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Muscular Performance and Neuromuscular Fatigue are not Sex-Dependent During Low-Load Fatiguing Bilateral Leg Extension Exercise

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Cover Page Footnote

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Introduction

Recently, Enoka and Duchateau (2016) proposed fatigue as a "disabling symptom in which physical and cognitive function is limited by interactions between performance fatigability and perceived fatigability (p. 3). In addition, investigators have speculated that the amount of active muscle mass engaged in a task may influence the duration the task can be performed (Rossman et al., 2012; Rossman et al., 2014; Thomas et al., 2018). Specifically, Thomas et al. (2018) hypothesized that during isolated muscle actions (i.e., unilateral or bilateral leg extension) there are larger declines in pre- to post-exercise force production (i.e., performance fatigability) compared to whole-body exercise due to the ability of the isolated muscle mass to incur greater disruptions to homeostasis. Conversely, during whole-body exercise like cycling, the greater amount of active musculature, as well as respiratory and cardiac muscle contributions, increases afferent feedback and causes more global fatigue, leading to lesser declines in performance fatigability as disruptions to homeostasis become more widespread (Thomas et al., 2018). This hypothesis is corroborated by two studies performed by Rossman and colleagues (2012, 2014) who demonstrated greater reductions in performance fatigability after bilateral leg extension exercise (-28%) compared to cycling (-16%) and unilateral leg extension exercise (-25%) compared to bilateral leg extension exercise (-12%). Further, previous investigators have suggested sex-dependent responses to fatigue may be due to greater muscle mass in men that leads to an earlier onset of altered blood flow and metabolite accumulation compared to women (Hicks et al., 2001). To this point, authors have reported that women were able to maintain force production longer than men during both sustained isometric and dynamic constant external resistance (DCER) exercise when performed at low loads (i.e., ~20-30% maximal strength capacity) (Clark et al., 2005; Dinyer et al., 2019a; Hunter et al., 2001; Hunter et al., 2006; Yoon et al., 2007). When fatiguing isometric and DCER exercise was performed at high loads or under arterial occlusion, however, men and women demonstrated no difference in the time force production was maintained (Clark et al., 2005; Maughan et al., 1986; Yoon et al., 2007). Thus, sex-dependent responses in fatigue may be mode- and intensity-specific that are influenced by disruptions in homeostasis due to the amount of active muscle mass engaged in the task and the potential disruptions to blood flow and metabolite clearance.

Surface electromyography (EMG) and mechanomyography (MMG) have been used to noninvasively examine neuromuscular parameters during fatiguing exercise (Clark et al., 2005; Hill et al., 2018a; Hill et al., 2018b; Hill et al., 2018c; Hunter et al., 2006; Hunter et al., 2001; Maughan et al., 1986; Yoon et al., 2007). Electromyography provides information regarding the electrical component of muscular contractions and contains amplitude (AMP) and frequency (mean power frequency: MPF) domains that reflect muscle activation and motor unit action potential conduction velocity, respectively (Basmajian, 1979; Beck and Housh, 2008), although recent investigations have reported high inter-subject variability in the relationship between surface EMG and motor unit action potential conduction velocities (Del Vecchio et al., 2017). Mechanomyography is the mechanical counterpart to EMG and contains an AMP domain that reflects motor unit recruitment and a MPF domain that reflects motor unit firing rate (Beck et al., 2007). Investigators have previously reported conflicting evidence on the sex-dependent responses of both EMG and MMG signals during fatiguing tasks. Clark et al. (2005) and Yoon et al. (2007) reported greater increases in EMG AMP in women compared to men during fatiguing isometric muscle actions of the leg extensors and forearm flexors performed at 20-80% maximal voluntary contraction. However, during eccentric isokinetic muscle actions of the forearm flexors performed at 40, 60, or 80% peak torque, investigators have reported no differences in the EMG AMP or EMG MPF responses between men and women (Hill et al., 2018a; Hill et al., 2018b). For MMG AMP and MMG MPF, men and women demonstrated no difference in the responses during fatiguing eccentric isokinetic muscle actions of the forearm flexors, while different patterns of responses were demonstrated between the sexes during concentric isokinetic muscle actions of the forearm flexors (Hill et al., 2018a; Hill et al., 2018b; Hill et al., 2018c). Therefore, additional research is warranted to further examine potential sex-specific neuromuscular responses during fatiguing resistance exercise.

