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ORIGINAL ARTICLE

Muscle activation during three sets to failure at 80 vs. 30 % 1RM resistance exercise

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Abstract
Purpose The purpose of this study was to investigate electromyographic amplitude (EMG AMP), EMG mean power frequency (MPF), exercise volume (VOL), total work and muscle activation (iEMG), and time under concentric load (TUCL) during, and muscle cross-sectional area (mCSA) before and after 3 sets to failure at 80 vs. 30 % 1RM resistance exercise.
Methods Nine men (mean ± SD, age 21.0 ± 2.4 years, resistance training week^{-1} 6.0 ± 3.7 h) and 9 women (age 22.8 ± 3.8 years, resistance training week^{-1} 3.4 ± 3.5 h) completed 1RM testing, followed by 2 experimental sessions during which they completed 3 sets to failure of leg extension exercise at 80 or 30 % 1RM. EMG signals were collected to quantify EMG AMP and MPF during the initial, middle, and last repetition of each set. Ultrasound was used to assess mCSA pre- and post-exercise, and VOL, total work, iEMG, and TUCL were calculated.
Results EMG AMP remained greater at 80 % than 30 % 1RM across all reps and sets, despite increasing 74 and 147 % across reps at 80 and 30 % 1RM, respectively. EMG MPF decreased across reps at 80 and 30 % 1RM, but decreased more and was lower for the last reps at 30 than 80 % 1RM (71.6 vs. 78.1 % MVIC). mCSA increased more from pre- to post-exercise for 30 % (20.2–24.1 cm^2) than 80 % 1RM (20.3–22.8 cm^2). VOL, total work, iEMG and TUCL were greater for 30 % than 80 % 1RM.
Conclusion Muscle activation was greater at 80 % 1RM. However, differences in volume, metabolic byproduct accumulation, and muscle swelling may help explain the unexpected adaptations in hypertrophy vs. strength observed in previous studies.

Keywords Electromyography · Skeletal muscle · Muscle fatigue · Muscle size · Resistance training intensity · Exercise volume

Abbreviations

1RM	One repetition maximum
ANOVA	Analysis of variance
EI	Echo intensity
EMG AMP	Electromyographic amplitude
EMG MPF	Electromyographic mean power frequency
iEMG	Total integrated electromyographic amplitude
mCSA	Muscle cross-sectional area
MVIC	Maximal voluntary isometric contraction
RF	Rectus femoris
TUCL	Time under concentric load
US	Ultrasound
VL	Vastus lateralis
VM	Vastus medialis
VOL	Volume

Introduction

To maximize muscle hypertrophy and strength in response to a resistance training program, heavy loads are often recommended. For example, the current American College of

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Sports Medicine's (ACSM) position stand addressing the appropriate intensity to improve muscular fitness (Garber et al. 2011) states "…robust gains in both hypertrophy and strength result from using a resistance equivalent to 60–80 % of the individual's one repetition maximum (1RM)…" (pg. 1343). Similarly, the National Strength and Conditioning Association (NSCA) recommends using loads of 67–85 % 1RM if the objective is muscular hypertrophy (NSCA 2008). However, Burd et al. (2010b) recently demonstrated that acute resistance exercise performed to failure at 30 % 1RM is as effective as resistance exercise at 90 % 1RM for the stimulation of muscle protein synthesis and anabolic signaling. In a 10-week training study, Mitchell et al. (2012) demonstrated that leg extension resistance training at 30 % 1RM increased muscle size similar to training at 80 % 1RM. However, training at 80 % 1RM was superior for increasing 1RM strength. Ogasawara et al. (2013) showed that 6 weeks of bench press resistance training at 30 % 1RM caused muscle hypertrophy equivalent to that observed following training at 80 % 1RM, but 80 % 1RM was superior for increasing isometric and 1RM strength. Similarly, Schoenfeld et al. (2015) demonstrated that resistance training at 25–35 RM was as effective as training at 8–12 RM for increasing muscle size, although training at 8–12 RM was more effective for increasing back squat 1RM in well-trained men. Thus, this disparity between resistance training recommendations (Garber et al. 2011; NSCA 2008) and experimental results (Burd et al. 2010a; Mitchell et al. 2012; Ogasawara et al. 2013) has sparked debate (Burd et al. 2013; Schuenke et al. 2013) regarding the most effective loads to prescribe to elicit hypertrophy with resistance exercise.

