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Original Article

Sex differences for fatigue-induced changes in muscle blood flow, but not eccentric peak torque or neuromuscular responses

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Abstract

Objectives: The purpose of this study was to examine the effects of exercise intensity and strength on sex-related differences in eccentric peak torque (PT), muscle blood flow, and neuromuscular responses following fatiguing, submaximal forearm flexion eccentric protocols. **Methods:** Thirty-six subjects were stratified by sex and strength into 4 equal groups and randomly performed fatiguing eccentric, isokinetic ($180°\cdot s^{-1}$), forearm flexion protocols at 40% or 80% of eccentric PT. Eccentric PT, muscle blood flow, and neuromuscular responses were measured prior to (pretest), immediately (posttest), and 5-min after (5-min recovery) performing the fatiguing protocols. **Results:** There was no sex-, intensity-, or strength-related difference in the magnitude of decrease in eccentric PT at posttest (80.0% of pretest) or the magnitude of recovery at 5-min (87.8% of pretest). Muscle blood flow increased similarly for men (139.8% of pretest) and women (178.7% of pretest) at posttest, but the magnitude of recovery was greater for the women (62.9%) than the men (41.4%). The neuromuscular responses were not affected by sex-, intensity-, or strength-related differences. **Conclusions:** These findings indicated that there were few sex-related differences in eccentric PT, muscle blood flow, and neuromuscular responses as a result of the fatiguing eccentric protocols performed at a high or low intensity of exercise.

Keywords: Gender, Motor Control, Isokinetic, Muscle Fatigue, Muscle Damage

Introduction

Human muscle fatigue is of great interest to researchers, clinicians, and athletes. Typically, muscle fatigue results in reduced maximal torque production, decreased time to exhaustion, and increased perceived effort[1]. Muscle fatigue also affects neuromuscular responses and the motor unit activation strategy used to modulate force production. Specifically, surface electromyography (EMG) records and quantifies the action potentials that activate skeletal muscle fibers. During fatiguing submaximal exercise, there are increases in EMG amplitude, but decreases in EMG mean power frequency[2]. These responses have been attributed to increases in motor unit recruitment, firing rate, and/or synchronization (EMG amplitude) and decreases in action potential conduction velocity (EMG mean power frequency)[2]. Mechanomyography (MMG), the mechanical counterpart of motor unit electrical activity as measured by EMG[3], has also been used to describe the intensity-dependent processes of muscle fatigue. For example, previous investigations[4,5] have reported that during low exercise intensities (10-60% of maximum), MMG amplitude tends to increase with the development of muscle fatigue, but at higher intensities (>80% of maximum), MMG amplitude decreases or remains unchanged. It has been suggested that the increases in MMG amplitude at low intensities reflect increases in motor unit recruitment, while at higher intensities it is speculated that MMG amplitude plateaus or decreases due to decreases in muscle compliance which is inversely related to force production[4]. In addition, MMG mean power frequency is qualitatively related to global motor unit firing rate and typically decreases with the progression of muscle fatigue

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that may reflect the effects muscle wisdom, motor unit synchronization, and/or increases in motor unit recruitment as explained by the Onion-Skin Scheme[6-8].

Muscle fatigue, however, is manifested uniquely in men versus women. For example, it has been well established that women are less susceptible to the effects of muscle fatigue during concentric and isometric exercise[9,10]. The sex-specific differences in fatigue responses during concentric and isometric exercise may be due to muscle blood flow and have been associated with a number of factors including: the intensity of the fatiguing task, the rest period between repetitions, strength differences, speed of contraction, and the muscle groups involved[9,10]. For example, Maughan et al,[11] reported that at intensities of 50, 60, and 70% of one-repetition maximum, women performed a greater number of forearm flexion muscle actions than men, but at 80 and 90% of one-repetition maximum there were no sex-related differences in the number of repetitions completed to failure. Furthermore, at a low intensity of exercise (20% of isometric peak torque), Yoon et al,[12] reported that women performed a greater number of isokinetic ($60°·s^{-1}$), forearm flexion muscle actions than men. Senefeld et al[13], however, reported that men and women experienced similar reductions in maximal voluntary isometric contraction force and EMG amplitude of the forearm flexors, but men experienced greater reductions in maximal voluntary isometric contraction (MVIC) and EMG amplitude than women for the knee extensors as a result of maximal velocity concentric muscle actions at 50% of one-repetition maximum. Furthermore, Hunter and Enoka[14] found that men fatigued more rapidly than women as a result of submaximal intermittent forearm flexion muscle actions, but this sex-specific response was eliminated when covaried for differences in absolute muscle strength. Similarly, Russ and Kent-Braun[15] reported that men experienced greater reductions in MVIC force following maximal intermittent dorsi-flexion muscle actions during non-ischemic conditions, but there were no sex differences when blood flow was occluded.