Recently, the critical load (CL) model has been utilized to examine the applicability of a fatigue threshold for resistance exercise that is sensitive to detect sex differences when exercise is performed at the CL (Dinyer et al., 2019a; Dinyer et al., 2019b). Theoretically, the CL represents the highest sustainable resistance that can be completed for an extended number of repetitions (>35) and has been reported to reflect ~40% of an individual's one-repetition maximum (1RM) for the deadlift (Dinyer et al., 2019b). It has previously been reported that this threshold for intermittent isometric muscle actions corresponded to 40% maximal capacity and only 14% maximal capacity for sustained isometric muscle actions (Monod and Scherrer, 1965). The authors suggested that the estimate of CL may reflect the point of alterations in local blood flow and represent a fatigue threshold that considers an individual's submaximal performance capabilities (e.g., metabolic system capacities, fiber-type characteristics) during the completion of fatiguing exercise (Monod and Scherrer, 1965). Thus, this model provides an estimate of a unique individualized fatigue threshold to examine the sex-related differences in physiological responses when resistance exercise is performed to failure at a low intensity. In addition, investigators have suggested the CL may be mode-specific, as greater muscle-specific fatigue has been reported for isolated muscle actions compared to whole-body exercise (Rossman et al., 2012; Rossman et al., 2014; Thomas et al., 2018). It has previously reported that there are sex-related differences in fatigue during the whole-body deadlift exercise (Dinyer et al., 2019a). However, little is known about the sex-related differences in fatigue when exercise is performed for an isolated muscle action at the CL. Therefore, the purpose of this study was to determine if there were sex-related differences in muscular performance and neuromuscular (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) responses during fatiguing DCER leg extension repetitions performed at CL. Based on previous studies (Clark et al., 2005; Dinyer et al., 2019a; Hunter et al., 2001; Hunter et al., 2006; Yoon et al., 2007), we hypothesized the women would be more fatigue resistant than the men and demonstrate: 1) the ability to perform more repetitions to failure at CL compared to the men and 2) a later onset of fatigue-induced changes in the EMG and MMG, AMP and MPF signals.

Methods

Experimental Design

Each subject visited the Exercise Physiology Laboratory on 6 separate occasions, with at least 24 hours between sessions. On visit 1, the subjects performed one-repetition maximum (1RM) testing for the leg extension. On visits 2-5, the subjects performed leg extension repetitions to failure at 50%, 60%, 70%, and 80% 1RM, in a random order, for the determination of critical load (CL). On visit 6, the subjects completed leg extension repetitions to failure at their estimated CL.

Subjects

Eleven men (Age: 23 ± 3 yrs; Height: 174 ± 8 cm; Body mass: 79 ± 9 kg) and nine women (Age: 20 ± 1 yrs; Height: 168 ± 6 cm; Body mass: 76 ± 18 kg) completed this study. The women in the current study were subjects in our previous study (Dinyer et al., 2020) but there is no overlap in the data presented. The subjects were included in this study if they were free from any musculoskeletal, metabolic, respiratory, or cardiovascular diseases or injuries and engaged in resistance training at least 3 days per week for the past year. The subjects also participated in one, or a combination of, the following activities: cycling (*n* = 3), running (*n* = 13), or recreational sport (*n* = 7). This study was approved by the University of Kentucky Institutional Review Board for Human Subjects. All subjects were informed of the risks and benefits of the study prior to data collection, and then completed a health history questionnaire and signed a written informed consent document before beginning the study.

Determination of One-Repetition Maximum

The subjects completed 1RM testing for the leg extension (Body-Solid, GLCE365, Forest Park, IL, USA) to derive the loads (50%, 60%, 70%, and 80% 1RM) used for the determination of CL. Prior to determining the 1RM, the subjects completed 3 warm up sets of the leg extension consisting of 8-10 repetitions, 5-6 repetitions, and 2-3 repetitions of increasing loads (Sheppard and Triplett, 2016). The subjects were then given a maximum of 5 attempts to establish a 1RM for the leg extension. The subjects were given 2 minutes rest between warm up sets, and 3-5 minutes rest between 1RM attempts. A 1RM attempt was considered successful when the subject performed the leg extension through the full range of motion (i.e., the leg was fully extended to 180°). To determine full extension, the subjects performed one leg extension repetition with 20.4 kg loaded on the machine and held at the position where the legs were fully extended. The distance from the back of the ankle to the ground was measured, and a pipe cleaner was attached to a stadiometer at the measured height to ensure the leg traveled through the full range of motion with each repetition. The stadiometer was placed next to the leg extension machine during each visit to allow for visual inspection of the bottom of the ankle breaking the line of the pipe cleaner, which indicated full extension of the repetition was achieved. Weight was added until the subjects could no longer perform the leg extension through the full range of motion.

