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ORIGINAL ARTICLE

Trained females exhibit less fatigability than trained males after a heavy knee extensor resistance exercise session

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Abstract

Purpose We examined differences between trained males and females in measures of muscular fatigability and central motor output after a resistance exercise session.

Methods Sixteen trained males ($n = 8$) and females ($n = 8$) participated in the study. Knee extensor maximal torque and rate of torque development were measured before and after the exercise session, and the twitch interpolation technique was used during the maximal efforts to derive measures of voluntary activation and muscle contractility by supramaximal stimulation of the femoral nerve using 10 and 100 Hz doublets. Surface electromyograms were recorded during all maximal efforts to examine maximal and rate of quadriceps muscle activation.

Results After exercise, maximal torque was reduced for both sexes by 26.3 ± 12.5% ($p < 0.001$). Absolute and relative vRTD was reduced only for males after exercise ($p < 0.05$). The early (0–50 ms) rate of muscle activation rise was similarly reduced for both sexes between 2.6 and 16.4% s^{-1} ($p < 0.01$), but males experienced an average decrease of 82.5 ± 72.1% s^{-1} for the maximal rate of muscle activation compared to no change for females ($p = 0.02$). Males had greater reductions ($p < 0.05$) for maximal twitch amplitudes and rate of twitch development (− 51.1 ± 21.5% and − 49.9 ± 22.8%, respectively) compared to females (− 35.8 ± 13.7% and − 31.5 ± 14.0%, respectively).

Conclusions These findings suggest that trained females are resistant to reductions in rapid torque development, despite similar reductions in maximal torque, after resistance exercise, with this result explained by better-maintained muscle contractility and maximal rate of muscle activation compared to males.

Keywords Fatigue · Exercise · Sex · Resistance · Physiology

Abbreviations

1-RM	1-repetition maximum strength test
½ RT	Half relaxation time
ANOVA	Analysis of variance
β	Beta, representing the estimate for type II experimental error
BW	Bodyweight
d	Cohen's effect size
MVC	Maximal voluntary isometric contraction
MVT	Maximal voluntary torque
M-wave	Muscle compound action potential
RER	Rate of EMG rise
sEMG	Surface electromyogram
TPT	Time to peak twitch
VA	Voluntary activation
VL	Vastus lateralis
VM	Vastus medialis
vRTD	Voluntary rate of torque development

Introduction

At present, between-sex differences in many physiological responses to exercise are unknown.

Specifically, there is a paucity of information regarding between-sex differences in muscular fatigability following an acute resistance exercise session in trained individuals. It is believed males and females exhibit differences in muscular fatigability following isometric and dynamic contractions,

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where fatigability may be defined by reductions in maximal voluntary torque and rate of torque development (Vøllestad 1997). Females appear to display longer time to exhaustion in both sustained and dynamic tasks across a range of contraction intensities and muscle groups (Hunter 2014). This between-sex difference in fatigability is explained via a number of factors such as greater perfusion to active muscle and increased utilisation of oxidative metabolism in females (Maughan et al. 1986; Russ and Kent-Braun 2003), the greater strength and muscle mass typically observed in males (Janssen et al. 2000; Miller et al. 1993), in addition to differences in muscle contractility and central motor output (Lee et al. 2017). The translation of these experimental findings to clinical practice to inform resistance exercise prescription for males and females is difficult. Studies typically use a fixed contraction intensity for the exercise bout (e.g. 20 or 80% maximal strength), or an isolated concentric or eccentric only movement (Hunter et al. 2004a, b; Russ and Kent-Braun 2003). No study has examined the sex-based differences in fatigability following a resistance exercise prescription typically used in a training environment that involves a range of contraction intensities and combination of both concentric and eccentric movements. Moreover, no study has examined whether between-sex differences in fatigability exist in trained males and females.

To our knowledge, previous research has only examined sex-based differences in fatigability of untrained individuals, with mechanistic measures typically investigating the contributions of muscle contractility (i.e. electrically evoked twitch responses of muscle) and central motor output (i.e. muscle activation, voluntary activation) (Hunter et al. 2004b; Maughan et al. 1986; Russ and Kent-Braun 2003; Yoon et al. 2007). For example, males exhibit greater reductions in evoked twitches of the elbow flexor muscles compared to females (Hunter et al. 2006a), suggesting that factors associated with the contractility of muscle (i.e. perfusion, fiber type) influence between-sex differences in fatigability. Studies on sex-based differences have also identified measures of central motor output as a contributor to the greater fatigability in males than females (Russ and Kent-Braun 2003), with males exhibiting greater reductions in voluntary activation of the ankle dorsiflexors (Russ and Kent-Braun 2003) and knee extensors compared to females (Hunter et al. 2004a, b). It is unclear whether similar between-sex differences for reductions in muscle contractility and measures of central motor output will be observed in resistance trained males and females.

