Neuromuscular fatigue following low-intensity dynamic exercise with externally applied vascular restriction

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ABSTRACT

This study investigated neuromuscular fatigue following low-intensity resistance exercise with vascular restriction (VR) and without vascular restriction (control, CON). Fourteen males participated in two experimental trials (VR and CON) each separated by 48 h. Each participant performed two isometric maximum voluntary contractions (MVCs) before and after five sets of 20 dynamic constant external resistance leg extension exercises (DCER-EX) at 20% of one-repetition maximum (1-RM). The participants were asked to lift (1.5 s) and lower (1.5 s) the load at a constant velocity. Surface electromyography (EMG) was recorded from the vastus lateralis during MVC and DCER-EX. Twitch interpolation was used to assess the percent of maximal voluntary activation (XVA) during the MVC. During performing five sets of 20 DCER-EX, the increases (p < 0.05) in EMG amplitude and decreases (p < 0.05) in EMG mean power frequency were similar for both VR and CON. However, there were significant differences between VR and CON for MVC force, XVA, and potentiated twitch force and significant interactions for EMG amplitude, VR decreased MVC force, XVA, potentiated twitch force, and EMG amplitude more than CON. Our findings suggest that the VR-induced fatigue may have been due to a combination of peripheral (decreases in potentiated twitch) and central (decreases in XVA and EMG amplitude) fatigue.

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1. Introduction

Maximal or near-maximal effort is necessary to recruit all available motor units and generate a high level of force (Wernbom et al., 2007). Coto et al. (2005) investigated the long-term effect (12 weeks) of metabolic stress on hormonal and hypertrophic responses. One group performed three different exercises consisting of 3–5 sets of 10 repetitions at 10-repetition maximum (10-RM) with a rest period of 1 min between sets. The other group also completed the same protocol, but they took an additional 30-s rest at the midpoint of each set of exercises. Even though the volume of training (sets × repetitions × loads) was matched between exercise groups, the group that rested for an additional 30 s in the middle of 10 repetitions for each set had a 4.0% increase in quadriceps cross-sectional area (CSA), while those who performed each set of 10 repetitions in a continuous manner to muscular failure had a 12.9% increase in quadriceps CSA. The authors suggested that near-maximal effort may be necessary to maximize the recruitment of motor units, which might be responsible for a greater hypertrophic response.

Training intensity at 67–85% of one-repetition maximum (1-RM) has been associated with increased skeletal muscle size and strength (Baechle and Earle, 2000). Although the number of motor units recruited is lower during low-intensity (20% 1-RM) submaximal resistance exercise compared to more vigorous training (greater than 65% 1-RM), several studies using low-intensity resistance training exercise (i.e., 20% 1-RM) combined with vascular restriction (VR) have observed increases in muscle size (Abd et al., 2006; Beedle et al., 2005; Takarada and Ishii, 2002; Takarada et al., 2000b, 2002) and strength (Shinohara et al., 1998; Takarada and Ishii, 2002; Takarada et al., 2002). Several hypotheses have been proposed to explain the hypertrophic adaptations to low-intensity resistance training combined with VR, which include motor unit recruitment patterns (Moritani et al., 1992; Takarada et al., 2000b; Yasuda et al., 2005) and increased metabolic stress (Sato et al., 2005; Takarada et al., 2000a; Yoshida and Watari, 1997).

Several techniques are used to investigate the muscular strength decrements associated with neuromuscular fatigue, such as surface electromyography (EMG) and twitch interpolation. The EMG signal reflects the linear algebraic summation of the electrical...
signals generated by the motor units within the electrode recording areas. The amplitude and frequency of the EMG may reflect motor unit activation and motor unit action potential conduction velocity (Basmajian and De Luca, 1985), respectively. Therefore, EMG signals have been used to investigate the mechanisms underlying neuromuscular fatigue (Beck et al., 2004; Esposito et al., 1998; Krogh-Lund, 1993; Pasquet et al., 2000; Perry-Rana et al., 2002).