Determination and Performance of Repetitions at Critical Load

During visits 2-5, the subjects completed repetitions to failure of the leg extension at 50%, 60%, 70%, and 80% of their 1RM on 4 separate days, in a randomized order, to determine their CL. The total number of repetitions completed for each load (50%, 60%, 70%, and 80% 1RM) was recorded. The CL was calculated as the slope of the line of the total work completed (repetitions x load [kg]) versus total repetitions. During visit 6, the subjects completed repetitions to failure at their estimated CL. Prior to the performance of repetitions to failure, the subjects received 3 warm up sets consisting of 8-10 repetitions, 5-6 repetitions, and 2-3 repetitions of increasing loads to get within 5-10 kg of the load that would be lifted to failure. For each load (50%, 60%, 70%, and 80% 1RM; CL), the subjects completed the repetitions to failure to a metronome set to 1.1 seconds for the concentric phase (leg is extended to 180°) and 1.1 seconds for the eccentric phase (leg returns to starting position of 90° knee bend). Failure was defined as: 1) the inability to complete the leg extension through the full range of motion (measured as previously described); or 2) the inability to maintain the repetitions to the set cadence.

Electromyographic and Mechanomyographic Measurements

During the repetitions to failure performed at CL, a bipolar surface EMG electrode (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) arrangement (30 mm interelectrode distance) was placed on the vastus lateralis of the dominant limb. Specifically, the EMG electrode was placed two-thirds the distance between the anterior superior iliac spine and the lateral superior border of the patella (Hermens et al., 1999). A goniometer was then used to place the electrodes at a 20° angle to approximate the pennation angle of the muscle fibers for the vastus lateralis (Abe et al., 2000). A reference electrode was placed over the anterior superior iliac spine of the dominant limb. Prior to electrode placement, the skin for each electrode site was shaved, carefully abraded, and cleaned with isopropyl alcohol. The site of electrode placement was marked with indelible ink to ensure the electrodes were placed at the same site for each visit. The MMG signals were recorded simultaneously with the EMG signals using an accelerometer (Entran EGAS FT, 10, bandwidth 0-200 Hz, dimensions: 1.0 x 1.0 x 0.5 cm, mass 1.0 g sensitivity 10 mV g^{-1}) that was placed between the bipolar electrode arrangement using double-sided adhesive tape. The signal was analyzed from the sensitive axis of the accelerometer positioned perpendicular to the skin surface. The other sensitive axis was positioned along the longitudinal axis of the muscle.

Signal Processing

The raw EMG and MMG signals were sampled at 1 kHz with a 16-bit analog-to-digital converter (Model MP150, BIOPAC Systems, Inc., Santa Barbara, CA, USA). The EMG signals were differentially amplified (EMG 100, BIOPAC Systems, Inc., Santa Barbara, CA, USA; bandwidth = 10-500 Hz; gain: x1,000) and the raw MMG signals were amplified with an in-line amplifier (gain: 200). The signals were recorded and stored in a personal computer for subsequent off-line analysis and processing using a custom program written with LabVIEW programming software (version 17.0, National Instruments, Austin, TX). The EMG and MMG signals were zero-meaned and digitally bandpass filtered (fourth-order Butterworth) at 10-500 Hz and 5-100 Hz, respectively. The EMG (microvolts root mean square, μVrms) and MMG (root mean square; $m \cdot s^{-2}$) AMP and MPF (measured as Hz) values from the middle 1/3 of the concentric portion of the leg extension repetition (leg extends to 180°) were calculated for the first 5% and every 25% of the total repetitions completed during the performance of repetitions to failure at CL. The EMG AMP, EMG MPF, MMG AMP, and MMG MPF were normalized to the corresponding neuromuscular signal from the 1RM load (LeVeau and Andersson, 1995, p. 73).

