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Muscle- and mode-specific responses of the forearm flexors in women as a result of fatiguing, concentric muscle actions

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Abstract

The purpose of the present investigation was to examine muscle- and mode-specific torque, electromyographic (EMG), and mechanomyographic (MMG) responses of women as a result of a fatiguing, submaximal task. Thirteen women performed concentric peak torque (PT) and isometric maximal voluntary contraction (MVC) trials before (pretest) and after (posttest) performing a fatiguing workout that consisted of 50 submaximal (65% of PT), concentric, isokinetic ($60^{\circ}\cdot s^{-1}$), forearm flexion muscle actions. There were similar decreases in PT (18.4%) and MVC (16.4%) following the fatiguing workout. From pretest to posttest, there were no changes in EMG amplitude or MMG frequency, but muscle-specific decreases in EMG frequency, and increases in MMG amplitude. In addition, there was a mode-specific (PT > MVC) effect for MMG frequency for both muscles. Thus, in women, the fatigue-related neuromuscular responses were dependent on the muscle and mode of assessment, while torque decreased similarly regardless of mode (concentric vs. isometric).

Key Words: Electromyography, mechanomyography, submaximal fatigue, motor control, isokinetic

1. Introduction

Surface electromyography (EMG) records and quantifies the action potentials that activate skeletal muscle fibers^[1]. The amplitude of the EMG signal is the linear summation of voltages from the action potential trains and is influenced by the number of active motor units, their firing rates, and synchronization^[1, 2]. The power density spectrum describes the frequency content of the EMG signal and is, in part, determined by average muscle fiber action potential conduction velocity^[3] and the shape of the action potential waveforms^[4]. Mechanomyography (MMG) has been described as the mechanical counterpart of motor unit activity as measured by EMG^[5]. MMG quantifies the lateral oscillations of activated muscle fibers that are generated by the: (a) gross lateral movement of the muscle at the initiation of a contraction generated by the non-simultaneous activation of muscle fibers; (b) smaller subsequent lateral oscillations generated at the resonant frequency of the muscle; and (c) dimensional changes of the active fibers^[6]. It has been suggested that under some conditions, the amplitude of the MMG signal is related to motor unit recruitment and the frequency content is related to the global firing rate of the activated, unfused motor units^[6-8].

Simultaneous measurements of EMG and MMG have been used to examine various aspects of muscle function including electromechanical and phonomechanical delay^[9], muscle fiber type distribution patterns^[10], muscle atrophy^[11], and excitation-contraction coupling associated with muscle fatigue^[12]. Clinically, EMG and MMG measurements have been used in pediatric, adult, and geriatric populations to examine neuromuscular disorders such as myotonic dystrophy^[13], mandibular disorders^[14], low back pain^[15], cerebral palsy^[16], and to control prostheses^[17]. A unique application of the simultaneous measurements of EMG and MMG is to examine the dissociation between the electrical and mechanical aspects of fatigue. Most EMG and MMG studies of fatigue have utilized maximal isometric or dynamic muscle actions^[10, 18-27]. Collectively, these investigations have indicated that the fatigue-related changes in the time and frequency domain parameters of EMG and MMG signals as a result of repeated maximal muscle actions can be affected by the mode of muscle action employed

(isometric vs. concentric vs. eccentric), the muscles involved, and the gender of the subjects. Most sport- and work-related activities, however, involve predominately submaximal movements. Thus, understanding the fatigue-related neuromuscular responses associated with repeated submaximal muscle actions may contribute to the ability to design training programs to: (a) improve athletic performance [10, 20, 22, 27-31], (b) reduce sport- and work-related musculoskeletal injuries [32-34], and (c) facilitate rehabilitation following injury [32-34]. Therefore, the purpose of the present investigation was to examine muscle- and mode-specific torque, EMG, and MMG responses of women as a result of a fatiguing, submaximal task. Based on previous investigations [27, 35], we hypothesized that torque, EMG mean power frequency (MPF), MMG amplitude (AMP), and MMG MPF would decrease as a result of the 50 submaximal, concentric muscle actions, while EMG AMP would remain unchanged.

2. Materials and Methods

2.1 Subjects

Thirteen women (mean age \pm SD = 23.0 \pm 3.24 yrs; body weight = 62.9 \pm 6.5 kg; height = 168.3 \pm 7.1 cm) volunteered to participate in this investigation. The subjects regularly participated in resistance training (6.6 \pm 4.0 hrs per wk) and had no known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease, or regularly used prescription medication. 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.