Allen et al. (1995) used twitch interpolation to determine maximal motor unit activation and the contributions of central and peripheral mechanisms. This technique is used to determine the level of completeness of muscle activation during voluntary effort. The underlying principle of this technique is that some motor units are not recruited during an isometric maximal voluntary contraction (MVC) and applying a supramaximal electrical stimulation to the muscle or peripheral nerve during MVC should activate these motor units (Haies and Gandevia, 1988). The created detectable twitch contractions by using electrical stimuli during MVC contraction and rest have been used to determine the degree of central activation. The twitch interpolation technique has also been used to examine neuromuscular fatigue (Biro et al., 2007), neural activation strategies (Desbrosses et al., 2006), neural resistance training adaptations (Juberg et al., 2006), and clinical neural deficits associated with diseases (Molloy et al., 2006). Therefore, the simultaneous use of EMG and twitch interpolation may help to evaluate the mechanism(s) responsible for neuromuscular fatigue during VR.

When blood flow is restricted, the changes in the number of motor units recruited and their firing rates during submaximal resistance exercise might be similar to the changes in neuromuscular mechanism during high intensity (greater than 65% 1-RM) resistance exercise and could be some of the factors responsible for muscle hyper trophy and strength gains. Since the metabolic demand imposed by exercises alter as a function of exercise mode (concentric vs. isometric) (Kay et al., 2000) and maximal and explosive strength loading (Linnamo et al., 1998), blood flow restriction during low-intensity exercise might also result in a greater metabolic demand and higher perceived intensity. Since neuromuscular fatigue is tightly coupled with metabolic demand, reduced blood flow during low-intensity exercise increases the intramuscular accumulation of metabolic subproducts such as lactate (Takarada et al., 2000a), H+, and Pi (Babault et al., 2006), which then stimulate chemoreceptors and afferent nerves resulting in a decline of supraspinal drive (central fatigue) (Gandevia, 2001; Taylor et al., 2000). More research is needed to elucidate the mechanisms responsible for neuromuscular fatigue during low-intensity exercise with blood flow restriction. Therefore, the goal of this study was to investigate the effects of VR on MVC force, the percent of voluntary activation (SVA), and EMG amplitude and frequency from the vastus lateralis before, during, and after five sets of 20 repetitions of a leg extension exercise performed at 20% 1-RM.

2. Methods

2.1. Overview of study design

A randomized, counterbalanced, within-subjects experimental design was used to investigate the effects of VR on neuromuscular function before, during, and after leg extension exercises. Each subject completed an informed consent, PAR-Q questionnaire, 1-RM tests and was familiarized with the study procedure during a familiarization session. Each participant visited the laboratory two times for the experimental trials separated by at least 48 h. The participants performed the same exercise protocol with two randomized conditions, with VR and CON. During the experimental trials, resting blood pressure was determined and a 5-min warm-up was completed on a stationary cycle ergometer with a power of 50 W. The participants performed two pre-exercise isometric MVCs with 1-min rest between trials. Then five sets of 20 dynamic constant external resistance leg extension exercises (DCER-EX) at 20% 1-RM were continuously performed with a 30-s inter-set rest period. Following DCER-EX, each participant performed two post-exercise isometric MVCs. The means (SE) of each variable measured for both conditions are presented in Table 1. More details regarding the study design will follow.

2.2. Subjects

Fourteen healthy men (mean ± SE: age = 23.9 ± 0.9 year; height = 176 ± 1.3 cm; weight = 82.3 ± 2.4 kg) participated in this study. None of the participants had participated in a regular resistance training program for at least 6 months prior to the study. There might be gender differences in some of the dependent variables of interest; therefore, females were excluded from the study to avoid additional confounding factors. The study protocol was approved by the University of Oklahoma Institutional Review Board for Human Subjects. An informed consent form and a health questionnaire (PAR-Q) were read and signed by participants prior to the start of the study.