Statistical Analyses

Independent samples *t*-tests were used to examine differences between the men and the women for the 1RM strength measure, as well as for the absolute load (kg) at CL, percent of 1RM that corresponded to CL, and the repetitions completed to failure at CL. Four separate 2 (sex: men and women) x 5 (time: 5%, 25%, 50%, 75%, and 100% of total repetitions completed) mixed factorial ANOVAs with follow-up one-way repeated measures ANOVAs and Sidak-Bonferroni corrected pairwise comparisons (5 comparisons; Sidak-Bonferroni corrected $p \leq 0.01$) were used to examine the neuromuscular (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) responses across time. Cohen's *d* and partial eta squared (p_{η}^{2}) were used as the measures of effect size for the independent samples *t*-tests and ANOVAs, respectively. The statistical analyses were conducted using Statistical Package for the Social Sciences Software (v.24.0. IBM SPSS Inc., Chicago, IL, USA) and an alpha level of $p \leq 0.05$ was considered statistically significant for the ANOVAs.

Results

Absolute (kg) and Relative (% 1RM and repetitions to failure) Measures

Table 1 includes the mean ± SD of the 1RM as well as the load (kg), percent of 1RM corresponding to, and the number repetitions completed at CL for both the men and the women. The independent samples *t*-test indicated the men had greater 1RM leg extension strength ($p = 0.004$, $d = 1.50$), as well as a greater absolute CL ($p = 0.018$, $d = 1.19$) compared to the women. There was no difference between the men and the women for the percent of 1RM that corresponded to CL ($p = 0.540$, $d = 0.28$) or the number of repetitions completed at CL ($p = 0.888$, $d = 0.07$).

Table 1. Mean ± SD for the one-repetition maximum (1RM) as well as the load, percent of 1RM corresponding to (%1RM), and number of repetitions completed at the critical load for the men and the women.

	1RM	Critical Load		
	(kg)	Load (kg)	%1RM	Repetitions Completed
Men (*n* = 11)	86 ± 15*	23 ± 6*	27 ± 5	61 ± 24
Women (*n* = 9)	65 ± 12	17 ± 4	26 ± 4	59 ± 25

* indicates men significantly different than the women ($p < 0.05$)

Neuromuscular Responses

For the normalized, EMG AMP, there was no 2-way interaction ($F(2.347,42.254) = 1.571$, $p = 0.217$, $p_{\eta}^{2} = 0.080$) for sex x time or main effect for sex ($F(1,18) = 0.103$, $p = 0.752$, $p_{\eta}^{2} = 0.006$). However, there was a main effect for time ($F(2.347,42.254) = 23.769$, $p < 0.001$, $p_{\eta}^{2} = 0.569$). Table 2 and Figure 1a show the results of the one-way repeated measures ANOVA (collapsed across sex) for the normalized EMG AMP for the men and the women across time.

Table 2. Mean ± SD of the normalized (% of 1RM) marginal means (collapsed across sex) of the EMG AMP for the % of total repetitions completed at the critical load.

% of Total Repetitions Completed	Mean ± SD (%)	Post-hoc comparisons
5%	40.8 ± 15.7	<25%*, 50%*, 75%*, 100%*
25%	50.0 ± 18.7	>5%*; =50%; <75%*, 100%*
50%	53.2 ± 21.5	>5%*; =25%, 50%; <100%*
75%	63.2 ± 26.6	>5%*, 25%*; =50%; <100%*
100%	82.2 ± 34.1	>5%*, 25%*, 50%*, 75%*

*indicates significant difference at $p \leq 0.01$ (Sidak-Bonferroni corrected p-value)
1RM = one-repetition maximum; EMG = electromyography; AMP = amplitude

There was no sex x time interaction for the normalized EMG MPF ($F(2.329,41.919) = 1.372$, $p = 0.265$, $p_{\eta}^{2} = 0.071$) or main effect for sex ($F(1,18) = 1.469$, $p = 0.241$, $p_{\eta}^{2} = 0.075$). However, there was a main effect for time ($F(2.329,41.919) = 21.536$, $p < 0.001$, $p_{\eta}^{2} = 0.545$). Table 3 and Figure 1b show the results of the one-way repeated measures ANOVA (collapsed across sex) for the normalized EMG MPF for the men and the women across time.