During eccentric muscle actions, the mechanisms underlying sex-specific fatigue responses may be different. For example, Power et al,[16] reported no sex-related differences in the magnitude of MVIC decrease following 150 maximal eccentric muscle actions[16], but power decreased to a greater extent in women than men under these same conditions. Other investigations, however, have reported greater fatigue-induced decreases in MVIC for women than men following submaximal[17] or maximal[18] eccentric muscle actions. Furthermore, the examination of sex-specific fatigue responses to eccentric exercise is of particular interest due to the unique characteristics of eccentric exercise that has application in both athletic and clinical settings. For example, eccentric muscle actions are characterized by greater maximal force production and are more mechanically efficient compared to concentric and isometric muscle actions[19-21]. While there has been considerable debate regarding the underlying mechanisms mediating this phenomenon, there is compelling evidence that the structural protein titin contributes to the enhanced force production and lower metabolic cost associated with eccentric exercise[19].

The fatigue resistant nature and lower metabolic requirements of eccentric exercise are particularly favorable for individuals with reduced exercise tolerance[20]. In addition, eccentric training has been demonstrated to reduce the risk of sports injuries by inducing a shift in the optimal angle of force production[22,23]. Despite the athletic and clinical applications of eccentric training, little is known regarding the potential sex-specific effects of eccentric muscle fatigue. For example, it has not been determined if sex differences exist during fatiguing eccentric exercise and if potential sex differences mediated by similar mechanisms as concentric and isometric exercise (i.e. muscle blood flow, muscle strength, exercise intensity). Thus, the purpose of this study was to examine the effects of exercise intensity and strength on sex-related differences in eccentric peak torque (PT), muscle blood flow, and neuromuscular responses following fatiguing, submaximal eccentric forearm flexion protocols. Based on the intensity and sex-specific responses observed during concentric and isometric exercise[11,12], we hypothesized that there would be sex-specific differences in PT production following the 40% fatiguing protocol, but no sex-specific differences following the 80% fatiguing protocol. Furthermore, we hypothesized that the sex-specific differences would be a function of muscle blood flow and muscle strength[9,10]. Finally, we hypothesized that MMG amplitude would track the sex-related differences in maximal torque production, but there would be no changes in EMG amplitude.

Methods

Subjects

Twenty men and 20 women volunteered to participate in this investigation, but 2 of the men and 2 of the women withdrew from the study due to time considerations. Thus, the data from 18 men (n=18; mean age±SD=23.2±3.0 yrs; body mass=85.4±12.1 kg; height=179.6±8.2 cm; resistance training=6.9±2.8 $hrs·wk^{-1}$) and 18 women (n=18; mean age±SD=22.4±1.7 yrs; body mass=63.6±8.2 kg; height=167.1±5.9 cm; resistance training=6.5±3.5 $hrs·wk^{-1}$) were used for subsequent analyses. The subjects had no known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease, or regularly used prescription medication. In addition, all subjects had been actively participating in resistance training for at least the past 6 months. The subjects visited the laboratory on 3 occasions (familiarization and 2 testing visits) separated by at least 72-h within a one-month period and performed the testing procedures at the same time of day. The subjects were instructed to avoid performing upper body exercise 48-h prior to the testing visit and subjects were rescheduled if they were currently experiencing any muscle soreness (score of 2 or greater) as determined by a visual analog scale[24]. 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. 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 isometric muscle actions as well as submaximal and maximal eccentric isokinetic muscle actions of the forearm flexors at a velocity of 180°·s^{-1}. To familiarize the subjects with the fatiguing protocols, the subjects practiced performing eccentric isokinetic muscle actions at 40% and 80% of their eccentric PT which was visually tracked using real-time torque displayed on a computer monitor.

Determination of Eccentric PT. During testing visits 1 and 2, the subjects performed a warm-up consisting of 3 sets of 10 repetitions of eccentric-concentric muscle actions of the dominant (based on throwing preference) forearm flexors with 1-min of rest between sets. Each repetition was performed at a velocity of 180°·s^{-1} on the calibrated isokinetic dynamometer at approximately 50% effort. Following the warmup, the subjects rested for 5 minutes and then randomly performed 2 maximal eccentric isokinetic muscle actions and 2 maximal isometric muscle actions to determine the eccentric PT and MVIC values. The eccentric muscle contractions were performed through a 90° range of motion (90-0° of forearm flexion, where 0° corresponds to full extension at the elbow). The MVIC muscle actions were performed at a joint angle of 45° and each MVIC trial was sustained for 3-s. The pretest MVIC muscle actions were used for normalization purposes[25]. Peak torque trials were also performed immediately (posttest) and 5 minutes after (5-min recovery) completing the fatiguing protocol. The posttest and 5-min recovery eccentric PT trials were performed using the same procedures as the pretest trials.

Fatiguing Protocols at 40% and 80% of Eccentric PT. Following the determination of the pretest eccentric PT, the subjects randomly (on separate visits) performed a fatiguing eccentric protocol at either 40% or 80% of their pretest eccentric PT at a velocity of 180°·s^{-1}. Real-time torque was displayed on a computer monitor and each eccentric contraction was followed by a passive concentric muscle action that was assisted by the investigator. To control for the potential fatigue-related effects of exercise volume, the subjects performed 72 consecutive repetitions during the 40% fatiguing protocol and 36 consecutive repetitions during the 80% protocol.