The recommendation of high-load resistance training (i.e., ≥60 % 1RM) to maximize strength and hypertrophy is predicated on Henneman's size principle (Carpinelli 2008; Henneman et al. 1965). Henneman et al. (1965) stated that recruitment of high-threshold motor units is dependent on the intensity of the stimulus. Therefore, in theory, more motor units will be recruited for a contraction at 80 % 1RM than at 30 % 1RM. However, the performance of sub-maximal contractions to the point of fatigue may also result in the recruitment of additional, higher-threshold motor units (Conwit et al. 2000). Consequently, Burd et al. (2012b) stated, "…it is reasonable to assume that lower intensities performed to volitional fatigue could achieve a similar degree of muscle fiber activation to that of high-intensity resistance exercise regimes…" (pg. 552–553). Mitchell et al. (2012) also hypothesized that maximal motor unit recruitment was necessary to sustain force production when resistance training with low loads performed to failure, and offered this as an explanation for the similar hypertrophy observed following 10 weeks of training at 80 and 30 % 1RM to failure. However, the authors (Mitchell et al. 2012) acknowledged that it is "difficult to experimentally verify this motor unit recruitment strategy during voluntary dynamic contractions in humans" (pg. 75). Consequently, few studies (Akima and Saito 2013; Cook et al. 2013; Schoenfeld et al. 2014) have attempted to test this hypothesis.

Akima and Saito (2013) showed that the change in electromyographic amplitude (EMG AMP) was lower during leg extension exercise at 70 % than 50 % 1RM for the vastus medialis (VM). However, the authors (Akima and Saito 2013) did not statistically analyze the absolute EMG AMP values at 70 vs. 50 % 1RM. Cook et al. (2013) showed that EMG AMP increased from the first five to the last five repetitions during three sets to failure of leg extension resistance exercise at 70 and 20 % peak torque, yet EMG AMP was consistently higher at 70 % than 20 %. Schoenfeld et al. (2014) recently reported greater peak and mean EMG AMP during a single set of leg press exercise to failure at 75 vs. 30 % 1RM. Collectively, however, these studies have either investigated EMG AMP responses during only a single set of resistance exercise (Akima and Saito 2013; Schoenfeld et al. 2014) or have quantified EMG AMP during only the initial 5 and final 5 repetitions of multiple sets (Cook et al. 2013). In addition, none of these previous studies have examined the frequency domain of the EMG signal, which may provide important information regarding the muscle fatigue that occurs during 80 vs. 30 % 1RM exercise. It is also possible that factors such as exercise volume, time under tension, or acute muscle swelling are different during acute exercise at 80 vs. 30 % 1RM (Burd et al. 2010a, 2012a; Schoenfeld 2010), which may influence the hypertrophic and strength adaptations to chronic high- vs. low-load resistance exercise. We are aware of no previous studies that have provided a simultaneous comparison of EMG AMP, EMG mean power frequency (MPF), exercise volume, time under tension, or acute muscle swelling during three sets to failure at 80 vs. 30 % 1RM leg extension resistance exercise, which was the specific protocol used by Mitchell et al. (2012). Therefore, the purpose of this study was to investigate electromyographic amplitude (EMG AMP), EMG mean power frequency (MPF), exercise volume (VOL), total work and muscle activation (iEMG), and time under concentric load (TUCL) during, and muscle cross-sectional area (mCSA) before and after three sets to failure at 80 vs. 30 % 1RM resistance exercise in men and women.

Based on the limited data from previous studies (Akima and Saito 2013; Cook et al. 2013; Schoenfeld et al. 2014), we hypothesized that EMG AMP would increase throughout each set at 80 and 30 % 1RM, but that EMG AMP would be greater at 80 % 1RM. Because it has been suggested that low-load training may result in pronounced metabolic byproduct accumulation (Loenneke et al. 2011;

Takarada et al. 2004) and because the frequency content of the EMG signal may be affected by metabolic byproduct accumulation and/or intramuscular pH (Brody et al. 1991), we hypothesized that there would be greater decreases in EMG MPF at 30 % than at 80 % 1RM. We also hypothesized that there would be greater muscle swelling at 30 % than at 80 % 1RM. Finally, due to the inherent nature of low-load resistance training, we hypothesized that exercise volume, total work, and time under load would be greater at 30 % 1RM than at 80 % 1RM.

Methods

Subjects

Eleven men (mean ± SD, age 21.5 ± 2.7 years, height 179.4 ± 6.3 cm, weight 80.6 ± 8.4 kg; resistance training week^{-1} 6.6 ± 3.7 h) and 11 women (mean ± SD, age 22.3 ± 3.6 years, height 169.7 ± 6.7 cm, weight 64.5 ± 8.3 kg, resistance training week^{-1} 3.7 ± 3.3 h) completed this study. However, only the data from nine men (mean ± SD, age 21.0 ± 2.4 years, height 179.8 ± 6.9 cm, weight 81.5 ± 8.9 kg, resistance training week^{-1} 6.0 ± 3.7 h) and nine women (mean ± SD, age 22.8 ± 3.8 years, height 170.0 ± 5.9 cm, weight 65.4 ± 6.0 kg, resistance training week^{-1} 3.4 ± 3.5 h) were analyzed and reported in this paper. The data from four subjects were excluded because they did not complete enough repetitions (i.e., ≤3) to analyze during the second and/or third sets of resistance exercise at 80 % 1RM. This study was approved by the university's Institutional Review Board for the protection of human subjects (IRB Approval #: 20140614266EP) on June 02, 2014 and complies with the ethical requirements asserted by the Declaration of Helsinki 1964. Prior to any data collection, all participants signed an informed consent form and completed a health history questionnaire. In order to be eligible, each participant must have been between the ages of 19 and 29, and free from any current or ongoing musculoskeletal injuries or neuromuscular disorders involving the hips, knees, or ankles. Each subject reported completing at least two resistance training sessions per week for at least 1 month prior to beginning the study.