Table 3. Mean ± SD of the normalized (% of 1RM) marginal means (collapsed across sex) of the EMG MPF for the % of total repetitions completed at the critical load.

% of Total Repetitions Completed	Mean ± SD (%)	Post-hoc comparisons
5%	103.9 ± 25.5	=25%; >50%*, 75%*, 100%*
25%	98.8 ± 13.2	=5%; >50%*, 75%*, 100%*
50%	89.0 ± 20.4	<5%*, 25%*; =75%; >100%*
75%	85.4 ± 26.0	<5%*, 25%*; =50%, 100%
100%	73.1 ± 19.6	<5%*, 25%*, 50%*; =75%

*indicates significant difference at $p \leq 0.01$ (Sidak-Bonferroni corrected p-value)
1RM = one-repetition maximum; EMG = electromyography; MPF = mean power frequency

For MMG AMP, there was no 2-way interaction (*F*(1.303, 23.453) = 0.138, *p* = 0.779, p_{η}^{2} = 0.008) or main effect for time (*F*(1.303,23.453) = 2.608, *p* = 0.112, p_{η}^{2} = 0.127) or sex (*F*(1,18) = 1.200, *p* = 0.288, p_{η}^{2} = 0.063). Table 4 and Figure 1c show the results of the one-way repeated measures ANOVA (collapsed across sex) for the normalized MMG AMP for the men and the women across time.

Table 4. Mean ± SD of the normalized (% of 1RM) marginal means (collapsed across sex) of the MMG AMP for the % of total repetitions completed at the critical load.

% of Total Repetitions Completed	Mean ± SD (%)
5%	83.6 ± 40.5
25%	103.3 ± 54.5
50%	110.2 ± 49.6
75%	91.0 ± 41.7
100%	105.3 ± 51.8

1RM = one-repetition maximum
MMG = mechanomyography; AMP = amplitude

There was no 2-way interaction for MMG MPF (*F*(4,72) = 0.673, *p* = 0.613, p_{η}^{2} = 0.036) or main effect for sex (*F*(1,18) = 0.137, *p* = 0.715, p_{η}^{2} = 0.008), but there was a main effect for time (*F*(4,72) = 4.368, *p* = 0.003, p_{η}^{2} = 0.195). Table 5 and

Figure 1d show the results of the follow-up one-way repeated measures ANOVA (collapsed across sex) for the men and the women for the normalized MMG MPF across time.

Table 5. Mean ± SD of the normalized (% of 1RM) marginal means (collapsed across sex) of the MMG MPF for the % of total repetitions completed at the critical load.

% of Total Repetitions Completed	Mean ± SD (%)	Post-hoc comparisons
5%	132.4 ± 43.5	=25%, 50%, 75%; >100%*
25%	129.0 ± 40.6	=5%, 50%, 75%; >100%*
50%	118.0 ± 56.1	=5%, 25%, 75%, 100%
75%	113.0 ± 65.5	=5%, 25%, 50%, 100%
100%	97.7 ± 54.8	<5%*, 25%*; =50%, 75%

*indicates significant difference at $p \leq 0.01$ (Sidak-Bonferroni corrected p-value)
1RM = one-repetition maximum; MMG = mechanomyography; MPF = mean power frequency

Discussion

Muscular Performance

In the present study, the men demonstrated greater absolute strength (1RM, CL) compared to the women, but there was no difference in the relative CL strength measure (% of 1RM that corresponded to CL) or the number of repetitions that were completed to failure at CL between the men and the women (Table 1). Previously, greater absolute strength (1RM and CL) has been reported for men compared to women when the deadlift was utilized for the determination of CL; however, the % of 1RM that corresponded to CL was greater for the women (41 ± 2% 1RM) than the men (37 ± 6% 1RM) (Dinyer et al., 2019a). In addition, the women (58 ± 12 repetitions) were able to complete a greater number of repetitions to failure than the men (45 ± 14 repetitions) when resistance exercise was performed at CL for the deadlift (women: 48 ± 2 kg; men: 62 ± 14 kg) (Dinyer et al., 2019a). Furthermore, Ansdell et al. (2019) and Chartonge et al. (2020) reported women demonstrated a greater relative CL measure (% of maximal voluntary contraction) compared to men when the CL was determined for unilateral, intermittent isometric or sustained isometric muscle actions of the leg extensors, as well as a longer time to task failure when repetitions were performed 10% above the CL (women: 3742 ± 1035 sec; men: 1826 ± 765 sec), but not 10% below the CL (all subjects reached the 45 min time cap) during intermittent isometric muscle actions (Ansdell et al., 2019). To this point, the current study used a DCER exercise that had reciprocal concentric and eccentric phases. While the current study did not demonstrate differences in muscular performance between the men and the women, the nature of the reciprocal muscle action may contribute to variability in the fatigue response as both concentric and eccentric muscle actions incur greater metabolic strain than isometric muscle actions (Ryschon et al., 1994). Therefore, sex differences in the performance of repetitions to failure at the CL during whole-body, bilateral, and unilateral muscle actions appear to be modality specific.