2.2 Procedures

Familiarization. The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, the subjects performed submaximal and maximal concentric, isokinetic ($60^\circ \cdot s^{-1}$) and isometric muscle actions of the forearm 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) and practiced performing concentric, isokinetic muscle actions at 65% of concentric peak torque (PT).

Determination of Concentric PT and Isometric Maximal Voluntary Contraction (MVC). During visit 2, the subjects performed a warm-up consisting of 10 – 15 submaximal (approximately 50 – 75% of PT), concentric, isokinetic muscle actions of the dominant (based on throwing preference) forearm flexors at $60^\circ \cdot s^{-1}$ on a calibrated Cybex II dynamometer. After 2-min of rest, the subjects randomly performed 5 PT and 5 MVC trials. The concentric muscle actions were performed at $60^\circ \cdot s^{-1}$ through a 90° range of motion and the isometric muscle actions were performed for 4-s at an elbow joint angle of 115° where 180° corresponded to full extension [36-39]. The highest values were selected as the pretest PT and MVC, respectively.

Determination of Submaximal, Concentric Muscle Actions. Following the determination of the pretest PT and pretest MVC, the subjects performed 50 submaximal (65% of their pretest concentric PT), concentric, isokinetic muscle actions at $60^\circ \cdot s^{-1}$. 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. After completing the 50 submaximal, concentric muscle actions, the subjects randomly performed 5 posttest PT and 5 posttest MVC trials using the same procedures as the pretest.

Electrode and Accelerometer Placements. During visit 2, bipolar (30 mm center-to-center) surface EMG electrode (circular 4 mm diameter silver/silver chloride, BIOPAC Systems, Inc.) arrangements were placed on the dominant arm over the biceps brachii (BB) and brachioradialis (BR) muscles according to the recommendations of Barbero *et al.*, [40]. The 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 BB and BR were detected using accelerometers (Entran EGAS FT 10, dimensions: 1.0 x 1.0 x 0.5 cm, mass: 1.0 g) that were placed between the proximal and distal EMG electrodes of each of the bipolar arrangement using double-sided adhesive tape.

Signal Processing. The raw EMG and MMG signals were digitized at 1000 Hz with a 12-bit analog-to-digital converter (Model MP100, Biopac Systems, Inc.) and stored in a personal computer (ATIV Book 9 Intel Core i7 Samsung Inc.) for subsequent analyses. The EMG signals were amplified (gain: x 1000) using differential amplifiers (EMG 100, Biopac Systems, Inc.). The EMG and MMG signals were digitally bandpass filtered (fourth-order Butterworth, zero-phase shift) at 10 – 500 Hz and 5 – 100 Hz, respectively. All signal processing was performed using custom programs written with the LabVIEW programming software. The EMG (μV root-mean-square, μV_{rms}) and MMG ($m \cdot s^{-2}$) AMP and MPF (Hz) values for the concentric and isometric muscle actions were calculated for the middle third of each contraction. Thus, during the concentric and isometric muscle actions signal epochs of 0.50-s and 1.33-s were used, respectively, to calculate the AMP and MPF values of the EMG and MMG signals. These portions of the signals were selected to avoid the acceleration and deceleration phases that are typical of isokinetic dynamometers [41] and to avoid the initial gross lateral movement of the muscle at the onset of muscle contraction [6]. For the MPF analyses, each data segment was processed with a Hamming window and the Discrete Fourier transform (DFT) algorithm [42, 43]. The MPF was selected to represent the power spectrum in accordance with the recommendations of Hermens *et al.*, [44].

2.3 Statistical Analyses

A 2 (Mode [PT, MVC]) X 2 (Time [pretest, posttest]) repeated measures ANOVA was used to analyze the absolute PT and MVC. In addition, Separate 2 (Muscle [BB, BR]) X 2 (Mode [PT, MVC]) X 2 (Time [pretest, posttest]) repeated measures ANOVAs were used to analyze the normalized (to pretest MVC) EMG AMP, EMG MPF, MMG AMP, and MMG MPF values assessed during the PT and MVC muscle actions. Partial eta squared effect sizes (η_p^2) were calculated for each ANOVA and significant 3-way interactions were decomposed with follow-up repeated measures ANOVAs, and significant 2-way interactions were decomposed with follow-up, Bonferroni-corrected dependent samples t-tests. All statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p \leq 0.05$ was considered statistically significant.