2.3. One-repetition maximum

The participants were instructed with proper lifting technique for one-repetition maximum (the greatest amount of weight that can be lifted for one-repetition, 1-RM) test and were familiarized with the strength-testing equipment at least 48 h prior to the study. Since exercises were performed by the left leg during testing, each participant completed the 1-RM test in a unilateral manner to determine the left leg muscular strength using a CYBEX knee extension machine (Medway, MA). After a warm-up set comprised of five leg extensions at 50% of their perceived maximum, the weight was increased progressively following each successful lift to reach the maximal weight that could be lifted once throughout the entire range of motion. Each participant was allowed to rest 1.5–2 min between attempts and reached 1-RM within five trials.

2.4. Isometric strength

A dynamic constant external resistance (DCER) machine (TDS Fitness Equipment Corp., Elmira, NY) was used to assess isometric MVC by connecting the lever arm to a load cell (Omega Engineering Inc., Stamford, CT). Each participant was seated in an upright position in the chair and the left knee was aligned with the rotational axis of the lever arm and the leg was secured with a strap just superior to the malleoli. Two 3–5 s pre- and two post-MVCs were performed with 1-min rest between contractions. The mean values of two pre- and two post-MVCs trials were used for the analyses. The MVC trials served two functions: (a) to determine the participant's maximal voluntary isometric strength and (b) to determine the extent of voluntary activation. The MVC trials were accompanied by verbal encouragement by the investigators to obtain a maximum effort from the participants.

2.5. Voluntary activation

The percent of voluntary activation (SVA) was estimated using the twitch interpolation protocol (Allen et al., 1995; Gandevia, 2001). Doublet stimuli were administered to the femoral nerve approximately 200–300 ms into the MVC. A second doublet was applied approximately 3 s after the cessation of the MVC at rest (Fig. 1) (Shield and Zhou, 2004). The stimuli were rectangular pulses of 200 µs duration and were delivered using a high-voltage
Table 1

<table>
<thead>
<tr>
<th></th>
<th>Pre-exercise</th>
<th>Post-exercise</th>
<th>Control Pre-exercise</th>
<th>Post-exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVC (Nm)</td>
<td>276.9 (16.8)</td>
<td>187.7 (14.1)</td>
<td>260.7 (13.4)</td>
<td>223.7 (15.9)</td>
</tr>
<tr>
<td>Percent voluntary activation</td>
<td>82.7 (3.2)</td>
<td>73.5 (5.9)</td>
<td>79.8 (2.9)</td>
<td>82.1 (3.4)</td>
</tr>
<tr>
<td>Potentiated twitch (Nm)</td>
<td>115.9 (7.5)</td>
<td>62.8 (6.3)</td>
<td>112.3 (3.9)</td>
<td>90.5 (7.1)</td>
</tr>
<tr>
<td>Superimposed twitch (Nm)</td>
<td>18.4 (2.6)</td>
<td>15.6 (5.0)</td>
<td>22.3 (3.2)</td>
<td>17.4 (3.9)</td>
</tr>
<tr>
<td>EMG MFF (µV)</td>
<td>650 (92)</td>
<td>543 (63)</td>
<td>940 (74)</td>
<td>519 (56)</td>
</tr>
<tr>
<td>EMG MFF (µV)</td>
<td>58.2 (39)</td>
<td>57.6 (39)</td>
<td>60.4 (35)</td>
<td>55.8 (24)</td>
</tr>
</tbody>
</table>

(maximal voltage = 400 V constant-current stimulator (Digitimer DS7AH, Herfordshire, UK). The femoral nerve was stimulated by a cathode probe (8 mm diameter). The tip of the cathode was covered in a saline soaked sponge and pressed over the femoral nerve in the lateral portion of the femoral triangle. The anode (9 × 5 cm, Durastick Supreme, Chattanooga Group, Hixon, TN) was positioned according to Babault et al. (2006). The probe was placed over the femoral nerve in the femoral triangle and a series of single stimuli (30 mA) were delivered to determine the optimal probe location. After applying each stimulus, the size of the M-wave in the EMG recording was checked and the probe was moved until finding the position resulting in the greatest M-wave response. Once the probe location was determined and marked based on the greatest M-wave response, the probe was pressed over the marked location and the intensity of stimuli was increased progressively until the plateau in twitch torque was achieved. An additional 20% was added to the highest current to ensure a supramaximal stimulus. The doublet consisted of two single stimuli (10 ms between stimuli) that were delivered successively to increase the signal-to-noise ratio and minimize the series elastic effects on torque production (Desbrosses et al., 2006). %VA was determined by the equation below where the superimposed twitch and potentiated twitch (details will follow) were obtained during the MVC plateau and about 3 s after the MVC trial at rest, respectively (Allen et al., 1995):