Electromyographic and Mechanomyographic Measurements. During testing visits 1 and 2 pre-gelled surface electrodes (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) were placed in a bipolar arrangement (30 mm center-to-center) on the dominant arm over the biceps brachii according to the recommendations of Barbero et al,[26]. The reference electrode was placed over the acromion process and prior to each electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The MMG signals from the biceps brachii were 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. The raw EMG and MMG signals were digitized at 2,000 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 1,000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA). 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 in LabVIEW (National Instruments, Austin, Texas) using custom written programs. The amplitude of the EMG (μV root-mean-square, μVrms) and MMG (m·s^{-2}) signals as well as the mean power frequency (Hz) values for the eccentric muscle actions were calculated from 30-60° of flexion at the elbow (0° corresponds to full extension at the elbow). Thus, signal epochs of 0.17-s (333 data points) were selected from the middle of the original 0.5-s (1,000 data points) signal epoch used to calculate the EMG and MMG values associated with the eccentric muscle actions. Similarly, the EMG and MMG values during the MVIC muscle actions were calculated for a time period that corresponded to 1-s (2,000 data points) over the middle one-third of the muscle action. These portions of the signals were selected to avoid the acceleration and deceleration phases that are typical of isokinetic dynamometers[27] and to avoid the initial gross lateral movement that occurs at the onset of a muscle action[4].

Ultrasound Measurements. Muscle blood flow was assessed via ultrasound prior to, immediately after (within 57±8 s), and 5 minutes (298±3 s) after completing the fatiguing protocol. Ultrasound images of the dominant forearm flexors were obtained using brightness mode (B-mode) and blood flow was assessed from the brachial artery proximal to the antecubital fossa[28] using Pulsed Wave Doppler at a repetition frequency of 10MHz obtained using an ultrasound-imaging device (GE Logiq e, USA) and a multi-frequency linear-array probe (12L-Rs; 5-13MHz; 38.4 mm field-of-view). All blood flow measurements were assessed at an insonation angle of 60° to the brachial artery collected over a period of 3 cardiac cycles[29,30] and derived from arterial cross-sectional area (arterial diameter^2 × 0.785) and time averaged flow velocity based on previous recommendations[31]. All measurements were taken while the subjects were lying in the supine position on the isokinetic dynamometer with both their arms and legs supported. Great care was taken to ensure that consistent, minimal pressure was applied with the probe to limit compression of the artery.

Table 1. Group stratification of the men and women by pretest eccentric peak torque. Each group of men and women was divided equally into 2 groups of strong men (or strong women) and less strong men (or less strong women Thus, 4 groups (strong men, less strong men, strong women, and less strong women) of nine were created, stratified by muscle strength according to their pretest eccentric peak torque values.

Group	Eccentric Peak Torque (Nm)			
	40% Protocol		80% Protocol	
	Mean	Range	Mean	Range
Less Strong Women	35.0 ± 3.8	28.1 - 40.2	33.4 ± 4.8	25.9 - 39.3
Strong Women	46.3 ± 3.5	41.6 - 51.1	46.3 ± 3.2	40.5 - 50.0
Less Strong Men	65.4 ± 6.9	56.7 - 76.0	63.5 ± 6.6	55.0 - 75.4
Strong Men	81.5 ± 6.0	77.3 - 91.0	80.3 ± 8.0	76.8 - 90.2

Data analysis

Normalization. To allow for the comparison between sexes and intensities (40% vs. 80%), the neuromuscular parameters (EMG amplitude, EMG mean power frequency, MMG amplitude, MMG mean power frequency) were normalized to each testing visit's pretest MVIC values. For all other analyses including eccentric PT values and blood flow measurements, absolute values were used.

Reliability. Test-retest reliability for pretest eccentric PT, EMG amplitude, EMG mean power frequency, MMG amplitude, MMG mean power frequency, and muscle blood flow were assessed from testing visit 1 to testing visit 2. Repeated measures ANOVAs were used to assess systematic error, and model 2,k[32] was used to calculate intraclass correlation coefficients (ICCs) and standard errors of measurement (SEMs) expressed as a percentage of the grand mean[33]. The 95% confidence intervals for the means of the dependent variables were calculated with the studentized *t*-distribution.

Subject stratification. To examine the effects of muscle strength on the fatigue-related responses, the men and women were stratified into 4 groups. Specifically, for the 18 men and 18 women, each respective group was divided equally into 2 groups of strong men (or strong women) and less strong men (or less strong women). That is, the strongest 9 men of the 18 men were placed in the strong men group, while the remaining 9 men of the 18 men were placed into the less strong group, the same was performed for the women. Thus, 4 groups (strong men, less strong men, strong women, and less strong women) of 9 were created, stratified by muscle strength according to their pretest eccentric PT values (Table 1).