3. Results

Table 1 and Figures 1 and 2 provide the pretest versus posttest responses for torque and the normalized neuromuscular

parameters during the PT and MVC muscle actions. There was no significant Mode X Time interaction for torque ($p = 0.709$, $\eta_p^2 = 0.012$). There were, however, significant main effects for Mode (MVC > PT; $p = 0.001$, $\eta_p^2 = 0.637$) and Time (pretest > posttest; $p < 0.001$, $\eta_p^2 = 0.973$) (Table 1).

Table 1. Means \pm SD for pretest versus posttest concentric peak torque (PT) and isometric maximal voluntary contraction (MVC).

	Pretest	Posttest
Concentric PT (Nm)	42.6 \pm 6.3 ^a	34.7 \pm 6.0
Isometric MVC (Nm)	50.5 \pm 6.1 ^{ab}	42.2 \pm 7.3 ^b

a. Significant at $p \leq 0.05$ for pretest > posttest

b. Significant at $p \leq 0.05$ for isometric MVC > concentric PT

There were no significant interactions or main effects ($p = 0.098 - 0.888$, $\eta_p^2 = 0.002 - 0.212$) for EMG AMP (Figure 1a). There was a significant 3-way interaction ($p = 0.025$, $\eta_p^2 = 0.353$) for EMG MPF and follow-up Muscle X Time repeated measures ANOVAs indicated a significant ($p = 0.003$, $\eta_p^2 = 0.528$) 2-way interaction during the MVC muscle actions, but no significant ($p = 0.995$, $\eta_p^2 < 0.001$) 2-way interaction during the PT muscle actions for EMG MPF. Dependent samples t-tests indicated that during the MVC muscle actions, there were significant simple main effects for the BB (pretest > posttest) (Figure 1b) and at posttest (BR > BB) for EMG MPF. In addition, during the PT muscle actions there was a significant ($p = 0.025$, $\eta_p^2 = 0.353$) main effect for Time (pretest > posttest) (Figure 1b).