\[
%VA = \left(1 - \frac{\text{superimposed twitch}}{\text{potentiated twitch}}\right) \times 100
\]

2.6. Superimposed and potentiated twitch

The peak superimposed and potentiated twitch force were calculated as the highest average of 10 consecutive data points (Fig. 1B and C). Superimposed and potentiated twitch signals were analyzed by the same custom written software used to analyze EMG signals (LabVIEW).

2.7. Dynamic exercise

The exercise session consisted of five sets of 20 repetitions of DCR-EX at 20% of the 1-RE with 30-s rest between each set. The participants were instructed to lift and lower (between full extension and 90° of knee flexion) the load at a constant velocity, taking about 1.5 s for each concentric and eccentric action. The intensity was decided based on previous studies (Taladura et al., 2000a, 2004). Each participant was able to complete the 20 repetitions of exercise for each set with the exception of one who did not complete the entire 20 repetitions during the 5th set. Each session of DCR-EX lasted approximately 8 min.

2.8. Blood flow restriction protocol

A 50 mm width elastic belt was placed around the most proximal part of each thigh to restrict blood flow. The device (KATSU-Master, Sato Sports Plaza, Tokyo, Japan) has a pneumatic bag along the inner surface of the belt connected to an electronic air pressure control system that monitors the restriction pressures set by the investigator. The following equation was used to determine the cuff pressure:

\[
\text{Pressure} = \text{Systolic Blood Pressure (SBP)} \times 1.44
\]

Before the test, each participant was seated on a chair and the cuffs were inflated to reach the approximate resting systolic blood pressure of 120 mmHg at heart level. The pressure was held at 120 mmHg for 30 s and released for 10 s. Then the pressure was increased by 20 mmHg while holding for 30 s at each pressure and releasing for 10 s between increments until the target pressure determined by the formula above was reached (Abe et al., 2006). During the VR session, the pre-MVC trials were performed without any pressure, but the post-MVC trials were performed with the cuff pressure immediately after exercises. The target pressure was maintained for the entire exercise session and released after the completion of the last post-exercise MVC trial.

![Image](https://via.placeholder.com/150)

Fig. 1. An example of the electromyographic (EMG) signals from the vastus lateralis (VL) muscle during an isometric maximum voluntary contraction (MVC). Each participant was allowed to reach and sustain maximum force production about 2–3 s during MVCs and then doublets stimuli were administered to the femoral nerve. Shaded area A, the average torque and the time and frequency domain estimates for the EMG signals were calculated during the 0.25-s epoch immediately prior to the superimposed twitch during the MVC trials. B and C, the superimposed and potentiated twitches, respectively.
2.9. EMG

Bipolar (5 cm center-to-center) surface EMG electrodes (Ag-AgCl, Quinton Quick Prep, Quinton Instruments Co., Bothell, WA) were placed along the longitudinal axis of the vastus lateralis (VL) of the left thigh. The electrode placements on the VL were 25 mm distal and proximal to a mark that was made at 50% of the distance between the greater trochanter and the lateral femoral epicondyle. The reference electrode was placed over the spinous process of the 7th cervical vertebrae. The skin was shaved, lightly abraded, and cleaned with isopropyl alcohol to reduce the electrode-skin impedance, which was kept below 2000 Ω, before placement of each electrode. The EMG signals were pre-amplified (gain: ×1000) using a differential amplifier (MP100A, Biopac Systems Inc., Santa Barbara, CA).