In trained males central motor output, as measured from both voluntary activation and changes in the normalized rate of rise in muscle activity, was well maintained after isometric leg extension contractions despite reductions in quadriceps twitch amplitude of up to 70% from baseline values (Marshall et al. 2015). This resilience in central motor output despite a large loss of muscle contractility was thought to be explained by the adaptations in the central nervous system (Carroll et al. 2002) exhibited by trained individuals such as increased supraspinal drive and greater input–output responses at the level of the α-motoneuron (Aargaard et al. 2002; Ekblom 2010; Vila-Chã et al. 2012). It is unclear whether any sex-based differences in central motor output will be observed in trained individuals. While it appears trained males are resistant to reductions in central motor output following single limb exercise (Marshall et al. 2015), this has not been examined in trained females. Therefore any differences in fatigability (i.e. reductions in maximal and rate of torque) observed after resistance exercise in trained males and females may only be explained by greater reductions in muscle contractility as opposed to central motor output.

The purpose of this study was to examine changes in fatigability and concomitant measures of muscle contractility and central motor output after a leg extension focused resistance exercise session in trained males and females. We hypothesized that reductions in maximal force and rate of force development would be greater in resistance trained males, and that these reductions would be associated with a larger reduction in evoked twitches from the quadriceps as an estimate of muscle contractility. Similar to previous reports in trained males, we also hypothesized that resistance trained females would exhibit no reductions in central motor output after a session of single-limb resistance exercise.

Methods

Subjects

Eight resistance trained males (mean ± SD; age 26 ± 5 years, height 1.77 ± 0.07 m, weight 78.2 ± 8.7 kg) and eight resistance trained females (mean ± SD; age 25 ± 3 years, height 1.62 ± 0.06 m, weight 68.2 ± 3.0 kg) volunteered to participate in this study after providing informed written consent. All volunteers had at least 3-year resistance training experience (≥ 3 times per week for most training weeks of the year), with regular performance of both upper and lower body resistance exercises. All participants were familiar with the required exercise task (i.e. knee extension), and were right leg dominant, but none reported weekly performance of the movement. All procedures in this study were approved by the local institution human research ethics committee (H10839), and were conducted in accordance with the Declaration of Helsinki.

Experimental design

Participants made two preliminary visits to the laboratory separated by 24 to 48 h for familiarisation with the femoral nerve stimulation protocol and isometric testing of the knee extensors (session 1), in addition to single-leg dynamic 1-repetition maximum (1-RM) knee extension testing (session 2; Hammer Strength Iso-lateral knee extension, Life Fitness, Sydney, AUS). The main experimental session took place 5–7 days after the second familiarization session. At the first familiarization session we ensured participants were not anticipating or reducing their torque output prior to stimulation by continuing to provide instruction and practise until there was no difference in maximal torque between trials with and without stimulation (Button and Behm 2008). We provide detailed instruction for how to perform the maximal contractions in the presence of the stimulation, which has been informed by our regular use of these techniques in our laboratories (Marshall et al. 2015, 2018). This instruction includes advice to "keep pushing through the stimulation", "don't try to guess when it will happen", in addition to the instruction for the maximal contraction to be "as fast and forceful as possible". Loud verbal encouragement was also provided throughout all maximal efforts. Participants were also familiarised with pre-test nutritional and exercise guidelines concerning restriction from alcohol (24 h) and caffeine (12 h) consumption, and resistance or strenuous aerobic exercise for the legs (48 h).

To standardize pre-workout nutrition, a beverage consisting of 0.5 g kg^{-1} BW of maltodextrin and 0.3 g kg^{-1} BW whey protein was consumed 1 h prior to testing. Maximal voluntary isometric contractions (MVC) of the knee extensors were performed before and after the experimental training session on a dynamometer (KinCom 125, Version 5.32, Chattanooga, USA). Participants were seated with their hip and knee joints flexed to 90° and 75°, respectively. The centre of rotation of the lever arm was aligned with the sagittal plane axis of the knee joint, and the lever arm of the dynamometer was firmly attached 2–3 cm superior to the lateral malleolus. The participant was firmly strapped into the chair with straps across the trunk during all MVCs. Torque output signals were continuously sampled from the dynamometer at 1000 Hz (Powerlab, ADI Instruments, Sydney, AUS), and low pass filtered at 10 Hz. Torque signals were calibrated in the resting test position for each participant's limb weight (after all straps were applied), and a predetermined calibration factor was applied to obtained signals for conversion of the recorded voltage to torque (N m).

Before pre-training MVCs, participants performed a series of sub-maximal isometric knee extension efforts (25, 50, 75% of perceived maximal effort). Two MVCs were then performed with 2 min rest between efforts. Each MVC was required to be as fast and forceful as possible, and maintained for 3–4 s. Surface electromyograms (sEMG) were continuously recorded from the vastus lateralis (VL) and vastus medialis (VM) during MVCs. Femoral nerve stimulation (see "Femoral nerve stimulation") was applied during and after each MVC. Strong verbal encouragement was provided during all MVCs. After the training session a post-training MVC was performed within 1–1.5 min after completion of the protocol.