Previously, authors have attributed the modality-specific fatigue response observed during exhaustive exercise to the amount of active muscle mass engaged in the activity (Rossman et al., 2012; Rossman et al., 2014; Thomas et al., 2018). Specifically, Rossman et al. (2012) demonstrated a 31% longer time to exhaustion, as well as a greater degree of quadriceps peripheral fatigue during bilateral leg extension exercise compared to cycling. Authors corroborated this finding when the performance of unilateral leg extension exercise demonstrated a similar time to exhaustion, but greater quadriceps peripheral fatigue compared to the bilateral leg extension exercise when tasks were performed at 85% peak workload capacity (Rossman et al., 2014). The authors concluded there were "…muscle mass-induced alterations in afferent feedback" (p. R938) that affected the degree of peripheral fatigue demonstrated after exhaustive exercise performed with varying levels of active muscle mass (Rossman et al., 2014). This theory could explain the greater number of repetitions performed during the leg extension in the present study, compared to that previously reported for the deadlift at the same relative intensity (i.e., CL) (Dinyer et al., 2019a). Specifically, the leg extension is an isolated bilateral movement that relies primarily on the quadriceps muscles of both limbs. Conversely, the deadlift, which requires extension of the lower limbs to complete the movement, utilizes the lower limbs, back, and some upper limb musculature for successful completion of a repetition. Consequently, performing a whole-body resistance training movement may result in more overall peripheral fatigue from greater active muscle mass and impact central drive to a greater extent due to increased afferent feedback (Amann et al., 2020), thus causing cessation of repetitions to occur sooner, relative to more local muscle actions. Therefore, the results of the present study, in conjunction with previous work (Dinyer et al., 2019a; Rossman et al., 2012, 2014) suggested there was variability in the fatigue process that was dependent on the total amount of active muscle mass contributing to force production. The variability in fatigue as it relates to the active muscle mass may explain, in part, the sex-specific responses observed for the whole-body dynamic deadlift exercise (Dinyer et al., 2019a), but not for isolated bilateral leg extension in this study. Specifically, the difference between the men and the women in total active muscle mass for the leg extension may not have been great enough to elicit differences in afferent feedback, while the greater total volume of active muscle mass for the men compared to the women for the deadlift may have resulted in greater afferent feedback and alternations in central motor drive. Future studies may wish to examine other mechanisms of fatigue, including measures of metabolic byproduct accumulation and the total activated muscle mass in men and women during isolated compared to whole-body DCER muscle actions, to further examine the potential sex- and modality-specific fatigue responses.