2.10. Signal processing

The EMG (μV) and force (Nm) signals were recorded and stored on a personal computer (Intel Pentium 4 CPU, Dell Computer Corp., Austin, TX) with custom software (LabVIEW v 7.1 Professional Instruments, Austin, TX) for subsequent analysis. All signal processing was performed offline using additional custom written software (LabVIEW). The EMG signal was digitized at 2 kHz and filtered (zero-phase 4th-order Butterworth filter) with a pass band of 10–500 Hz. The load cell signal was low-pass filtered with a 10 Hz cutoff (zero-phase 4th-order Butterworth filter) (Fig. 1).

Isometric MVC force was represented as the average force calculated during the 0.25-s epoch immediately prior to the superimposed twitch. Consequently, the same (concurrent) 0.25-s epoch was selected from the EMG signal to calculate the time and frequency domain estimates during the MVC trials (Fig. 1). For the DCER-EX, files containing the EMG signals recorded during each 20-repetition set were divided into five separate, consecutive epochs of equal duration. Root mean square (RMS) amplitude and mean power frequency (MPF) values were calculated for each of the five signal epochs separately. Since each of the five epochs contained four consecutive repetitions (i.e., repetitions 1–4, 5–8, 9–12, 13–16, and 17–20, respectively), for the MPF values, each epoch was processed with a Hamming window and a discrete Fourier transform (Kowzny et al., 1970). The MPF was used to represent the power spectrum according to the recommendations of Hermens et al. (1999).

2.11. Statistical analyses

Four separate two-way repeated measures ANOVAs (trial [pre- vs. post-exercise] × condition [VR vs. CON]) were used to analyze the MVC torque, %VA, EMG amplitude, and EMG MPF values. For each subject, EMG values during DCER-EX were normalized as a percentage of the average of the two pre-exercise MVCs (SMVC). Two separate three-way repeated measures ANOVAs (condition [VR vs. CON] × sets [1 vs. 2 vs. 3 vs. 4 vs. 5] × repetitions [approximately 1–4 vs. 5–8 vs. 9–12 vs. 13–16 vs. 17–20]) were used to analyze the EMG amplitude and MPF data during the DCER-EX. When appropriate, post-hoc analyses were performed using Bonferroni corrections. A t-test was used to compare the percent change from pre- to post-exercise for each condition (VR vs. CON). Percentage changes in dependent variables from pre- to post-exercise were calculated with the following equation:

\[ \% \text{Changes} = \left( \frac{\text{post-pre}}{\text{pre}} \right) \times 100 \]

Data were expressed as mean ± SE. The sample size for each SE calculation was listed below its corresponding figure when SE values were reported. An alpha of 0.05 was used to determine statistical significance and data were analyzed using SPSS 14.0 for Windows (SPSS Inc., Chicago, IL).

3. Results

All trials were completed without injuries. For all analyses, the observed power, a post-hoc power calculation that has been performed after the completion of the study, was 1.0 for MVC, 1.0 for potentiated twitch, 0.34 for superimposed twitch, 0.28 for %VA, 0.29 for EMG amplitude, and 0.05 for EMG MPF.

3.1. Isometric strength

There was a trial × condition interaction (p = 0.01). Isometric MVC force decreased pre- to post-exercise for both VR (p < 0.001) and CON (p = 0.02). There were no significant differences between the pre-exercise MVCs (p = 0.2), but the post-exercise MVC force for the VR was 18% lower than the CON (p = 0.02) (Fig. 2).

3.2. Percent voluntary activation

There was a trial × condition interaction (p = 0.04). The post-hoc tests did show a significant decrease in %VA for the VR (p = 0.04), but the changes observed for the CON was not significant (p = 0.39). There was also a 13% decrease in %VA from pre- to post-exercise for the VR condition, but a 3.5% increase in %VA for the CON condition (p = 0.07) (Fig. 3).

3.3. Potentiated twitch

A trial × condition interaction (p < 0.001) was observed (Fig. 4). The VR resulted in a 44% decrease, whereas the CON resulted in a 19% decrease (p < 0.001).