Exercise session

Knee extension range of motion for each repetition was from the seated starting position on the knee extension machine with the participant reclined so the lower limb was vertical and the knee joint angle at 110° flexion, to the end range of motion with the lower limb approximately parallel to the floor (just before terminal knee extension). The session commenced with an un-weighted warm-up set of ten self-paced repetitions, followed by a self-paced warm-up set at 40% of 1-RM, from which range of motion was established (approximately 105°). Knee joint angular position was continuously monitored at 1000 Hz (10 Hz low pass filter) from a single axis electrogoniometer (ADI Instruments, Sydney, AUS). A coloured area, starting from 10° below maximal normal range of motion, was subsequently marked on the computer screen for a research assistant to objectively determine a successful knee extension repetition.

The resistance exercise session was prescribed to accrue volume across a range of high-intensity contractions based on the previously measured single leg 1-RM (male average 1-RM, 40.3 ± 8.3 kg; female average 1-RM, 21.3 ± 4.6 kg), similar to a strength-based session in clinical practice. The working sets included 10 repetitions (reps) × 60% 1-RM, 2 sets × 5 reps at 80% 1-RM, 1 set × 5 reps at 85% 1-RM, 1 set × 3 reps at 87.5% 1-RM, and 1 set × 2 reps at 90% 1-RM. Finally, participants were required to perform two sets to repetition failure (inability to reach minimum range of motion) at 80% 1-RM (1.5–2 min rest between sets). All repetitions were required to be performed as explosively as possible in the concentric phase, with a controlled lowering of 1.5–2 s.

Surface electromyography

sEMG was recorded from the VL and VM using pairs of Ag/AgCl surface electrodes (Maxsensor, Medimax Global, Australia). Electrodes (10 mm contact diameter, 10 mm inter-electrode distance) were placed in bipolar configuration parallel to the direction of the muscle fibres after careful skin preparation (shaving excess hair, careful abrasion with fine sandpaper and cleaning the skin with isopropyl alcohol swabs). The inferior VL electrode was placed 8–12 cm superior to the lateral aspect of the patella, and the inferior VM electrode 3–4 cm superior to the medial aspect of the patella. The reference electrode was placed on the right patella. sEMG signals were recorded using the ML138 Octal BioAmp (common mode rejection ratio > 85 dB at 50 Hz, input impedance 200 MΩ) with 16-bit analog-to-digital conversion, sampled at 4000 Hz (ADI instruments, Sydney, AUS). Raw signals were filtered with a fourth-order Bessel filter between 20 and 500 Hz, and subsequently smoothed for analysis using a 50 ms root-mean-square calculation (RMS).

Femoral nerve stimulation

A 5 × 9 cm custom electrode of aluminium foil and conduction gel was taped to the lateral aspect of the hip, between the iliac crest and greater trochanter as the anode. To identify femoral nerve location for cathodal stimulation, a rubber insulated portable cathodal probe was used. The probe was moved around the femoral triangle using a single stimulus intensity of 30 mA until the largest muscle compound action potential (M-wave) was elicited from both the VL and VM recording sites. When optimal nerve location was identified, this was marked with a felt-tip pen and a 2 cm diameter Ag/AgCl surface electrode was applied.

The quadriceps were stimulated during all MVCs by supramaximal doublets applied to the femoral nerve (200-µs square pulses) at 100 Hz and 10 Hz by a high voltage (400 V) constant current stimulator (Digitimer DS7AH; Digitimer, Hertfordshire, UK). The two different stimulation frequencies were used to provide a profile of low-frequency fatigue (by comparison of the 100–10 Hz responses), and to provide two different methods for calculation of voluntary activation (VA) to ensure an accurate representation of maximal central motor output. Stimulation intensity to be used during testing was determined by progressively increasing the current in 10 mA increments until plateaus occurred in twitch amplitude and M-waves in response to 10 Hz doublet stimulation. Supramaximal stimulation was ensured by increasing the final intensity from the plateau by 30% (intensity range for testing 80–190 mA).

During each MVC two superimposed doublets (100 Hz and 10 Hz) were applied to the femoral nerve when torque had reached a visible plateau (Behm et al. 1996). A 1.5 s time period was used between applied doublets. Quadriceps resting potentiated twitches were evoked by delivering two doublets (10 Hz and 100 Hz) to the resting muscle, with the first stimulation in the doublet sequence delivered 2–3 s post contraction. Doublets were applied in a random order between all measurements. Similar to our previous report (Marshall et al. 2015a), dependent variables were not influenced by the order of doublet stimulation.

MVC data processing

Contraction onset for voluntary torque and resting evoked twitches were identified with an automated algorithm in the software as the point after which torque exceeded the baseline by 2.5 N m and 1 N m, respectively. VL and VM muscle onsets were visually determined (Hodges and Bui 1996). Torque recordings were used to analyse (1) the maximal voluntary torque recorded during the contraction up to the first point of stimulation (MVT, N m), (2) rate of voluntary torque development (vRTD) calculated as the average slope of the torque–time curve (Δtorque/Δtime) during the time periods 0–25 ms (vRTD_{25}), 0–50 ms (vRTD_{50}) and 0–75 ms (vRTD_{100}) post contraction onset, and (3) maximum voluntary RTD ($\mathrm{vRTD}_{\mathrm{MAX}}$) was calculated as the greatest average 10 ms slope throughout the first 200 ms of the contraction. All vRTD measures were normalised to the corresponding MVT to control for between-sex differences in strength.