Experimental design

A randomized, repeated measures cross-over design was used for this study. Each participant visited the laboratory four times separated by 48–168 h at the same time of day (±2 h). Subjects were asked to refrain from any lower body exercise for at least 48 h prior to each visit. For the purposes of familiarization and calculation of test–retest reliability, at visits 1 and 2 the subjects were familiarized, ultrasound (US) scans of the subjects' rectus femoris (RF) and vastus lateralis (VL) muscles were taken, and one repetition maximum (1RM) and maximal voluntary isometric contractions (MVIC) were performed. During visits 3 and 4, the subjects completed 3 sets of unilateral leg extension resistance exercise performed to failure with a high (80 % 1RM) or low load (30 % 1RM), and US scans of the RF and VL muscles were performed pre- and post-exercise. The order of the load used (80 vs. 30 % 1RM) was randomized for visits 3 and 4. During all visits, EMG signals were recorded from the three superficial quadriceps femoris muscles [RF, VL, and vastus medialis (VM)] of the thigh. An electrogoniometer was placed across the dominant knee joint to measure joint angle (°). Only the dominant leg (determined by kicking preference) was used in this study.

All leg extension muscle actions were performed on a commercially available plate-loaded leg extension device (Hammer Strength Plate-Loaded, Iso-Lateral Leg Extension Machine; LifeFitness, Rosemont, IL, USA) that was custom fitted with a load cell (Omegadyne, model LCHD-500, 0–500 lbs; Stamford, CT, USA) between the leg pad and the lever arm. During testing and exercise, the subjects were seated on the leg extension machine with a strap securing their pelvis. The axis of rotation of the lever arm was aligned with the lateral epicondyle of the femur of the dominant leg. The hip joint angle was 120° between the trunk and the thigh for all subjects.

One repetition maximum testing

Testing was carried out according to the guidelines established by the National Strength and Conditioning Association (2008). Specifically, the subjects performed a light warm-up set with 5–10 repetitions at 50 % of the estimated 1RM, followed by two heavier warm-up sets of 2–5 repetitions with loads increasing by 10–20 % for each set. Subjects then began completing trials of one repetition with increasing loads (10–20 %) until they were no longer able to complete a single repetition. The highest load (kg) successfully lifted through the entire range of motion was denoted as the 1RM, which was determined in ≤4 trials for all subjects. Two to 4 min of rest was allowed between successive warm-up sets and 1RM trials. Force, EMG, and electrogoniometer signals were recorded during the 1RM attempts.

Isometric testing

For normalization purposes, each subject completed a 4-s leg extension MVIC at a knee joint angle corresponding to the dominant leg positioned at 65° below the horizontal plane during visits 1 and 2 on the leg extension device. This

knee joint angle was selected based on pilot data, which demonstrated that peak force occurred at this point in the range of motion during 1RM attempts. Force and EMG signals were recorded during the MVICs.

Resistance exercise protocol

During visits 3 and 4, subjects performed three sets of unilateral leg extension resistance exercise to failure with loads corresponding to either 80 or 30 % of 1RM (random order). A metronome (Pro Metronome, EUMLab, Berlin, Germany) was set to 1 Hz, and subjects were instructed to perform the concentric and eccentric phases corresponding with each tick of the metronome (i.e., 1 s concentric phase, 1 s eccentric phase). Verbal instruction and encouragement were provided during each set. Failure was defined as the inability to complete another concentric muscle action throughout the full range of motion. Two min of rest were provided between all sets for both conditions. Force, EMG, and electrogoniometer signals were recorded during all exercise sets.

Volume

The number of repetitions performed prior to failure was recorded for each set. Resistance exercise VOL, total work, and TUCL were calculated to quantify the work performed during exercise with the 80 and 30 % 1RM loads. VOL [repetitions × weight (kg)] was calculated as the product of the number of repetitions performed during each set and the plate weight (kg added to the resistance training device). Total work (kJ) was calculated as the sum of the products of the average force (N) during the 60° concentric epoch of each repetition and the distance (0.25 m) completed during each repetition within each set. TUCL was expressed in s and calculated as the sum of the times to completion of the 60° concentric epoch used to analyze the EMG signals during each repetition within each set.