Statistical analyses

Separate 4 (Group [strong men, less strong men, strong women, less strong women]) × 3 (Time [pretest, posttest, 5-min recovery]) × 2 (Intensity [40%, 80%]) mixed factorial ANOVAs were used to analyze the eccentric PT values. Muscle blood flow was examined using separate 4 (Group [strong men, less strong men, strong women, less strong women]) × 3 (Time [pretest, posttest, 5-min recovery]) × 2 (Intensity [40%, 80%]) mixed factorial ANOVAs and the normalized neuromuscular responses during the eccentric PT trials were examined using separate 4 (Group [strong men, less strong men, strong women, less strong women]) × 3 (Time [pretest, posttest, 5-min recovery]) × 2 (Intensity [40%, 80%]) mixed factorial ANOVAs. Significant interactions were decomposed with follow-up repeated measures ANOVAs and Bonferonni-corrected independent or dependent samples *t*-tests. Greenhouse-Geisser corrections were applied when sphericity was not met according to Maulchy's Test of Sphericity and partial eta squared effect sizes (η^2_p) were calculated for each ANOVA. All statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $p \leq 0.05$ considered statistically significant for all comparisons.

Results

Reliability

Table 2 includes the mean values (± SD) for each variable for the pretest measurements for visit 1 and visit 2. There were no mean differences for visit 1 versus visit 2 ($p>0.05$) for any of the variables. The ICC values ranged from 0.692-0.976 and the SEM values ranged from 4.1-19.1% of the grand mean. Furthermore, there was no difference ($p=0.862$) in exercise volume for the 40% (1618.4±423.3 Nm) versus 80% (1631.7±573.4 Nm) protocols.

Eccentric PT responses

There was no significant ($p=0.703$, $\eta^2_p=0.083$) 3-way (Intensity × Group × Time) interaction. There was, however, a significant ($p<0.001$, $\eta^2_p=0.463$) Group × Time interaction and significant follow-up one-way (collapsed across Intensity) repeated measures ANOVAs for Group ($p<0.001$, $\eta^2_p=0.894$-0.994) and Time ($p<0.001$, $\eta^2_p=0.911$-0.936). Specifically, there were significant Group differences in eccentric PT at pretest, posttest, and 5-min recovery (strong men > less strong men > strong women > less strong women). In addition, across Time all groups experienced a decrease in eccentric PT from pretest to

Table 2. The intraclass correlation coefficient (ICC), standard error of the measurement (SEM), percent of grand mean, and mean (± SD) of visits 1 and 2 for all measured variables from the combined sample (n=36) of men (n=18) and women (n=18).

Variables	ICC	SEM	% Grand Mean	Mean Visit 1	Mean Visit 2
Eccentric PT (Nm)	0.961	5.42	9.7%	56.79 ± 20.19	54.52 ± 17.90
Arterial Cross-Sectional Area	0.957	0.011	9.9%	0.111 ± 0.036	0.111 ± 0.043
Time Averaged Flow Velocity ($cm\cdot s^{-1}$)	0.827	4.06	19.1%	21.24 ± 7.14	21.31 ± 7.67
Muscle Blood Flow ($mL\cdot min^{-1}$)	0.888	31.35	21.8%	142.07 ± 65.7	145.16 ± 72.37
Eccentric PT EMG Amplitude (μV)	0.751	192.11	15.8%	1186.3 ± 446.7	1240.7 ± 670.7
Eccentric PT EMG Mean Power Frequency (Hz)	0.671	7.86	12.2%	65.54 ± 8.47	63.70 ± 10.47
Eccentric PT MMG Amplitude ($m\cdot s^{-2}$)	0.584	0.115	15.9%	0.738 ± 0.475	0.706 ± 0.331
Eccentric PT MMG Mean Power Frequency (Hz)	0.412	5.54	17.2%	31.85 ± 6.98	32.65 ± 8.67

There were no significant ($p > 0.05$) mean differences for visit 1 versus visit 2 for any of the variables. All measurements were performed at baseline prior to the fatiguing protocol.

Table 3. Pretest, posttest, and 5-min recovery normalized (to maximal isometric electromyographic (EMG) amplitude, EMG mean power frequency, mechanomyographic (MMG) amplitude, and MMG mean power frequency) neuromuscular responses (collapsed across Group and Intensity) during the eccentric peak torque (PT) muscle actions as a result of the fatiguing protocols.

Variables	Pretest	Posttest	5-min Recovery
Eccentric PT EMG Amplitude	0.957 ± 0.027	**0.843 ± 0.029***	**0.852 ± 0.024***
Eccentric PT EMG Mean Power Frequency	0.999 ± 0.021	0.985 ± 0.018	**1.066 ± 0.021†**
Eccentric PT MMG Amplitude	1.811 ± 0.139	1.700 ± 0.104	1.902 ± 0.246
Eccentric PT MMG Mean Power Frequency	1.178 ± 0.035	1.116 ± 0.059	1.151 ± 0.060

Values are collapsed across Group and Intensity because there were no significant ($p<0.05$) Group or Intensity effects.
*†Significant ($p<0.05$) greater than pretest (main effect for Time). *Significant ($p<0.05$) less than pretest (main effect for Time).*