Voluntary activation (VA) was estimated from the 10 Hz (VA_{10}) and 100 Hz (VA_{100}) stimulations using the superimposed twitch technique (Merton 1954) according to the following formula (Strojnik and Komi 1998): VA (%) = 100 − ($D \times (T_{\mathrm{sup}}$/MVT)/PT) × 100, where D is the difference between the torque level just before the superimposed twitch (T_{sup}) and the maximum torque recorded during the twitch, MVT is maximal voluntary torque during the entire contraction (not including the twitch response), and PT is the maximal amplitude of the resting potentiated twitch for either the 10 Hz or 100 Hz doublet. In addition to the maximal amplitude of the resting potentiated twitch (PT_{10} and PT_{100}), the following variables were calculated: (1) the time-to-peak twitch (TPT_{10} and TPT_{100}) and (2) the half relaxation time (½ RT_{10} and ½ RT_{100}), calculated as the time from the peak amplitude until 50% of the maximal amplitude had been reached on the descending slope of the twitch torque curve.

All sEMG variables during maximal contractions were normalised to the first respective M-waves elicited during 10 Hz stimulation applied to each contraction for data analysis (EMG/M, %). sEMG recordings were used to analyse the following variables from each MVT measurement: (1) the electrically evoked M-wave from the first response to the 10 Hz doublet, calculated from the peak-to-peak amplitude of the VL and VM sEMG raw signal elicited during contraction, (2) the maximal amplitude of the VL ($\mathrm{VL}_{\mathrm{MAX}}$) and VM ($\mathrm{VM}_{\mathrm{MAX}}$) sEMG signal during MVTs based on processing the greatest average 250 ms RMS value, (3) the rate of sEMG rise for VL and VM ($\mathrm{VL}_{\mathrm{RER}}$ and $\mathrm{VM}_{\mathrm{RER}}$) were calculated from the average slope of the RMS sEMG-time curve during the time periods 0–25, 0–50, and 0–75 ms post contraction onset, and (4) the maximal rate of sEMG rise for VL ($\mathrm{VL}_{\mathrm{RERmax}}$) and VM ($\mathrm{VM}_{\mathrm{RERmax}}$) calculated from the greatest 10 ms slope of the RMS EMG-time curve throughout the first 200 ms of the contraction.

Statistical analyses

Analysis of variance (ANOVA) procedures were used to examine the changes in the dependent variables over time, and compare these changes between the sexes. When a significant main effect was observed, post-hoc tests with Bonferonni's correction were applied to identify differences. G-Power statistical software was used for d effect size and post-hoc power estimates (Erdfelder et al. 1996), where $d = 0.8$ is a large effect, $d = 0.5$ is moderate, and $d = 0.3$ a small effect. Unless otherwise stated data are mean ± SD. Statistical significance was defined as $p \leq 0.05$.

Results

Maximal torque and rate of torque development

Males and females experienced similar changes in maximal torque from baseline values of 254.5 ± 31.9 N m and 180.6 ± 32.0 N m, respectively, with an average reduction of − 26.3 ± 12.5% (main time effect $p < 0.001$: $d = 1.52$, $1 - \beta = 0.99$; males − 26.6 ± 16.9%, females − 25.9 ± 6.8%). Differences between the sexes were observed for reductions in vRTD in time intervals of 0–50, 0–75, and 0–100 ms after contraction onset in addition to vRTD max (Fig. 1; $p < 0.05$; effect size range for between-sex differences for vRTD measures, $d = 1.4$–2.2; lowest post-hoc power estimate $1 - \beta = 0.84$). Males experienced a mean reduction of between 446.5 and 806.3 N m s^{-1} ($p < 0.05$) after exercise in vRTD measures, while females did not decrease from pre-exercise values. An interaction between the sexes was observed for NvRTD in time intervals of 0–50, 0–75, and 0–100 ms post contraction onset ($p < 0.05$; effect size range for between-sex differences for vRTD measures, $d = 1.27$–1.6; lowest post-hoc power estimate $1 - \beta = 0.78$), and for NvRTDmax ($p = 0.014$). No reductions were observed for females (effect size range, $d = 0.15$–0.21). For males, NvRTD was reduced between 26.3 and 36.4% in time intervals from 0–50 to 0–100 ms post contraction onset, and 25.4 ± 14.5% for NvRTD max. For NvRTD 0–25 ms, a trend for the between-sex difference observed at all other time points was observed ($p = 0.064$, $d = 1.01$, $1 - \beta = 0.61$).