Neuromuscular Responses

In the current study, the men and the women demonstrated similar neuromuscular responses (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) throughout the performance of fatiguing leg extension repetitions performed at CL (Tables 2-5; Figures 1a-d). Specifically, for both the men and women, EMG AMP increased from the initial repetition from 25-100% of total repetitions completed (Figure 1a) and EMG MPF decreased from the initial repetition from 50-100% of total repetitions completed (Figure 1b). For the MMG responses, the men and the women demonstrated no change across time for MMG AMP (Figure 1c) and decreases in MMG MPF (Figure 1d) from the initial repetition at only 100% of total repetitions completed. During fatiguing tasks, increases in EMG AMP are associated with increases in muscle excitation due to increases in motor unit recruitment or motor unit firing rate (Basmajian, 1979; Beck and Housh, 2008), while decreases in EMG MPF are associated with a decrease in motor unit action potential conduction velocity due to the accumulation of metabolic byproducts such as ammonia, inorganic phosphate, H+ ions, and potassium ions (Enoka and Stuart, 1992). Furthermore, fatigue-induced increases in MMG AMP are associated with increases in motor unit recruitment, while fatigue-induced decreases in MMG MPF reflect decreases in the global motor unit firing rate (Beck et al., 2005; Beck et al., 2007). Further, the MMG AMP can be influenced by increases in intramuscular pressure, that can attenuate the MMG AMP signal (Beck et al., 2007; Orizio, 1993). Thus, there may have been competing influences between motor unit recruitment, which increases the signal, and intramuscular pressure, which decreases the signal, and thus resulted in no change in MMG AMP over time during repetitions performed to failure at CL in the current study (Beck et al., 2007; Orizio, 1993). The lack of sex differences in EMG and MMG responses in this study are in contrast to previous investigators findings who reported a sex difference in the neuromuscular responses during fatiguing muscle actions of the leg extensors (Clark et al., 2005; Keller et al., 2020). Specifically, Clark et al. (2005) reported women had a greater increase in quadriceps muscle activation (41.6%) compared to men (32.6%) during fatiguing, isometric muscle actions of the leg extensors performed at 25% maximal voluntary contraction. In addition, Keller et al. (2020) reported similar patterns of responses for EMG AMP and EMG MPF between men and women during fatiguing, isometric muscle actions of the leg extensors performed at a rating of perceived exertion of 2. However, for the MMG signals, the men demonstrated increases in MMG AMP and decreases in MMG MPF while the women demonstrated no change across time (Keller et al., 2020). Unlike the present study, previous investigations anchored exercise intensity based on a relative percentage of maximal capacity (Clark et al., 2005) or perceived exertion (Keller et al., 2020), while the current study anchored performance based on individual fatigue capabilities. Thus, the current study suggests a lack of sex differences in neuromuscular responses when resistance exercise is performed to failure at an intensity related to an individual fatigue threshold (i.e., the CL).

Limitations and Future Directions

This study is one of the first to examine sex-specific responses in muscular performance and neuromuscular parameters when an isolated, lower-body, DCER exercise is performed to failure at the CL. However, there were still limitations to this study. For example, we did not control for the menstrual cycle or oral contraceptive use. Although there are conflicting conclusions on the effect of the menstrual cycle and oral contraceptives on strength and performance (Constantini et al., 2005; Elliot et al., 2003; Sarwar et al., 1996), consideration of these variables is important for examining the full effect of sex-differences and performance. Future studies should control for the menstrual cycle and oral contraceptives and perform trials during the phase least affected by changes in hormonal concentrations. In addition, we were unable to obtain a performance measure of muscle fatigue, such as a maximal voluntary contraction pre- and post-exercise. Therefore, future studies should include a maximal voluntary contraction before and immediately after performing repetitions to failure at the CL to examine performance fatigability when exercise is performed at a threshold reflective of individual fatigue capabilities.