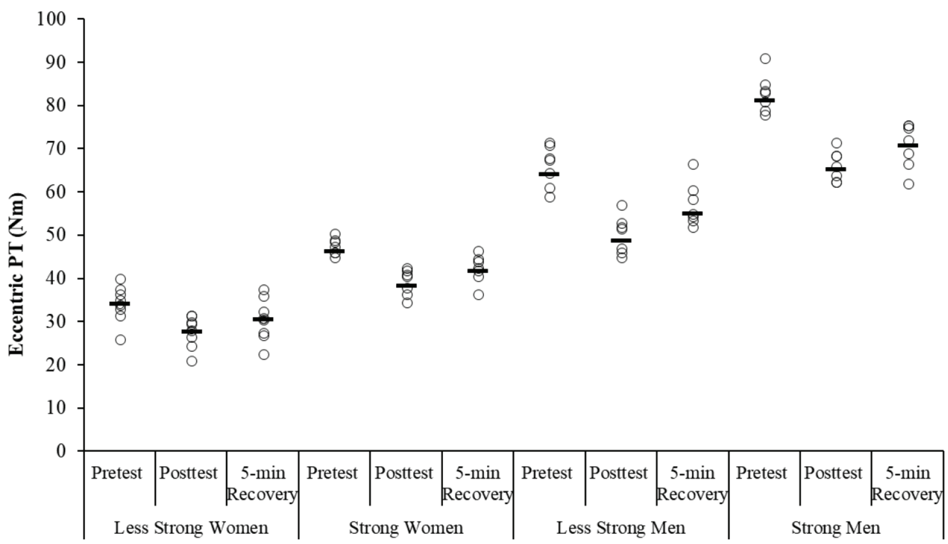

Figure 1. The individual (empty circles) and mean (solid horizontal lines) eccentric peak torque (PT) responses (collapsed across the 40% and 80% protocols) at pretest, posttest, and 5-min recovery for the less strong women, strong women, less strong men, and strong men. For all groups, eccentric PT decreased from pretest to posttest and for all groups, eccentric PT partially returned to pretest levels at 5-min recovery.

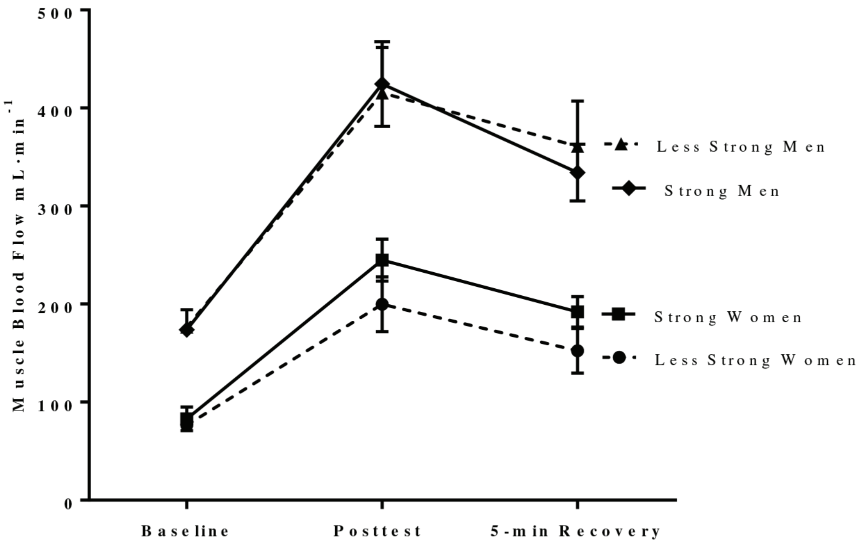

Figure 2. The mean (±SE) muscle blood flow responses (collapsed across the 40% and 80% protocols) at baseline, posttest, and 5-min recovery for the less strong women (circles with dotted line), strong women (squares with solid line), less strong men (triangles with dotted line), and strong men (diamonds with solid line). There were significant increases in muscle blood flow from pretest to posttest for all groups. At 5-min recovery, muscle blood flow partially returned to pretest levels for both groups of women, but remained elevated for both groups of men.

posttest, and eccentric PT partially recovered (pretest > 5-min recovery > posttest) for all groups at 5-min recovery. Thus, all groups responded similarly to the fatiguing intervention from pretest to posttest and from posttest to 5-min recovery (Figure 1). Furthermore, there were no intensity-related effects on eccentric PT.

Muscle blood flow

There was no significant (p=0.351, η_p^2 =0.141) 3-way (Intensity × Group × Time) interaction. There was, however, a significant (p=0.035, η_p^2=0.265) Group × Time interaction and significant follow-up one-way (collapsed across Intensity) repeated measures ANOVAs for Group (p<0.001, η_p^2=0.598-0.988) and Time (p=0.001-0.011, η_p^2 =0.664-0.904). Specifically, there were significant Group differences in muscle blood flow at pretest (strong men and less strong men > strong women and less strong women), posttest (strong men, less strong men, and strong women > less strong women), and 5-min recovery (strong men > less strong men and strong women > less strong women). Thus, at pretest the men had greater levels of resting muscle blood flow, but at posttest compensatory muscle blood flow increased to similar levels for all groups except the less strong women. Furthermore, at 5-min recovery muscle blood flow was greatest in the strong men and least for less strong women, while muscle blood flow was the same for less strong men and strong women.