Central motor output

No changes were observed for VA_{10} ($d = 0.09$, $1 - \beta = 0.06$), VA_{100} ($d = 0.50$, $1 - \beta = 0.60$) (Table 1), or VL and VM max% ($d = 0.09$ and $d = 0.19$ respectively). Males and females experienced similar reductions in VL_{RER} sEMG in time intervals of 0–25 ms ($p = 0.032$, $d = 0.62$, $1 - \beta = 0.76$) and 0–50 ms ($p = 0.002$, $d = 0.99$, $1 - \beta = 0.99$) of between 7.9 to 16.4%.s^{-1} (Fig. 2). Similar reductions for both sexes were observed for VM_{RER} sEMG in time intervals of 0–25 ms and 0–50 ms between 2.6 and 10.6% s^{-1} ($p < 0.05$, $d = 0.54$ and $d = 0.62$, respectively, $1 - \beta = 0.66$). Between-sex differences in VL_{RERmax} were detected ($p = 0.02$, $d = 1.19$, $1 - \beta = 0.99$), with females not displaying a change over time while males experienced an average decrease of 82.5 ± 72.1% s^{-1} (Fig. 2).

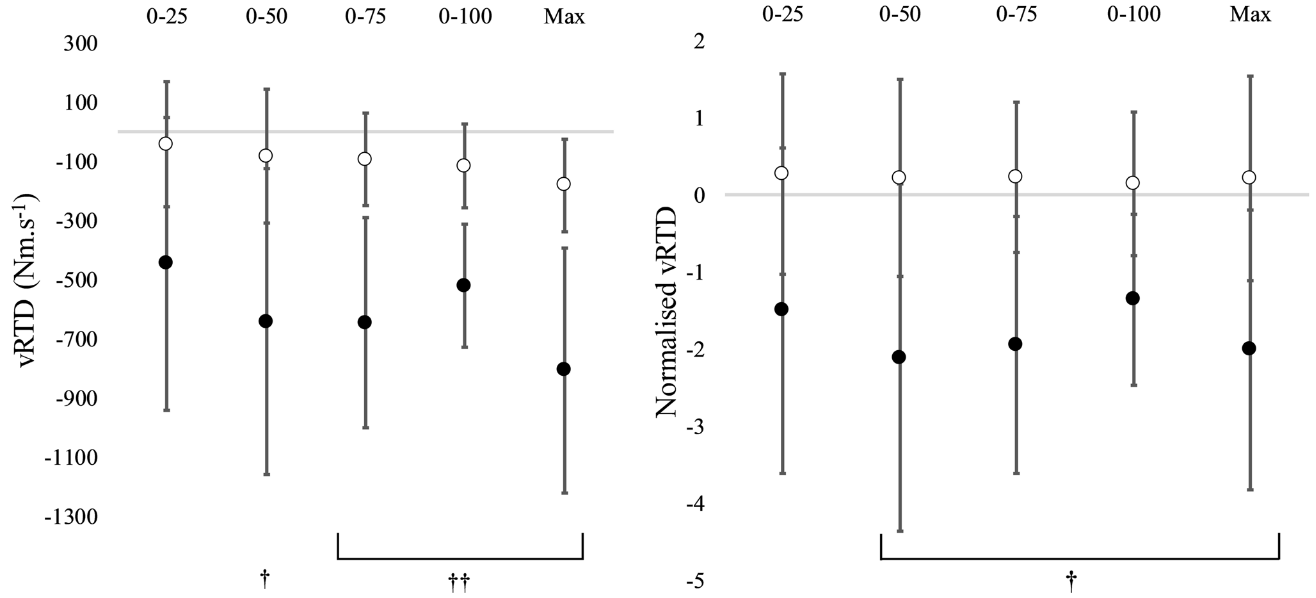

Fig. 1 Change from PRE exercise for voluntary (vRTD) and normalized rate of torque development (NvRTD) for males (filled circles) and females (open circles) after contraction onset. Values were only reduced from pre-exercise for males ($p < 0.05$). $^{\dagger}p < 0.05$ and $^{\dagger\dagger}p \leq 0.01$ for between-sex differences in the change score. Data are mean ± SD

Table 1 Change after the exercise session for measures of voluntary activation (VA, %), time-to-peak twitch (TPT, ms), ½ relaxation time (1/2 RT, ms), and peak amplitude of the resting twitches (PT, N m) measured with 10 Hz and 100 Hz stimulation frequencies

Doublet	Sex	VA (%)		TPT (ms)		½ RT (ms)		PT (N m)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
10 Hz	Male	88.2 ± 3.5	86.7 ± 5.1	158.6 ± 2.5	161.9 ± 16.3	76.3 ± 8.0	100.5 ± 23.7	92.5 ± 17.5	36.6 ± 13.8†
	Female	88.9 ± 5.1	89.6 ± 7.2	150.3 ± 5.3	148.1 ± 6.8	109.4 ± 43.1	94.3 ± 36.8	75.9 ± 5.7	40.8 ± 6.9***
100 Hz	Male	82.8 ± 84.6	84.6 ± 7.2	90.3 ± 4.5	88.2 ± 9.8	65.9 ± 7.7	89.8 ± 29.9	102.0 ± 11.0	55.2 ± 18.2†
	Female	76.0 ± 10.6	84.2 ± 8.1	90.9 ± 9.0	83.3 ± 10.9	82.2 ± 27.3	86.6 ± 20.7	68.4 ± 3.4	51.1 ± 6.2***