Electromyography

Pre-gelled bipolar surface electrodes (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) were placed on the RF, VL, and VM muscles of the right thigh with an interelectrode distance of 30 mm (Hermens et al. 1999). For the RF, the center of the bipolar electrode pair was placed at 50 % of the distance between the ASIS and the medial superior border of the patella. For the VL, the center of the bipolar electrode pair was placed at 66 % of the distance between the anterior superior iliac spine (ASIS) and the lateral superior border of the patella. The longitudinal axis of the bipolar electrode pair was parallel to the angle of pennation of the vastus lateralis fibers (approximately 20°) (Fukunaga et al. 1997). For the VM, the center of the bipolar electrode pair was placed at 80 % of the distance between the ASIS and the joint space in front of the anterior border of the medial ligament. The longitudinal axis of the electrode pair was parallel to the angle of pennation of the vastus medialis fibers (approximately 50°) (Hermens et al. 1999). A single pre-gelled surface electrode (Ag/AgCl, AccuSensor, Lynn Medical, Wixom, MI, USA) was placed on the ASIS and served as the reference electrode. To reduce inter-electrode impedance and increase the signal-to-noise ratio (Beck and Housh 2008), local areas of the skin were shaved, abraded, and cleaned with isopropyl alcohol prior to the placement of the electrodes. Interelectrode impedance was measured using a digital multimeter (Fluke 179 True RMS Multimeter, Everett, WA, USA) and was always less than 2000 Ω (Beck and Housh 2008).

Signal processing

The force, EMG, and electrogoniometer signals were sampled simultaneously at 2 kHz with a Biopac data acquisition system (MP150WSW, Biopac Systems, Inc., Santa Barbara, CA, USA), recorded on a personal computer, and processed off-line with custom written software (Labview v. 12.0, National Instruments, Austin, TX, USA).

The EMG signals were amplified (gain 1000) using a differential amplifier (EMG 100, Biopac Systems, Inc., Santa Barbara, CA, USA, bandwidth 1–5000 Hz) with a common mode rejection ratio of 110 dB min and an impedance of 2 M Ω, and digitally filtered (zero-phase shift fourth-order Butterworth filter) with a band-pass of 10–499 Hz. The force and electrogoniometer signals were low-pass filtered (zero-phase shift fourth-order Butterworth filter) with a 15 Hz cutoff. All subsequent analyses were completed on the filtered signals. The EMG and force values were calculated from the signal epochs corresponding to the 60° range of motion occurring between 100° and 160° of leg extension (180° = full extension) during the concentric portion of each repetition based on the electrogoniometer signal (Fig. 1).

The time domain of the EMG signals was expressed as the time-averaged, integrated amplitude value (EMG AMP), which was calculated as the integral of the full-wave rectified EMG signal divided by the time interval over which it occurred (Basmajian and De Luca 1985). The absolute EMG AMP values were expressed as $\mu V\ s^{-1}$. The frequency domain of the EMG signals was expressed as the mean power frequency (MPF) in Hz. To quantify EMG MPF, each signal epoch was processed with a Hamming window and a discrete Fourier transformation (DFT) based on the recommendations of Diemont et al. (1988) and calculated as described by Kwatny et al. (1970). The EMG AMP and EMG MPF values from the second repetition (denoted as