Across time, all groups experienced increases in compensatory muscle blood flow from pretest to posttest. At 5-min recovery, muscle blood flow partially recovered for both groups of women (pretest < 5-min recovery < posttest), but remained elevated for both groups of men (pretest < posttest and 5-min recovery). Thus, all groups responded similarly to the fatiguing intervention from pretest to posttest, but there was a sex-related effect on the 5-min recovery responses for compensatory muscle blood flow which recovered to a greater extent in women than men (Figure 2).

Neuromuscular responses

EMG amplitude. There were no significant 3- (Intensity × Group × Time) or 2-way interactions (p=0.124-0.936, η_p^2= 0.041-0.235). There was, however, a significant (p=0.001, η_p^2=0.659) main effect for Time that included a decrease from pretest to posttest and 5-min recovery (pretest > posttest and 5-min recovery) for EMG amplitude (Table 3). Thus, all groups responded similarly to the fatiguing intervention at posttest and 5-min recovery, and there was no intensity- or group-specific effects for EMG amplitude.

EMG mean power frequency. There were no significant 3- (Intensity × Group × Time) or 2-way interactions (p=0.115-0.994, η_p^2=0.004-0.266). There was, however, a significant (p<0.001, η_p^2 =0.739) main effect for Time that included an increase from pretest and posttest to 5-min recovery (pretest and posttest < 5-min recovery) for EMG mean power frequency (Table 3). Thus, all groups responded similarly to the fatiguing intervention at posttest and 5-min recovery, and there was no intensity- or group-specific effects for EMG mean power frequency.

MMG amplitude. There were no significant 3- (Intensity × Group × Time) or 2-way interactions (p=0.115-0.994, η_p^2=0.004-0.266) or main effects (p=0.436-0.845, η_p^2=0.037-0.121). Thus, there were no changes in MMG amplitude as a result of the fatiguing intervention.

MMG mean power frequency. There were no significant 3- (Intensity × Group × Time) or 2-way interactions (p=0.115-0.618, η_p^2=0.067-0.303) or main effects (p=0.372-0.897, η_p^2=0.015-0.118). Thus, there were no changes in MMG mean power frequency as a result of the fatiguing intervention.

Discussion

Eccentric PT responses

In the present study, there was no sex-, intensity-, or group-specific pretest to posttest decreases or recovery (posttest to 5-min recovery) responses for eccentric PT as a result of the fatiguing protocols. There were, however, significant decreases from pretest to posttest for eccentric PT for the stronger men (19.3%), less strong men (23.7%), stronger women (17.4%), and less strong women (18.5%) (collapsed across the 40% and 80% protocols). In addition, there were significant increases from posttest to 5-min recovery for the stronger men (8.5%), less strong men (13.2%), stronger women (9.5%), and less strong women (10.6%). Thus, the current findings indicated that the fatigue-related patterns of decrease in eccentric PT as a result of the repeated submaximal eccentric muscle actions and the partial recovery of eccentric PT following 5-min of rest were not affected by the sex or strength of the subjects or the intensity of the fatiguing protocols when the total work performed was equal (torque × number of repetitions).

The present findings suggested a mode-specific difference for the eccentric responses in the present study versus MVIC and concentric PT responses from previous studies[11-13]. For example, as a result of high intensity (80-90% of MVIC or concentric PT) fatiguing isometric and concentric protocols, previous investigations[11,12] reported that men and women experienced similar decreases in MVIC or concentric PT. As a result of low intensity (20% of MVIC) isometric forearm flexion muscle actions and low to moderate intensity (20-70% of MVIC or concentric PT) concentric forearm flexion or leg extension muscle actions, however, previous investigations[11,12,14], reported that men experienced greater fatigue-induced decreases in MVIC or concentric PT than women. Thus, as a result fatiguing isometric and concentric protocols there were sex-specific torque responses that were manifested at 20-70%, but not at 80-90% of MVIC or concentric PT. In the present study, however, there were no sex-specific torque responses from pretest to posttest as a result of fatiguing eccentric muscle actions performed at the low (40% of eccentric PT) or high intensity (80%).

The eccentric PT recovery responses were not consistent with those of Russ and Kent-Braun[15] and Hunter et al,[34] who reported that MVIC recovered to a greater extent in women than men when measured at 5- and 10-min following fatiguing isometric exercise. Specifically, in the present study, the magnitude of recovery was similar for the men and women regardless of differences in strength as a result of the 40% and 80% protocols. The discrepancy between the current findings and previous investigations[15,34] may have been due to the modes (isometric vs. eccentric) of the fatiguing interventions. It is possible that the mechanisms underlying sex- and/or intensity-related effects on eccentric PT recovery responses, as well as pretest to posttest decreases in eccentric PT were related to the mode of assessment. Specifically, the present study examined the effects of fatiguing submaximal eccentric muscle actions on changes in eccentric PT, while previous investigations[15,34] have utilized fatiguing concentric and isometric protocols and assessed fatigue by changes in MVIC and concentric PT. The mode-specific torque responses at recovery may be due, in part, to the fatigue-resistant nature of eccentric muscle actions that was related to recovery in torque regardless of sex, intensity, or strength. Thus, there may exist mode-specific decreases in torque that are manifested differently following fatiguing eccentric muscle actions.