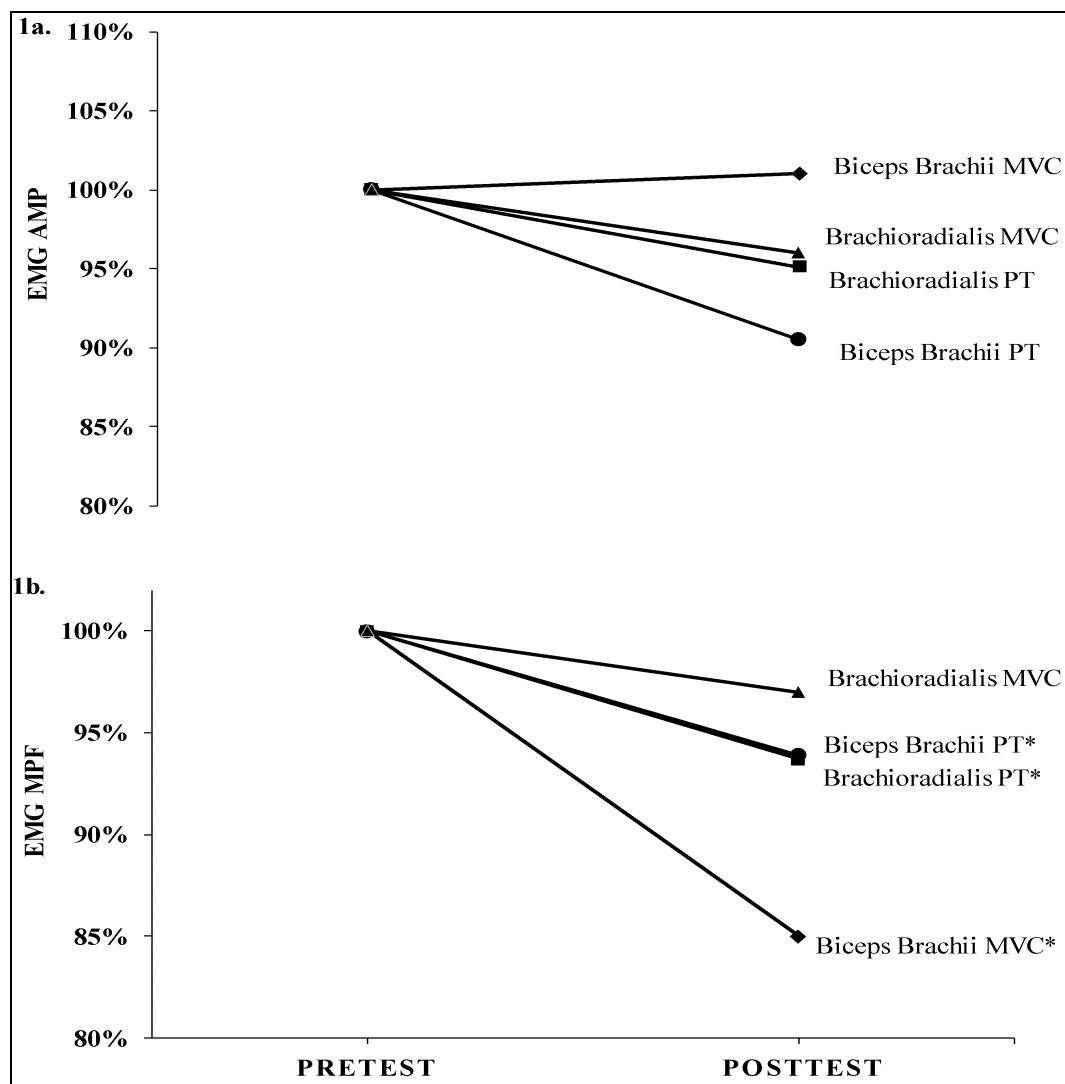


Fig 1a-b: The composite results from the pretest versus posttest analyses (expressed as percent of pretest) for electromyographic amplitude (EMG AMP; Figure 1a) and EMG mean power frequency (EMG MPF; Figure 1b) during the concentric peak torque (PT) and isometric maximal voluntary contraction (MVC) muscle actions from the biceps brachii and brachioradialis.

*Significant at $p \leq 0.05$ for pretest > posttest.

There were no significant 3-way interactions for MMG AMP ($p = 0.951$, $\eta_p^2 < 0.001$) or MMG MPF ($p = 0.805$, $\eta_p^2 = 0.005$). There were, however, significant 2-way interactions for MMG AMP (Muscle X Time; $p = 0.006$, $\eta_p^2 = 0.482$) and MMG MPF (Muscle X Mode; $p = 0.028$, $\eta_p^2 = 0.344$). For MMG AMP, collapsed across Mode, there was no significant 2-way interaction ($p = 0.110$, $\eta_p^2 = 0.119$), but there were significant

main effects for Time (posttest > pretest; $p = 0.008$, $\eta_p^2 = 0.453$) (Figure 2a) and Muscle (BR > BB; $p = 0.004$, $\eta_p^2 = 0.506$). For MMG MPF, collapsed across Time, there was no significant 2-way interaction ($p = 0.924$, $\eta_p^2 = 0.001$), but there was a significant ($p = 0.003$, $\eta_p^2 = 0.524$) main effect for Mode (PT > MVC).