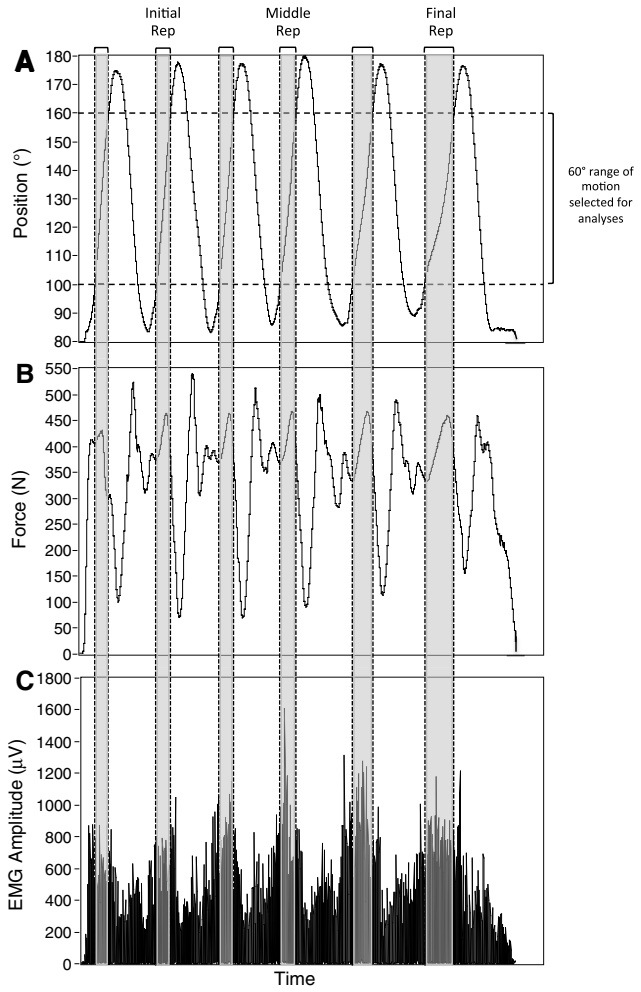

Fig. 1 An example of **a** position (°), **b** force (N), and **c** the full-wave rectified electromyographic (EMG) signal (μV) from the vastus lateralis during set 1 at 80 % 1RM for one subject. The *dashed vertical* and *horizontal* (**a**) *lines* indicate the 60° concentric range of motion used to calculate force, time averaged integrated EMG AMP, and EMG MPF based on the position signal. The initial, middle, and last repetitions are denoted at the *top*

the "initial rep"), the repetition corresponding to 50 % of the completed set (middle rep), and the last repetition (last rep) of each set were used for subsequent analyses. We also compared EMG AMP during the final common repetitions of sets 1, 2, and 3 separately during the 80 and 30 % 1RM conditions. The number of repetitions analyzed at the end of each set was established by the minimum number of repetitions achieved by any one subject during sets 1, 2, and 3 in the 80 % 1RM condition. Therefore, the average EMG AMP for the final 6, 4, and 4 repetitions was analyzed during sets 1, 2, and 3, respectively. In addition, the total integrated EMG (iEMG; μV) value was calculated using the 60° concentric epoch for all repetitions completed and summed across each set. The standard trapezoidal rule was used to calculate all EMG integrals. The EMG AMP, EMG MPF, and total concentric iEMG values obtained during the exercise sessions were normalized to the EMG AMP, EMG MPF, and total iEMG values calculated for a 1 s epoch corresponding with the highest consecutive force values recorded during the MVIC at visit 2 (%MVIC).

Muscle cross-sectional area and echo intensity

Ultrasound images of the leg extensors were obtained using a portable brightness mode (B-mode) ultrasound-imaging device (GE Logiq e, USA) and a multi-frequency linear-array probe (12L-RS; 5–13 MHz; 38.4 mm field-of-view) (Ahtiainen et al. 2010; Jenkins et al. 2015). The participants were positioned on a padded wooden table while lying in the supine position with their legs extended, relaxed, supported on the table, and their feet braced. To ensure that the probe moved perpendicular to the skin and along a transverse plane, high-density foam padding was taped to the skin perpendicular to the longitudinal axis of the leg. Great care was taken to ensure that consistent, minimal pressure was applied to the probe to limit compression of the muscle. To enhance acoustic coupling and reduce near field artifacts, a generous amount of water-soluble transmission gel was applied to the skin. All panoramic US measurements were taken at 50 % of the distance from the ASIS to the medial, superior border of the patella (Korhonen et al. 2009).

The equipment settings for mCSA and echo intensity (EI) measurements were optimized for image quality using the musculoskeletal mode prior to all testing using a gain of 58 dB and a frequency of 10 MHz. These equipment settings were held constant between visits and across participants. The depth, however, was adjusted based on each participant's leg size and was then held constant within participants between visits. The US probe was slowly and continuously moved from the most medial to the most lateral aspect of the thigh. GE Logiq e LogicView™ software was used to produce panoramic images of the RF and VL in real time. Panoramic US images were taken until three scans with acceptable image quality were obtained. The panoramic images with the highest visual contrast (determined by investigator NY) were used for subsequent analyses. The US images at visits 1 and 2 were taken prior to any exercise, while the images at visits 3 and 4 were taken immediately before and immediately after performing 3 sets to failure with the designated load (80 or 30 % 1RM) (Fig. 2).

All US image analyses were performed using Image-J Software (National Institutes of Health, USA, version 1.47v). Prior to all analyses, each image was scaled from pixels to cm using the straight-line function in Image-J. To determine RF and VL mCSA, a region of interest was selected using the polygon function in Image-J that included as much of the muscle as possible, without including any surrounding fascia. RF and VL muscle EI values