Compensatory muscle blood flow posttest and 5-min recovery responses

There were group-specific compensatory (post-contraction hyperemia) muscle blood flow responses as a result of the fatiguing protocols that were not associated with the intensity of the fatiguing interventions. Specifically, compensatory muscle blood flow increased similarly from pretest to posttest for both groups of men and women. At 5-min recovery, however, compensatory muscle blood flow partially recovered for both groups of women, but remained elevated for both groups of men. Thus, there were sex-specific compensatory muscle blood flow recovery responses that recovered to a greater extent in women than men, regardless of intensity. Post-exercise increases in compensatory muscle blood flow have been used to make inferences regarding the magnitude of blood flow occlusion in men versus women as a result of fatiguing exercise[10,14,35]. The extent to which muscle blood flow contributes to muscle fatigue in men versus women during dynamic exercise, however, remains unclear[14,36]. It has been theorized that in men (compared to women), there is greater mechanical compression of the arteries (due to greater strength and/or related to exercise intensity) which results in increases in metabolites and causes greater muscle fatigue[14,37,38].

The findings of the present study indicated that there were no sex-specific compensatory muscle blood flow responses from pretest to posttest. These findings were not consistent with previous investigations[36,39,40] that have reported sex differences in muscle blood flow as a result of dynamic exercise. For example, women experienced greater post exercise increases in femoral blood flow than men as a result of maximal effort leg extension muscle actions performed to exhaustion[36]. Furthermore, following 3-min of blood flow occlusion, women experienced greater absolute and relative increases in brachial artery diameter compared to men[39]. The lack of sex-specific posttest compensatory muscle blood flow responses as a result of both protocols in the present study, may have been due to the mode (eccentric) of the fatiguing intervention. For example, while previous investigations[36,39,40] have examined the sex-related effects of muscle blood flow as a result of concentric or isometric interventions, this study examined the effects of fatiguing eccentric muscle actions on sex-specific muscle blood flow. Furthermore, in the present study, the lack of sex-specific posttest compensatory muscle blood flow responses was consistent with the lack of sex-specific eccentric PT responses. In previous investigations[10,14,35], compensatory muscle blood flow has been used to make inferences regarding sex-specific torque responses following fatiguing isometric and concentric exercise. Thus, the findings of the present study indicated that both men and women experienced similar changes in compensatory muscle blood flow that may help explain the lack of sex-specific eccentric PT responses as a result of low (40%) and high intensity (80%) eccentric muscle actions.

There were, however, sex-specific compensatory muscle blood flow responses during recovery that partially returned to pretest levels for both groups of women, but remained elevated for both groups of men. The greater time duration of compensatory muscle blood flow for the men may have been due to strength differences between the men and women. Specifically, it has been reported[41] that complete forearm blood flow occlusion occurred at approximately 50% of MVIC in stronger individuals (67.4 kg of force) compared to 75% in less strong individuals (56.5 kg of force). Therefore, it is possible that due to strength differences, the men experienced greater muscle blood flow occlusion (collapased across Intensity) that resulted in increased time to recovery. It is also possible that compared to men, women exhibited an enhanced ability to restore muscle blood flow to baseline levels following fatiguing eccentric exercise[36,39].

EMG amplitude, EMG mean power frequency, MMG amplitude, and MMG mean power frequency responses

There were no intensity- or group-specific EMG amplitude, EMG mean power frequency, MMG amplitude, or MMG mean power frequency responses as a result of the 40% or 80% protocols. There were, however, main effects for Time (collapsed across Intensity and Group) for EMG amplitude and EMG mean power frequency. Specifically, EMG amplitude decreased from pretest to posttest and recovery, and EMG mean power frequency increased from pretest and posttest to recovery. The lack of sex-specific neuromuscular responses was consistent with previous investigations[13,42,43]. For example, as a result of submaximal isometric forearm flexion muscle actions at 20% of MVIC, there were no sex-specific differences in EMG amplitude or reductions in voluntary activation (as a percentage of a superimposed twitch)[42]. Furthermore, a previous investigation[43] reported that there were no sex-specific differences in EMG or MMG amplitude and mean power frequency responses as a result of submaximal isometric forearm flexion muscle actions at 65% of MVIC. Consistent with the present findings, previous findings[13] indicated that, there were no sex-related differences in EMG amplitude for the forearm flexors as a result of submaximal concentric muscle actions at 50% of concentric PT, but men experienced a greater reduction in EMG amplitude for the leg extensors than women. Thus, the results of the present study, in conjunction with previous investigations[13,42,43], indicated that there were no sex-specific EMG or MMG, time or frequency domain responses for the forearm flexors as a result of submaximal eccentric, concentric, or isometric fatiguing interventions.