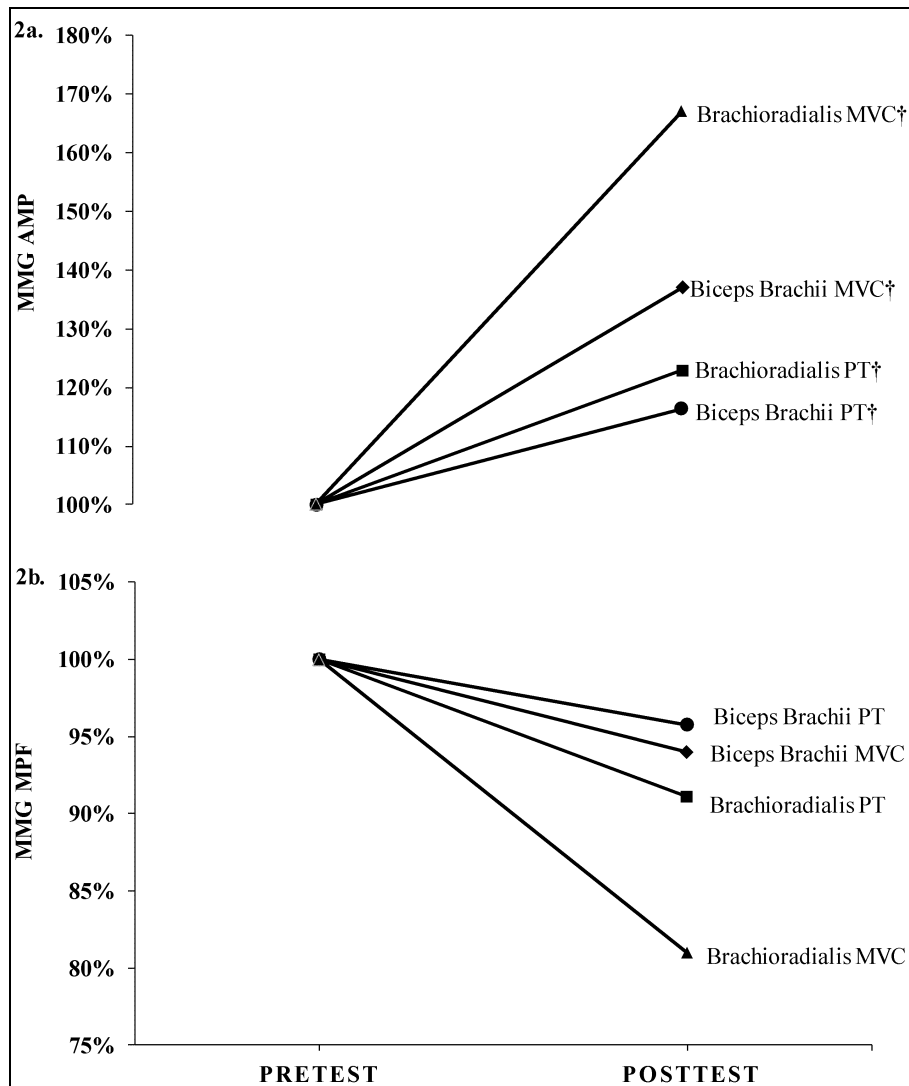


Fig 2a-b: The composite results from the pretest versus posttest analyses (expressed as percent of pretest) for mechanomyographic amplitude (MMG AMP; Figure 2a) and MMG mean power frequency (MMG MPF; Figure 2b) during the concentric peak torque (PT) and isometric maximal voluntary contraction (MVC) muscle actions from the biceps brachii and brachioradialis.

†Significant at $p \leq 0.05$ for pretest < posttest.

4. Discussion

4.1 Torque

The results of the present study indicated that there was no mode-specific effect for percent decline in maximal torque following the submaximal fatiguing workout in women. That is, even though the fatiguing workout involved concentric, isokinetic muscle actions, there was no difference in the percent declines in PT (18.4%) versus isometric MVC (16.4%). These findings were consistent with our previous study in men [35] that reported a 23.3% decline in PT and a 17.8% decline in MVC as a result of 50 submaximal, concentric, isokinetic, forearm flexion muscle actions. Furthermore, following 30 maximal, concentric, isokinetic, leg extension muscle actions, Camic [27] reported a 20.3% decline in PT and a 16.5% decline in MVC in women. Thus, the results of the present study in conjunction with those of Hill [35] and Camic [27] indicated similar decreases in PT and MVC following both submaximal and maximal, fatiguing, concentric workouts for both genders.

4.2 Pretest versus Posttest EMG and MMG Responses.

During the PT muscle actions, the pretest versus posttest EMG and MMG responses from the BB and BR were the same (EMG AMP = no change, EMG MPF = decreased, MMG AMP = increased, and MMG MPF = no change). During the