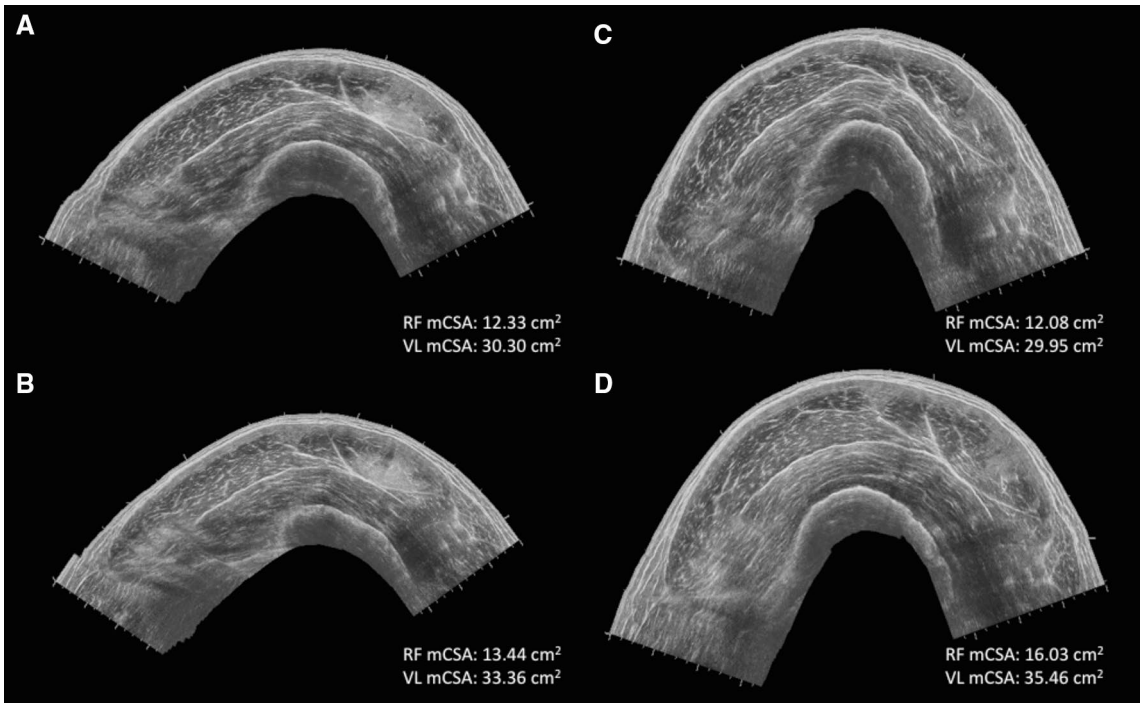

Fig. 2 Example of panoramic ultrasound scans **a** pre- and **b** post-exercise at 80 % 1RM and **c** pre- and **d** post-exercise at 30 % 1RM

were assessed by computer-aided gray-scale analysis using the standard histogram function and was determined from the same region of interest used to determine mCSA. The mean EI value was reported as a value between 0 (black) and 255 (white) arbitrary units (au).

Statistical analyses

Two separate four-way mixed factorial analyses of variance (ANOVAs) [load (80 % 1RM vs. 30 % 1RM) × muscle (RF vs. VL vs. VM) × set (Set 1 vs. Set 2 vs. Set 3) × repetition (Initial Rep vs. Middle Rep vs. Last Rep)] were used to analyze the EMG AMP and EMG MPF data during the first, middle, and last repetition. Three separate two-way mixed factorial ANOVAs [load (80 % 1RM vs. 30 % 1RM) × repetition] were used to analyze the EMG AMP data during the final repetitions of each set. Four separate two-way mixed factorial ANOVAs [load (80 % 1RM vs. 30 % 1RM) × set (Set 1 vs. Set 2 vs. Set 3)] were used to analyze VOL, total work, TUCL, and total iEMG. Two separate three-way mixed factorial ANOVAs [load (80 % 1RM vs. 30 % 1RM) × muscle (RF vs. VL) × time (pre-exercise vs. post-exercise)] were used to analyze US mCSA and EI. Significant interactions were decomposed with follow-up repeated measures ANOVAs, Bonferroni-corrected dependent samples *t* tests, and/or independent samples *t* tests on the simple main effects. Significant main effects that were not involved in an interaction were analyzed with Bonferroni-corrected dependent samples *t* tests on the marginal means.

Test–retest reliability for 1RM and MVIC force, EMG AMP during 1RM and MVIC, EMG MPF during 1RM and MVIC, and US assessments of mCSA and EI were assessed from visit 1 to visit 2. Repeated measures ANOVAs were used to assess systematic error, and model 2,k (Shrout and Fleiss 1979) was used to calculate intraclass correlation coefficients (ICCs) and standard errors of measurement (SEMs). The SEMs were expressed as a percentage of the grand mean and are also reported as coefficients of variation (CV). The 95 % confidence intervals for the ICCs were calculated according to the procedure described by Shrout and Fleiss (1979). The 95 % confidence intervals for the means of the dependent variables were calculated with the studentized *t*-distribution. Partial eta squared effect sizes (η_p^2) were calculated for each ANOVA. All statistical analyses were completed using IBM SPSS Statistics (v. 22; Armonk, NY, USA) and a type I error rate was set a priori at 5 %.