Data are mean ± SD

***$p < 0.001$ from pre exercise

$^{\dagger}p < 0.05$ for between-sex interaction

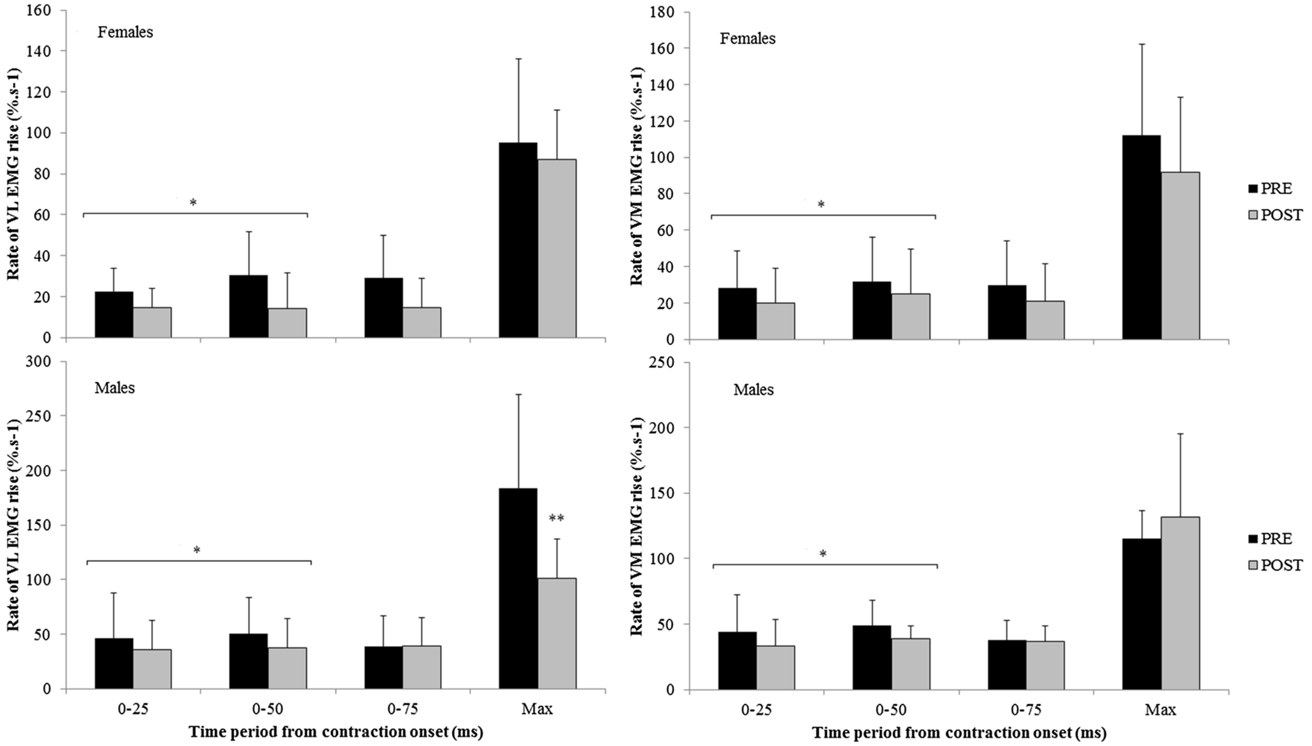

Fig. 2 VL and VM rate of EMG rise (RER, % s^{-1}) for female and male participants measured PRE and POST the resistance exercise session. Main time effects were observed for the 0–25 and 0–50 ms time periods for males and females. *$p < 0.05$ from PRE exercise values for the encompassed time intervals after contraction onset, and **$p < 0.01$ for the reduction from baseline for males. Data are mean and SD

Muscle contractility

Maximal twitch amplitudes measured at 10 Hz (males 92.5 ± 17.5 N m, females 75.9 ± 5.7 N m) and 100 Hz (males 102.0 ± 11.0 N m; females 68.4 ± 3.4 N m) were reduced for both sexes after exercise ($p < 0.001$, Table 1), although the reduction for males was greater than females for both stimulation intensities (Table 1, $p = 0.022$, between-sex differences for 10 Hz $d = 0.84$, 100 Hz $d = 1.24$, lowest $1-\beta = 0.94$). No changes were observed for ½ RT and TPT (Table 1). Declines in rate of twitch development were observed for both sexes ($p < 0.01$, Fig. 3), with greater reductions observed for males (i.e. maximum rate of twitch development, − 49.9 ± 22.8% for males, − 31.5 ± 14.0% for females; $p = 0.01$, $d = 1.04$, $1-\beta = 0.98$). VL and VM M-waves were 8.4 ± 2.5 mV and 16.4 ± 4.4 mV respectively at baseline, and remained unchanged after exercise.