MVC muscle actions, however, 3 of the 4 neuromuscular parameters responded the same for both muscles (EMG AMP = no change, MMG AMP = increased, and MMG MPF = no change), while EMG MPF decreased for the BB, but remained unchanged for the BR. These findings were in partial agreement with those of Hill [35] who reported no change in EMG AMP, MMG AMP, or MMG MPF, but mode-specific responses for EMG MPF from the BB in men. It is possible that the gender-specific difference in fatigue-related MMG AMP responses between the current findings in women and those of Hill [35] in men were due to differences in absolute strength. Theoretically, greater absolute muscle strength increases mechanical compression of vascular beds, which results in greater occlusion of blood flow and increases intramuscular fluid pressure [26, 45, 46]. Increased intramuscular fluid pressure from repeated and prolonged muscle actions can decrease muscle compliance [47] and restrict the lateral oscillations of the activated muscle fibers, and thereby, affect fatigue-related MMG AMP responses [25]. Thus, the increase in MMG AMP for women in the present study suggested that, unlike the findings of Hill [35] for men, blood flow occlusion and increased intramuscular pressure were not sufficient to restrict the lateral oscillations of the active muscle fibers. Fatigue-induced increases in MMG AMP have been associated with motor unit recruitment, synchronization, and/or decreased

muscle stiffness [8, 36, 37]. Theoretically, however, voluntary motor unit recruitment is maximal or near maximal during PT and MVC muscle actions [20, 4]. Motor unit synchronization is associated with a slowing of the firing rate of the activated motor units to optimize force production [1, 48, 49] and muscle stiffness is a function of the number of attached cross-bridges [50, 51]. A recent investigation [52], however, has questioned the validity of motor unit synchronization as a motor unit activation strategy and has referred to it as an “epiphenomenon” (p. 178). Specifically, Kline and De Luca [52] suggested that motor unit synchronization decreases with the progression of fatigue and with increasing force production. Therefore, the fatigue-induced increases in MMG AMP were likely a function of decreased muscle stiffness. That is, the effects of the accumulation of metabolic byproducts on excitation-contraction coupling (as evidenced by the decreases in PT and MVC) decreased muscle stiffness, which allowed greater oscillations of the activated muscle fibers, and therefore, increased MMG AMP [8].

In the present study, the neuromuscular responses suggested that muscle activation (EMG AMP) and global motor unit firing rate (MMG MPF) were unaffected by the fatiguing workout when assessed during the PT and MVC muscle actions. Fatigue-induced decreases in action potential conduction velocity (EMG MPF), however, have been associated with the buildup of metabolic byproducts such as lactate, inorganic phosphate, and ammonia which interfere with contractile properties of the activated muscle fibers [53-57]. Although there is disagreement [58, 59], the effect of lactate and inorganic phosphate accumulation on force production may be due to the effects on calcium release and reuptake by the sarcoplasmic reticulum, actin-myosin binding affinity, troponin-calcium binding affinity, ATP breakdown via ATPase, and ATP production in the metabolic pathways [56]. In addition, ammonia accumulation during exercise can adversely affect action potential propagation [54, 57]. Thus, it is possible that the fatigue-induced decreases in EMG MPF reflected the buildup of metabolic byproducts which may have caused excitation-contraction coupling failure which led to the decreases in PT and MVC.

4.3 Pretest versus Posttest Muscle-Specific EMG and MMG Responses during the PT and MVC Muscle Actions.

There were muscle-specific (BB vs. BR) responses as a result of the submaximal, fatiguing, concentric, isokinetic workout for EMG MPF and MMG AMP, but not for EMG AMP or MMG MPF. Specifically, during the MVC muscle actions, EMG MPF decreased from pretest to posttest for the BB, but remained unchanged for the BR. Thus, at posttest, EMG MPF was greater for the BR than the BB. During the PT and MVC muscle actions, MMG AMP increased for both muscles, but MMG AMP was greater for the BR than the BB. These findings were not consistent with the neuromuscular responses to fatiguing, isometric workouts [60]. For example, following 60 intermittent, submaximal (25 and 50% of MVC), forearm flexion muscle actions, Seghers and Spaepen [60] reported that EMG AMP and EMG median frequency (MDF) increased and decreased, respectively, for both the BB and BR when assessed during isometric muscle actions performed at 75% of MVC. The differences between the present study and those of Seghers and Spaepen [60] may be related to the mode of the fatiguing workouts (concentric isokinetic vs. isometric fatigue), the intensity of the fatiguing workouts (65 vs. 25 and 50% of MVC), and/or the assessment of neuromuscular responses at MVC vs. 75% of MVC. Together, these findings

indicated that fatigue-induced neuromuscular parameters can be affected by the muscles involved, the mode of muscle actions, and the intensity of the fatiguing workouts.