Results

Volume

The mean ± SD (range) for the numbers of repetitions completed during sets 1, 2, and 3 at 80 % 1RM were 8.9 ± 2.7

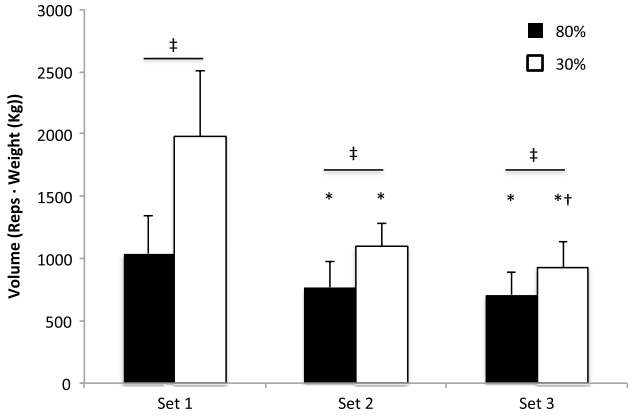

Fig. 3 The set × load interaction for resistance exercise volume during sets 1, 2, and 3. Values are means ± 95 % confidence intervals. *<Set 1; †<Set 2; ‡significant difference between groups

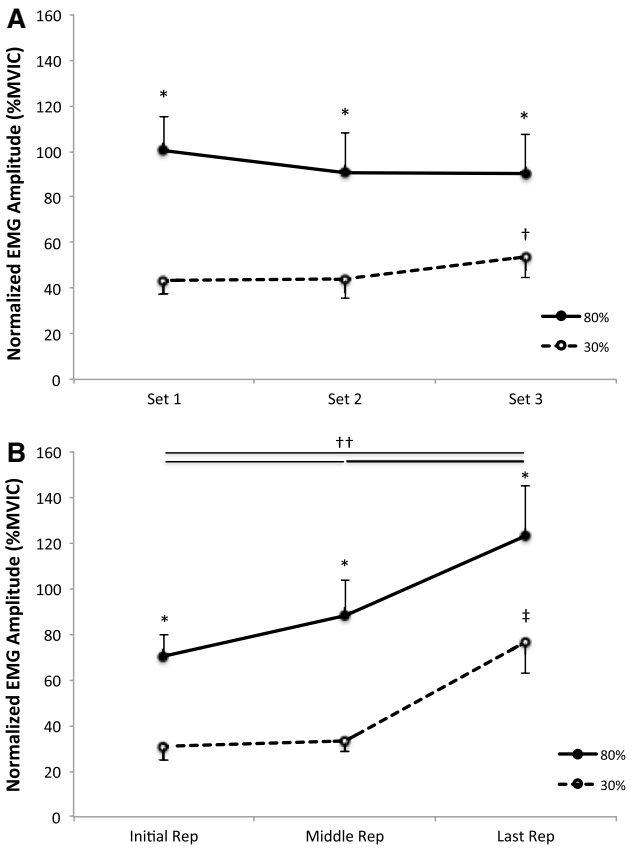

Fig. 4 The **a** load × set (collapsed across muscle and rep) and **b** load × rep (collapsed across muscle and set) for normalized electromyographic (EMG) amplitude. Values are means ± 95 % confidence intervals. *80 % > 30 %, †Set 3 > Sets 1 and 2; ††Initial Rep < Middle Rep and Last Rep, Middle Rep < Last Rep; ‡Last Rep > Initial Rep and Middle Rep

(6–14), 6.7 ± 1.9 (4–10), and 6.2 ± 1.7 (4–9) repetitions, respectively. The numbers of repetitions completed during sets 1, 2, and 3 at 30 % 1RM were 45.6 ± 14.3 (24–79), 26.8 ± 8.3 (17–46), and 22.2 ± 8.6 (13–46) repetitions, respectively. VOL and total work responded the same statistically. For VOL and total work, there were load × set ($p < 0.01$; $\eta_p^2 = 0.39$ and $p = 0.02$; $\eta_p^2 = 0.41$, respectively) interactions (Fig. 3). VOL and total work were significantly greater for 30 % than for 80 % 1RM during all sets. VOL and total work decreased significantly from set 1 to set 2 and plateaued from set 2 to set 3 for 80 % 1RM, while VOL and total work decreased significantly from set 1 to set 3 for 30 % 1RM. For TUCL, there was also a load × set ($p < 0.01$; $\eta_p^2 = 0.67$) interaction (data not shown). TUCL was significantly greater for 30 % than 80 % 1RM during all sets. For both 80 and 30 % 1RM, TUCL decreased significantly from set 1 to 2 and plateaued from set 2 to 3.

For total concentric iEMG, there were no interactions ($p > 0.05$); however, there were main effects for set ($p \leq 0.01$, $\eta_p^2 = 0.59$) and load ($p = 0.02$, $\eta_p^2 = 0.29$) (data not shown). Total iEMG during set 1 was significantly greater than set 2, but equal to set 3. In addition, total iEMG was significantly greater for 30 % than 80 % 1RM during all sets.