3.4. Electromyography

There was a trial × condition interaction for EMG amplitude (p = 0.04), but post-hoc follow-up tests did not detect a significant difference for either the VR (p = 0.08) or the CON (p = 0.56) condition (Fig. 5). There was a 12% decrease in EMG amplitude from pre- to post-exercise for the VR condition, but a 3% increase in EMG amplitude for the CON condition (p = 0.03). For EMG MPF, there was no significant trial × condition interaction (p = 0.19) and no main ef-
effects for either trial ($p = 0.28$) or condition ($p = 0.98$). There were no significant differences in percentage change in EMG MPF (from pre- to post-exercise) between the VR and CON conditions ($p = 0.20$).

The average normalized EMG amplitude (SMVC) was plotted for each set across repetitions with and without VR (Fig. 6). There was no significant three-way interaction for condition $\times$ sets $\times$ repetitions ($p = 0.55$), no significant two-way interactions for condition $\times$ sets ($p = 0.15$), condition $\times$ repetitions ($p = 0.29$), set $\times$ repetitions ($p = 0.052$), and no significant main effect for condition ($p = 0.09$). However, there were main effects for sets ($p < 0.001$) and repetitions ($p < 0.001$). An increase ($p < 0.05$) was detected in EMG amplitude from set 1 to 5, except between set 1 and 2 ($p = 0.10$) and set 3 and 4 ($p = 0.21$). EMG amplitude increased from repetitions 1 to 4 to 5–8 ($p = 0.001$), then 8 to 9–12 ($p = 0.04$), and from 9–12 to 13–16 ($p = 0.29$), but decreased from repetitions 13–16 to 17–20 ($p = 0.04$).

The average normalized EMG MPF (%) values were plotted for each set across repetitions with and without VR (Fig. 7). There was no significant three-way interaction for condition $\times$ sets $\times$ repetitions ($p = 0.99$), no significant two-way interactions for condition $\times$ sets ($p = 0.71$), condition $\times$ repetitions ($p = 0.32$), set $\times$ repetitions ($p = 0.13$), and no significant main effect for condition ($p = 0.09$). However, there were main effects for sets ($p < 0.001$) and repetitions ($p < 0.001$). The follow-up analyses collapsed across condition indicated that there were significant decreases in EMG MPF across sets ($p < 0.05$), except between set 1 and 2 ($p = 0.13$) and set 4 and 5 ($p = 0.08$) and main effect decreases in EMG MPF between repetitions 9–12, 13–16, and 17–20 ($p < 0.04$) and between repetitions 5–8 and 17–20 ($p > 0.02$).

4. Discussion

Low-intensity (20% of 1-RM) exercise combined with vascular restriction resulted in significant decreases in MVC force and peak potentiated twitch force for both VR and CON and significant interactions between VR and CON for the VTA and EMG amplitude from pre- to post-exercise. Neuromuscular fatigue during the VR session might be due to a combination of central and peripheral fatigue, whereas for the condition, declines in peak potentiated twitch velocities, but an increase in the VTA from pre- to post-exercise it was indicated that peripheral fatigue was likely the primary factor responsible for decreases in MVC force values.

Loss of muscle strength due to previous exercises performed is defined as fatigue (Perry-Rana et al., 2002). The present study reported a significantly greater decreases in MVC following exercise for the condition (31%) compared to CON (13%). In addition, while the condition resulted in decreases in EMG amplitude (3%) and VTA (3.5%), the VR condition caused significant decreases in VTA values from pre- to post-exercise (13%) ($p = 0.04$) and in the percentage changes from pre-to post-exercise in EMG amplitude (12%) ($p = 0.03$). Significant reductions in EMG amplitude and VTA for the VR condition may indicate an inhibition of central drive to motor units resulting in some of the additional decline in the force generation capacity following exercises with VR. A decline in skeletal muscle activation level estimated by the twitch interpolation technique suggested that a reduced number of motor units was voluntarily recruited by the participants following the exercises with VR. In other words, electrical stimuli applied during the contraction...
evoked additional force indicating the central drive was not maximal and the participants were experiencing central fatigue. It should be noted that changes in EMG amplitude could be related to changes in peripheral factors, but combination of decreases in both EMG amplitude and SVA supports the hypothesis that changes in EMG amplitude may be due, at least in part, to a decline in central drive. Reduction in efferent motor command (central fatigue) may be because of increased intracellular concentration in H⁺ and β₅., causing an inhibition of α-motoneurons and a decline of supraspinal drive (Babaault et al., 2006). Since slow-twitch fibers rely heavily on oxidative phosphorylation, slow-twitch muscle fibers might be making a decreased contribution to isometric force production due to reduced blood flow to skeletal muscles during the post-exercise MVC trials with VR. Decrements in EMG MVC would have been expected during fatigue because of reduction in fiber conduction velocity and/or change in the shape of the action potential (Basmajian and De Luca, 1985; Hermens et al., 1992). However, the present experiment did not detect any significant changes in EMG MVC pre-to post-exercise for either condition.