The muscle-specific responses for EMG MPF and MMG AMP may have been due to the joint angle at which PT and MVC were assessed [61-64]. Specifically, in the present study, PT was assessed over a 30° range of motion (120 – 150°, where 180° corresponds to full extension) and MVC was assessed at a joint angle of 115°. It has been reported [63, 64], however, that there are joint angle-specific neuromuscular responses for the BR. For example during PT muscle actions, Nakazawa *et al*, [64] reported that the BR was less activated (as a percentage of peak activation) than the BB through a 120 – 150° range of motion. Furthermore, Nakazawa *et al*, [64] reported that EMG AMP from the BR decreased significantly from a joint angle of 90° to 135 and 170° during MVC muscle actions. Therefore, in the present study, it is possible that the BR was less activated than the BB during the submaximal, fatiguing muscle actions at 65% of PT which accounted for the fatigue-induced decrease in EMG MPF for the BB, but not the BR. It is also possible that the differences in muscle activation between the BB and BR contributed to the muscle-specific MMG AMP responses. For example, less activation of the BR would allow greater oscillations of the activated muscle fibers, thereby, increasing MMG AMP relative to the more highly activated BB [50]. Therefore in the present study, the joint angle at which PT and MVC were assessed likely contributed to the muscle-specific responses for EMG MPF and MMG AMP.

4.4 Pretest versus Posttest Mode-Specific EMG and MMG Responses during the PT and MVC Muscle Actions.

There were no mode-specific (PT vs. MVC muscle actions) responses as a result of the submaximal, fatiguing, concentric, isokinetic workout for EMG AMP, EMG MPF, or MMG AMP, but there was a mode-specific response for MMG MPF which was greater during the PT than MVC muscle actions for the women in the present study. These findings were in partial agreement with Hill [35] who reported no mode-specific (PT vs. MVC muscle actions) responses for EMG AMP, MMG AMP, or MMG MPF, but mode-specific EMG MPF responses from the BB in men. Specifically, in men [35], there were no pretest vs. posttest changes in EMG AMP, MMG AMP, or MMG MPF, but a decrease in EMG MPF during the PT muscle actions that was not evident during the MVC muscle actions. Furthermore, in women, Camic [27] reported that MMG MPF was greater during PT than MVC muscle actions following a maximal, fatiguing, concentric, isokinetic workout, while there were no mode-specific responses for EMG AMP, EMG MPF, or MMG AMP. Collectively, these findings indicated that mode-specific responses to fatigue for women were primarily associated with motor unit firing rate (MMG MPF) which was greater during PT than MVC muscle actions. For men, the mode-specific responses to fatigue were primarily associated with action potential conduction velocity (EMG MPF) which decreased during PT muscle actions, but remained unchanged during MVC muscle actions. Thus, mode-specific responses as a result of fatiguing workouts may provide insight regarding gender-related differences in motor unit activation strategies.

5. Conclusions

The results of the present study indicated similar decreases in PT (18.4%) and MVC (16.4%) following the submaximal fatiguing workout. Furthermore, during the PT muscle actions, EMG AMP and MMG MPF remained unchanged,

MMG AMP increased, and EMG MPF decreased from pretest to posttest for both the BB and BR muscles. During the MVC muscle actions, however, EMG AMP and MMG MPF remained unchanged, MMG AMP increased, and EMG MPF decreased for the BB, but remained unchanged for the BR from pretest to posttest. The fatigue-induced decreases in EMG MPF were likely due to the buildup of metabolic byproducts. The increases in MMG AMP, however, likely reflected decreased muscle stiffness (as evidenced by the decreases in PT and MVC) which allowed greater oscillations of the activated muscle fibers. In the present study, there were muscle-specific (BB vs. BR) responses for EMG MPF and MMG AMP which may have been due to the effects of joint angle on muscle activation. Specifically, it is possible that the BR was less activated (as a percentage of peak activation) than the BB during the fatiguing workout which accounted for the fatigue-induced decrease in EMG MPF for the BB, but not the BR. In addition, a lower level of activation for the BR would allow greater oscillations of the activated muscle fibers, thereby, increasing MMG AMP relative to the more highly activated BB. In the present study, there was also a mode-specific (PT vs. MVC muscle actions) effect for MMG MPF which was greater during the PT than MVC muscle actions for women. These findings, in conjunction with Camic [27], suggested that mode-specific responses to fatigue in women were primarily associated with motor unit firing rate (MMG MPF) which was greater during PT than MVC muscle actions.

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