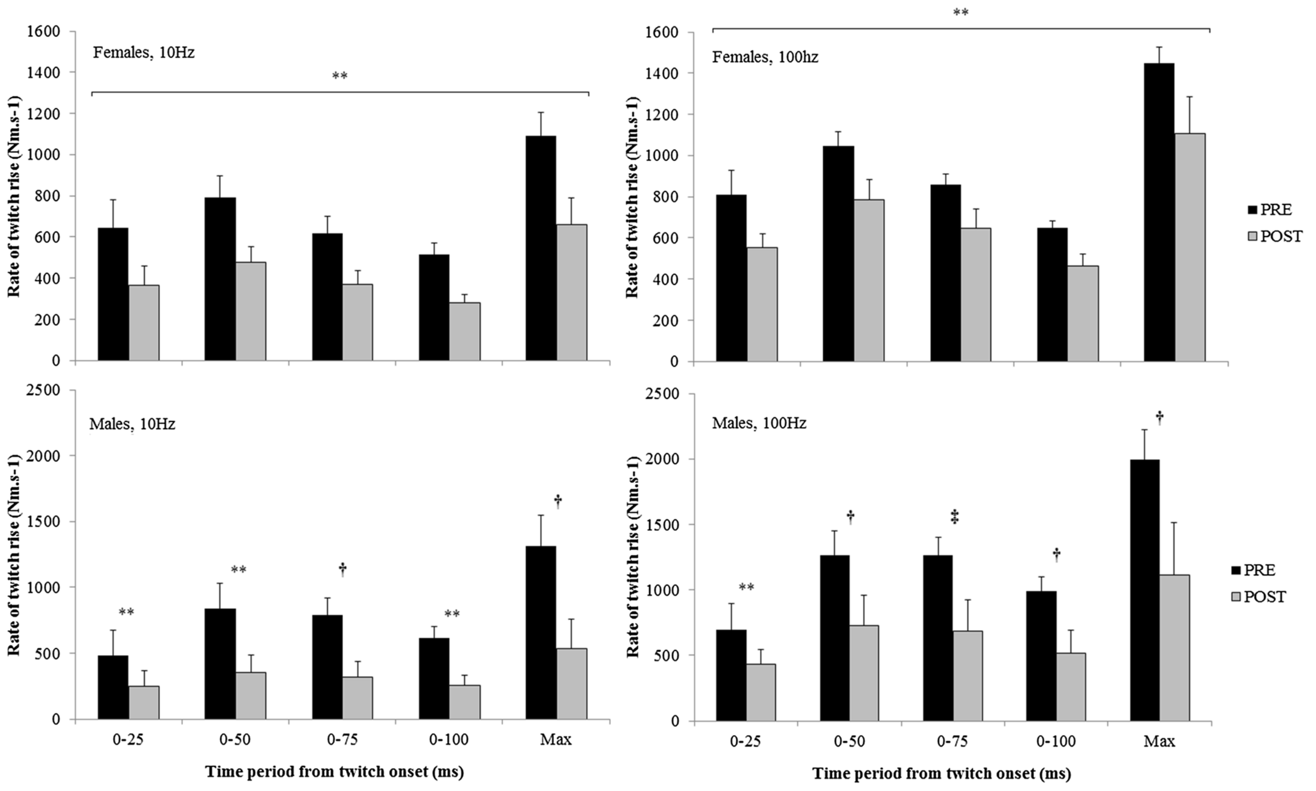

Fig. 3 Rate of twitch rise (N m s^{-1}) for female and male participants measured from the resting potentiated twitch PRE and POST the resistance exercise session. Twitch data is from the 10 Hz and 100 Hz doublets applied to the femoral nerve. $^{**}p < 0.01$ from PRE values for the encompassed time intervals after twitch onset, $^{\dagger}p < 0.05$ and $^{\ddagger}p < 0.01$ for greater reductions from PRE observed for males. Data are mean and SD

Discussion

To our knowledge, this is the first study that has assessed between-sex differences in the fatigability of trained individuals following a heavy resistance exercise session modeled off current industry best practice. The main finding of this study was that compared to trained females, trained males experienced larger absolute and relative reductions in voluntary rate of torque development while no between-sex differences were observed for declines in maximal torque. These between-sex differences appear to be explained by greater reductions in muscle contractility for trained males. A novel finding of this study was that resistance trained females maintained voluntary rate of torque development after the exercise session, despite reductions in maximal torque, early rates of muscle activation, and muscle contractility. These findings suggest females are less fatigable than males when exposed to the same exercise stimulus.

