 484). In the present study, the men were stronger, taller, and heavier than the women (Table 1). Thus, it is likely that the sex-related difference in MVIC torque recovery after 5-min was a function of muscle mass (men > women) as well as possible differences in metabolic substrate utilization (i.e. greater glycolytic activity in men) which may have resulted in an increased time to recover for men.

MVIC neuromuscular responses

In the present study, there were no sex-related differences for any of the EMG or MMG responses to the fatiguing, intermittent isometric workbouts when assessed during the MVIC muscle contractions. Specifically, as a result of the fatiguing workbouts, EMG MPF decreased 20.0 and 25.3% and MMG AMP increased 22.5 and 17.5% for the men and women, respectively. The EMG AMP and MMG MPF responses, however, remained unchanged for both sexes. After 5-min of recovery, EMG MPF and MMG AMP returned to the pretest levels for the men and women. The current findings were consistent with those of Hunter et al[32] who also reported no sex-related differences for EMG AMP assessed during MVIC muscle contractions following fatiguing, submaximal (50% of MVIC) intermittent finger flexion muscle contractions. The results of the present study and those of Hunter et al[32] indicated that fatiguing, submaximal intermittent isometric workbouts resulted in no sex-related differences for EMG or MMG responses from the elbow flexor or finger flexor muscles.

The EMG and MMG responses in the present study suggested that muscle activation (EMG AMP) and global motor unit firing rate (MMG MPF) assessed during the MVIC muscle contractions were unaffected by the fatiguing workbouts. Fatigue-induced decreases in action potential conduction velocity (EMG MPF), however, have been associated the buildup of metabolic byproducts[33-35], and fatigue-induced increases in MMG AMP have been associated with motor unit recruitment, synchronization, and/or decreased muscle stiffness[9,36,37]. In the present study, it is possible that the decrease in EMG MPF was a related to the buildup of metabolic byproducts, while the increase in MMG AMP was likely due to decreased muscle stiffness and not motor unit recruitment or synchronization. That is, theoretically voluntary motor unit recruitment is maximal during an MVIC muscle contraction[38,39] and, therefore, motor unit recruitment would not be expected to change from pretest to posttest. Motor unit synchronization is associated with a slowing of the firing rate[7,40,41], but in the present study MMG MPF, which reflects the global firing rate of the activated motor units remained unchanged. Muscle stiffness, however, is proportional to force production[42,43]. Thus, the decrease in MVIC torque from pretest to posttest may have led to a decrease in muscle stiffness which allowed greater oscillations of the activated muscle fibers, and, therefore, increased MMG AMP.

At 5-min of recovery, EMG MPF and MMG AMP returned to pretest levels for the men and women, while MVIC torque partially recovered for the men (posttest < 5-min recovery), but returned to pretest levels for the women (pretest = 5-min recovery). It has been reported[39,44-46] that 1- to 5-min of re-

covery was sufficient to restore action potential conduction velocity (EMG MPF) to pre-fatigued levels and may reflect the clearance of fatigue-induced buildup of metabolic byproducts following fatiguing exercise bouts. Thus, in the present study, it is possible that 5-min of recovery was adequate to reduce the buildup of metabolic byproducts within the muscle fibers and restore action potential conduction velocity to pretest levels (as indicated by EMG MPF which increased from posttest to 5-min recovery). Furthermore, the increase in MMG AMP indirectly suggested that the increase in force production (as indicated by MVIC torque which increased from posttest to 5-min recovery) resulted in an increase muscle stiffness (as indicated by MMG AMP which decreased from posttest to 5-min recovery). In the present study, for the women EMG MPF tracked the fatigue-induced decreases in MVIC torque at posttest and the recovery in MVIC torque at 5-min recovery. Thus, the EMG and MMG responses were consistent with the MVIC torque responses for women, but not for men. Specifically, for men there were dissociations between MVIC torque recovery and the EMG and MMG responses. It is possible, however, that greater muscle mass and different metabolic substrate utilization in men caused the increased time to recovery for MVIC torque, but these sex-related differences were not of sufficient magnitude to affect EMG MPF or MMG AMP which returned to pretest levels at 5-min of recovery.

Limitations of the current findings include the use of the neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) to reflect motor unit activation strategies as well as potential metabolic changes within the muscle fibers. In the present study, although metabolic byproducts were not directly measured a number of studies have assessed the time and frequency domain parameters of the EMG and MMG signals during fatiguing tasks[49-55]. It has been reported, however, that the EMG and MMG signals can be affected by physiological and non-physiological factors[7,9,56-59]. The MMG signal can also be affected by factors not related to motor unit activation strategies including muscle stiffness, intramuscular fluid pressure, and tremor[9,59-61]. Furthermore, MMG MPF is qualitatively, but not quantitatively, related to the global motor unit firing rate of the activated motor units. Therefore, the neuromuscular parameters assessed in the present study are indirect indicators of motor unit activation strategies.

In summary, within the limitations of the present study the results indicated that there was a sex-related difference in muscle strength (men > women), as well as the magnitude of recovery of MVIC torque at 5-min (women > men) following the fatiguing workbout. The sex-related differences in recovery may have been due to muscle mass, as well as metabolic differences between the men and women. There were not, however, any sex-related differences in the percent decreases in MVIC torque from pretest to posttest. In addition, there were no sex-related differences for any of the normalized EMG or MMG parameters at any of the time points. As a result of the fatiguing exercise, however, EMG MPF decreased, MMG AMP increased, while EMG AMP and MMG AMP remained unchanged for both sexes. Thus, the fatigue-induced decreases in MVIC torque may have been due to the effects of the accumulation of metabolic byproducts which affected excitation-contraction coupling and resulted in a decrease in EMG MPF, but an increase in MMG AMP. After 5-min of recovery, EMG MPF and MMG AMP returned to pretest levels which may have reflected the clearance fatigue-induced buildup of metabolic byproducts. Furthermore, for the women, but not the men, EMG MPF tracked the fatigue-induced decreases in MVIC torque at posttest and the recovery in MVIC torque at 5-min recovery.

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