Decreases in EMG amplitude as a result of fatiguing submaximal and maximal eccentric muscle actions have been attributed to inhibitory feedback[44,45]. Specifically, high contractile forces associated with maximal or near-maximal eccentric muscle actions may adversely affect muscle activation by stimulating Golgi tendon organs and muscle spindles[44,45] which may explain decreases in EMG amplitude (muscle activation) observed in the present study. The lack of changes in MMG amplitude and MMG mean power frequency do not support decreased muscle activation which would have likely led to a decrease in motor unit recruitment (MMG amplitude) and/or changes in motor unit firing rate (MMG mean power frequency). The dissociation among MMG amplitude (motor unit recruitment) and eccentric PT at posttest and recovery, however, may have been due to the high contractile forces associated with eccentric muscle actions. Specifically, MMG amplitude from the biceps brachii typically tracks isometric forearm flexion torque production up to approximately 80% of MVIC and then plateaus or decreases due, in part, to increases in muscle stiffness[46,47]. Under eccentric conditions, where force generation is greater than isometric conditions, it is plausible that MMG amplitude plateaus earlier (i.e. < 80% of eccentric PT) and, consequently, limits the ability of MMG amplitude to track changes in motor unit recruitment due to high levels of muscle stiffness. Similarly, the lack of changes in MMG mean power frequency which has been used as a qualitative measure of motor unit firing rate[6] suggested that fatigue-induced decreases in eccentric PT were unrelated to changes in motor unit firing rate at posttest or recovery.

It is also possible that the decreases in EMG amplitude were related to the unique motor unit activation strategies associated with eccentric muscle actions. Specifically, eccentric muscle actions have been characterized by lower levels of muscle activation and faster action potential conduction velocities compared to concentric or isometric muscle actions[48-50] that may reflect a greater distribution of mechanical stress on a fewer number of motor units[44]. In support of this, EMG mean power frequency which is reflective of action potential conduction velocity[51], remained unchanged at posttest and increased at recovery. Typically, however, fatiguing concentric or isometric exercise is associated with decreases in EMG mean power frequency due to increases in the accumulation of metabolic byproducts[43,52,53]. As a result of the fatiguing eccentric protocols, EMG mean power frequency was unaffected by the fatiguing protocol at posttest and increased at recovery. Thus, in the present study, the decreases in eccentric PT may have been related to unique motor unit activation strategies associated with eccentric muscle actions as characterized by decreased muscle activation (EMG amplitude) and faster action potential conduction velocity (EMG mean power frequency).

The findings of the present study indicated that both the 40% and 80% protocols induced similar fatigue-related effects on the neuromuscular parameters regardless of sex or strength. In addition, EMG amplitude tracked the fatigue-induced decreases in eccentric PT. The EMG mean power frequency, MMG amplitude, and MMG mean power frequency responses were dissociated from the eccentric PT responses at all time points and support the unique physiological (motor unit activation strategies) and/or non-physiological (high contractile forces) responses associated with eccentric muscle actions compared to concentric or isometric muscle actions. Collectively, the current findings indicated that the neuromuscular mechanisms underlying decreases in torque as a result of fatiguing eccentric muscle actions were different than those typical of isometric or concentric fatiguing muscle actions, but are not related to sex or strength.

Summary. There were significant decreases in eccentric PT from pretest to posttest that were not affected by sex or group (strength). In addition, eccentric PT partially returned to pretest levels at 5-min recovery and the magnitude of increase was similar for both sexes and all groups. These findings were different than the effects of concentric and isometric fatiguing interventions on sex-specific decreases in torque production and may be due, in part, to the fatigue-resistant nature of eccentric muscle actions. There was no sex- or group-specific increases in compensatory muscle blood flow at posttest, but compensatory muscle blood flow partially returned to pretest levels for both groups of women and remained elevated for both groups of men. The similar changes in compensatory muscle blood flow may help explain the lack of sex-specific eccentric PT responses as a result of low (40%) and high intensity (80%) eccentric muscle actions, while greater time duration of compensatory muscle blood flow at recovery for the men may have been due to strength differences between the men and women. There was no intensity- or group-specific neuromuscular responses, but EMG amplitude tracked the changes in eccentric PT. The decreases in EMG amplitude may reflect muscle inhibition associated with high contractile forces and/or the effects of unique motor unit activation strategies associated the eccentric muscle actions. The EMG mean power frequency, MMG amplitude, and MMG mean power frequency responses were dissociated from the eccentric PT responses at all time points and support non-physiological (high contractile forces) and/or physiological (motor unit activation strategies) responses associated with eccentric muscle actions compared to concentric or isometric muscle actions.

Author contributions

ECH was a substantial contributor to study concept and design, carried out data acquisition, analysis, and interpretation, and was the primary author. JLK, CMS, RJS and GOJ helped carry out data acquisition. TJH was the primary manuscript reviser and a substantial contributor to study concept and design. All authors approved the final version of this manuscript.

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