The between-sex difference for declines in both absolute and relative rate of torque development after the exercise session can be attributed to the greater loss in muscle contractility experienced by the males. While VL RERmax declined for males, all other measures for early rates of muscle activation declined similarly for both sexes. We believe the overall pattern of results suggest that early muscle activation declines similarly for both sexes, and therefore does not explain the greater declines in rate of torque development for males. Of interest, the greater decline for males in relative rate of torque development were present even when controlled for the between-sex differences in absolute muscle strength, which is often thought to be (combined with muscle mass) a primary reason for the greater fatigability of males (Hunter et al. 2004a, 2006b; Hunter and Enoka 2001). The between-sex differences in contractility observed in this study support similar findings in untrained males and females (Lee et al. 2017; Russ and Kent-Braun 2003), and extends these findings to trained individuals. Two factors that may contribute to the between-sex difference in muscle contractility loss after the resistance exercise session are the greater muscle perfusion (Hunter 2014; Tarnopolsky et al. 1990), and proportion of type I muscle fibers in females (Hunter 2014; Roepstorff et al. 2006; Staron et al. 2000).

Greater capillarization in the vastus lateralis of females (Roepstorff et al. 2006) combined with hormonally mediated vasodilation (Parker et al. 2007) allows increased perfusion and thus delivery of oxygen to the working muscle in addition to increased clearance of metabolites (e.g. H^+) which may otherwise impede muscular contraction (Hunter 2014). Between-sex differences in fatigability have been eliminated through occlusion of blood flow to the muscle (Russ and Kent-Braun 2003), illustrating the relationship between muscle perfusion and fatigability. In addition to greater perfusion females also have a higher proportion of type I fibers relative to the area of muscle compared to males (Hunter 2014; Roepstorff et al. 2006; Staron et al. 2000). Type I fibers and muscles that are predominantly type I (e.g. triceps surae) exhibit slower electrically evoked contractile properties (e.g. time to peak twitch, rate of twitch development, relaxation time), and lower voluntary rate of torque development (Harridge et al. 1996; Siegler et al. 2016), but are more fatigue resistant than type II fibers and muscles that are predominantly type II (e.g. triceps brachii) (Fitts 2003; Schiaffino and Reggiani 2011). Therefore the greater contractility loss of males in this study may, in part, be explained by the greater area of muscle contributed to by type II fibers. A limitation to this study was that neither muscle perfusion or muscle fiber type and area were measured to provide insight into the between-sex contractility differences observed here.

In contrast to previous research, no between-sex differences were observed for declines in maximal central motor output, measured from voluntary activation and normalized quadriceps surface electromyograms. Indeed, we observed no reductions for either sex in measures of central motor output that are associated with production of maximal torque, and no difference between sexes for declines in early rates of muscle activation. Therefore, the overall pattern of results suggests that declines in both maximal torque and rate of torque development are likely explained by the reductions in muscle contractility observed in this study. The difference in findings between this study and previous reports suggesting greater voluntary activation reductions in males (Lee et al. 2017; Martin and Rattey 2007) is probably explained by our use of trained as opposed to untrained or novice individuals. Our findings support and extend recent observations from trained males to resistance trained females (Marshall et al. 2015), with these resistance trained participants exhibiting no reductions in maximal central output despite large reductions in muscle contractility. This resilience of the nervous system in trained participants to high levels of muscle fatigability may be influenced by both the duration and single type of resistance exercise used in the session. Similar to the previous observation for no declines in voluntary activation for trained males, we used a knee extension exercise model to provide a controlled exercise stimulus with a rapid post-exercise testing position (i.e. same movement for exercise and test). In contrast we recently observed declines in voluntary activation after a 1 h full-body resistance exercise session in trained males which included multiple lower body movements and incurred ~ 50% reduction in quadriceps twitch amplitude (Marshall et al. 2018). It may be likely that a different between-sex response in measures of central motor output could be observed after a longer duration full-body session. A longer session of resistance exercise may allow between-sex differences in both muscle perfusion and metabolism to manifest in different central motor output and contractility responses. It is a limitation of this study that we did not examine a longer full-body training session.

At present, the role of muscular fatigability as a necessary stimulus for positive training outcomes (e.g. strength, hypertrophy, and power) in combination with the manipulation of volume and load is still debated (Morton et al. 2016; Schoenfeld et al. 2015; Yoon et al. 2007). In this study, the reduced fatigability of female participants highlights multiple areas in which sex-specific exercise prescription should be further examined. In the present study, due to the acute nature of the study design, we were not able to assess inter-session recovery. As we demonstrated an acute reduced fatigability in females, it is logical to hypothesize that a shortened recovery time between sessions when compared to males may be warranted. Extrapolating further, this may have implications with regards to training frequency and the flow on effect of accumulation of volume, which is a known variable positively associated with muscular adaptation (Marshall et al. 2011; Morton et al. 2016). These questions need to be examined in a well-designed training study surrounding these particular sex-specific outcomes.

Conclusion

The results of this study show for the first time that trained females exhibit less fatigability of muscle contractile function, maximal rate of muscle activation, and rate of torque development compared to males after a resistance exercise session. These findings have implications for coaches and trainers in regards to the level of fatigue expected from a given training stimulus, which may have flow on ramifications regarding other prescriptive variables including frequency and volume.

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