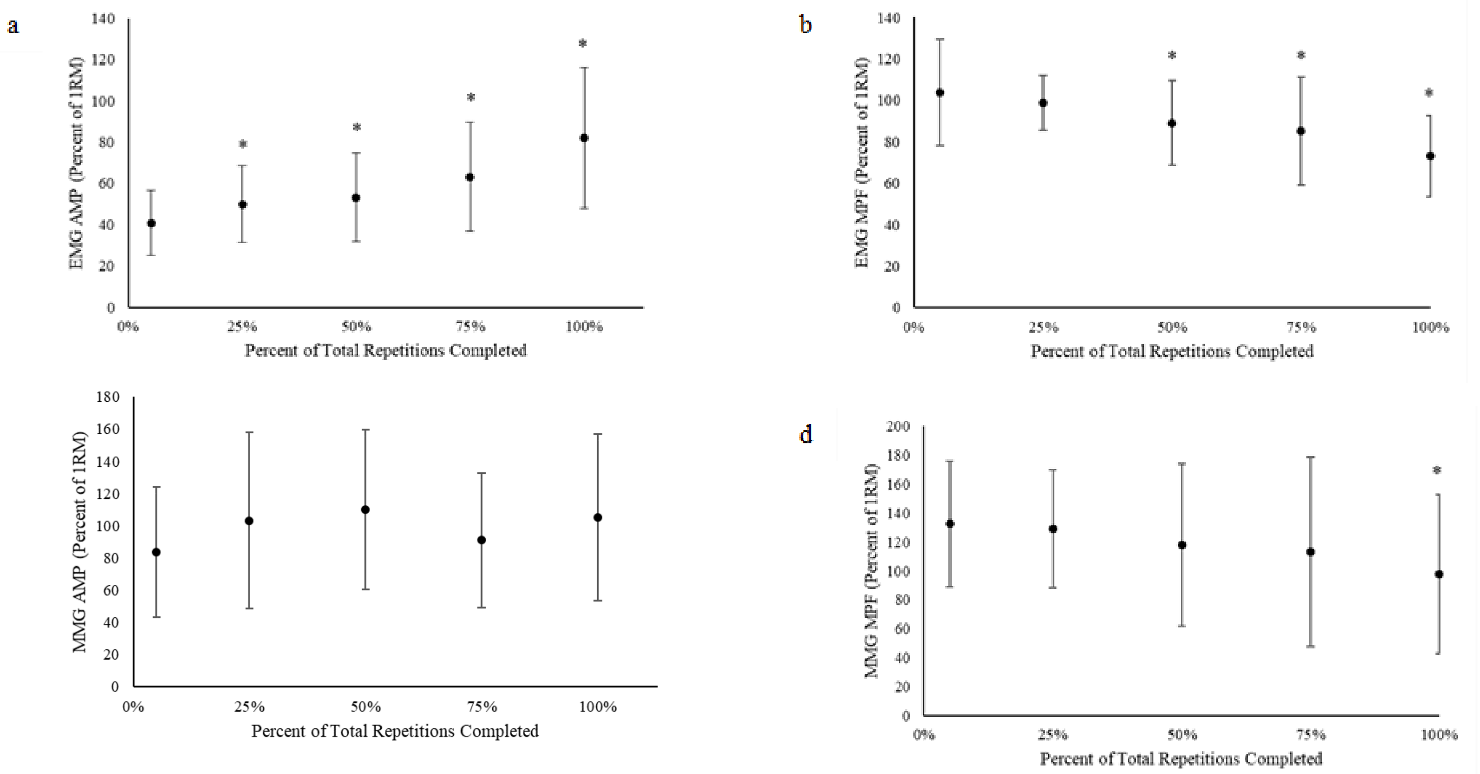

Fig. 1 Normalized a) electromyography (EMG) amplitude (AMP), b) EMG mean power frequency (MPF), c) mechanomyography (MMG) AMP, and d) MMG MPF responses (mean ± SD) collapsed across sex during leg extension repetitions performed to failure at critical load.

*indicates significantly different than the initial 5% of total repetitions completed (See Results section and Tables 2-5 for complete ANOVA decomposition)

1RM = one-repetition maximum

Conclusion

The present study examined the sex-related differences in the neuromuscular parameters (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) during fatiguing, bilateral, leg extension exercise performed at the CL. Previously, investigators have demonstrated women were more fatigue resistant than men when repetitions of the deadlift were performed to failure at the CL (Dinyer et al., 2019a). In the current study, however, there were no sex-dependent responses in the number of leg extension repetitions performed to failure at CL, or in the neuromuscular parameter responses between the men and the women. In addition, more repetitions were performed to failure during an isolated resistance training movement (i.e., leg extension) in the present study compared to a whole-body resistance training movement (i.e., deadlift) (Dinyer et al., 2019a). Thus, this study demonstrated a mode-specific response to fatiguing exercise that may be related to the total amount of active muscle mass involved in the task. Specifically, sex-specific fatigue responses may be less apparent when the active muscle mass engaged is much smaller (i.e., isolated leg extension) compared to a whole-body exercise (i.e., deadlift). As such, consideration of sex-specific exercise prescription may be more important when whole-body exercises are performed but require less of a consideration during isolated muscle actions. In addition, the current study used a DCER exercise to examine sex-dependent responses in muscular performance. Typically, DCER exercises are more commonly prescribed in traditional resistance training programs and include an eccentric muscle action that is not present during intermittent isometric or sustained isometric muscle actions. Therefore, while sex-differences have been reported for intermittent and sustained isometric muscle actions (Ansdell et al., 2019; Chartogne et al., 2020), this may not translate to more commonly prescribed DCER exercises. Thus, future studies should examine a wide array of DCER exercises to provide insight on the fatigue response during these exercises performed at the CL.

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