Increased EMG amplitude during the submaximal fatigue exercises could be explained by additional motor unit recruitment (Krogh-Lund, 1993; Weir et al., 2000). Yasuda et al. (2006) recorded the EMG from the triceps brachii and the pectoralis major during dynamic bench press exercises at 30°/1-2RM with and without VR. Normalized integrated EMG (lEMG) was higher during the VR session. According to changes in normalized lEMG values, the exercise intensity for the first set was the same for both the control and VR sessions, but the mean exercise intensity was ~10–20% higher in the VR session during the fourth set compared with the control session. EMG amplitude increases with time during sub-maximal (Weir et al., 2000) and sustained isometric exercises (Krogh-Lund, 1993). The present study also reported an increase in EMG amplitude across repetitions and a decline towards the end of 20 repetitions, which may indicate an impairment of motor unit recruitment and firing rate. Fatiguing isokinetic knee extensions also resulted in decreases in EMG mean frequency (Gerdle et al., 2000), perhaps due to changes in shape of the action potentials and/or decreases in muscle action potential conduction velocity (Basmajian and De Luca, 1985; Hermens et al., 1992). EMG MFP decreased during sustained isometric knee extension at 50% of the MVC for 1 min (Yamada et al., 2008). EMG MFP decreased across sets and repetitions in the present study, but no significant difference between conditions was observed. This suggests that the DCER-EX elicited similar fatiguing effects during the exercise for both VR and CON. It was not until after the exercises were complete that a difference could be observed between conditions. It is worth to mention that since EMG is an indirect measure of motor unit activity and EMG signals can be affected by several factors such as variations in the subcutaneous layer thickness, force level, and the tissue filtering effect (less attenuation of lower frequency signals), the amplitude of EMG might be affected by these confounding factors. Therefore, further studies using different techniques and/or investigating additional variables might be helpful to better understand the physiological aspects and the location of central failure with fatigue.

The change in the potentiated twitch amplitude may reveal the development of peripheral fatigue due to the alterations in the contractile system such as excitation–contraction coupling and/or reduced number of strong binding cross-bridges (Babaault et al., 2006). There was a 35% greater decrease in potentiated twitch force following VR compared to CON. These findings suggest that VR caused a greater peripheral change in muscle contractile properties than CON. However, because SVA decreased after VR, but was unaltered after CON, both peripheral and central mecha-
nisms may have caused fatigue with VR, whereas only peripheral mechanisms may have been involved with CON.

These data suggest that fatigue after the VR might be due to a combination of central and peripheral mechanisms. Since VR often results in blood accumulation in the lower extremities, concentration of metabolites might be higher and cause an increase in the inhibitory effect of small diameter afferents (Gandevia, 2001; Taylor et al., 2000). In addition, alterations of the excitation-contraction coupling and reduced number of cross-bridges might be mechanisms for peripheral fatigue. In conclusion, the results of the present study suggest that greater decreases in MVC, 3VA, EMG amplitude, and potentiated twitch following five sets of 20 dynamic knee extension exercises at 20% 1-RM with VR are due to a combination of central and peripheral fatigue.

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