Electromyography

For EMG AMP, there were load × set ($p < 0.01$; $\eta_p^2 = 0.62$) and load × rep ($p = 0.01$, $\eta_p^2 = 0.43$) interactions (Fig. 4). There were no significant differences in EMG AMP between sets for 80 % 1RM, while for 30 % 1RM, EMG AMP for set 3 was significantly greater than sets 1 and 2 regardless of muscle or repetition. EMG AMP increased significantly from the initial to the last rep for 80 % 1RM; while for 30 % 1RM, EMG AMP stayed the same from the initial rep to the middle rep, and increased significantly from the middle rep to the last rep regardless of muscle or set. EMG AMP was significantly greater for 80 % than 30 % 1RM during all sets (Fig. 4a) and all reps (Fig. 4b) for all three muscles.

For EMG AMP during the final repetitions of set 1 (Fig. 5a), there was a load × rep interaction ($p < 0.01$; $\eta_p^2 = 0.27$). EMG AMP increased significantly from repetition 1 to repetition 6 for both 80 and 30 % 1RM. EMG AMP was significantly greater for 80 % than 30 % 1RM during all repetitions. For EMG AMP during the final repetitions of set 2 (Fig. 5b), there was a load × rep interaction ($p < 0.01$; $\eta_p^2 = 0.27$). EMG AMP increased significantly from repetition 1 to repetition 4 for both 80 % and 30 % 1RM. EMG AMP was significantly greater for 80 % than 30 % 1RM during all repetitions. For EMG AMP during the final repetitions of set 3 (Fig. 5c), there was no load × rep interaction ($p = 0.15$; $\eta_p^2 = 0.10$). However, there were main effects for load ($p < 0.01$; $\eta_p^2 = 0.43$) and rep ($p < 0.01$; $\eta_p^2 = 0.57$). EMG AMP (collapsed across load)

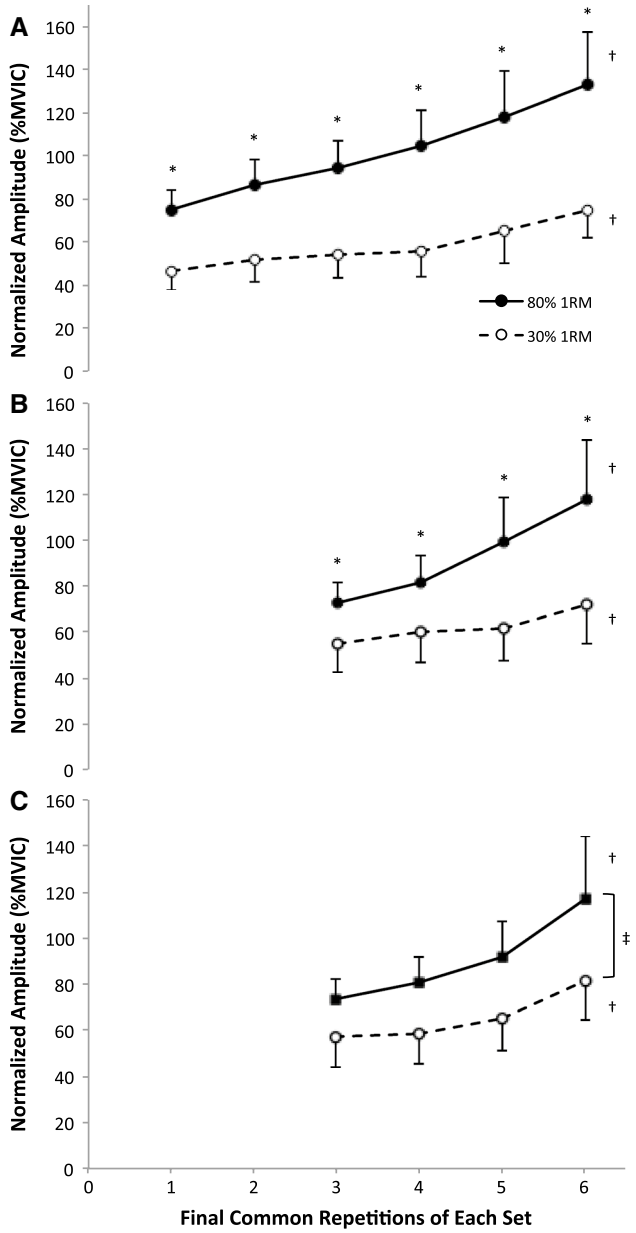

Fig. 5 A comparison of electromyographic (EMG) amplitude during the final repetitions for the 80 vs. 30 % 1RM conditions at **a** set 1, **b** set 2, and **c** set 3. The number of repetitions analyzed for each set was based on the minimum number of repetitions achieved by any one subject during sets 1, 2, and 3. Values are means ± 95 % confidence intervals. *80 % > 30 %, †Final Rep > Initial Rep; ‡Main Effect for Load, 80 % > 30 %

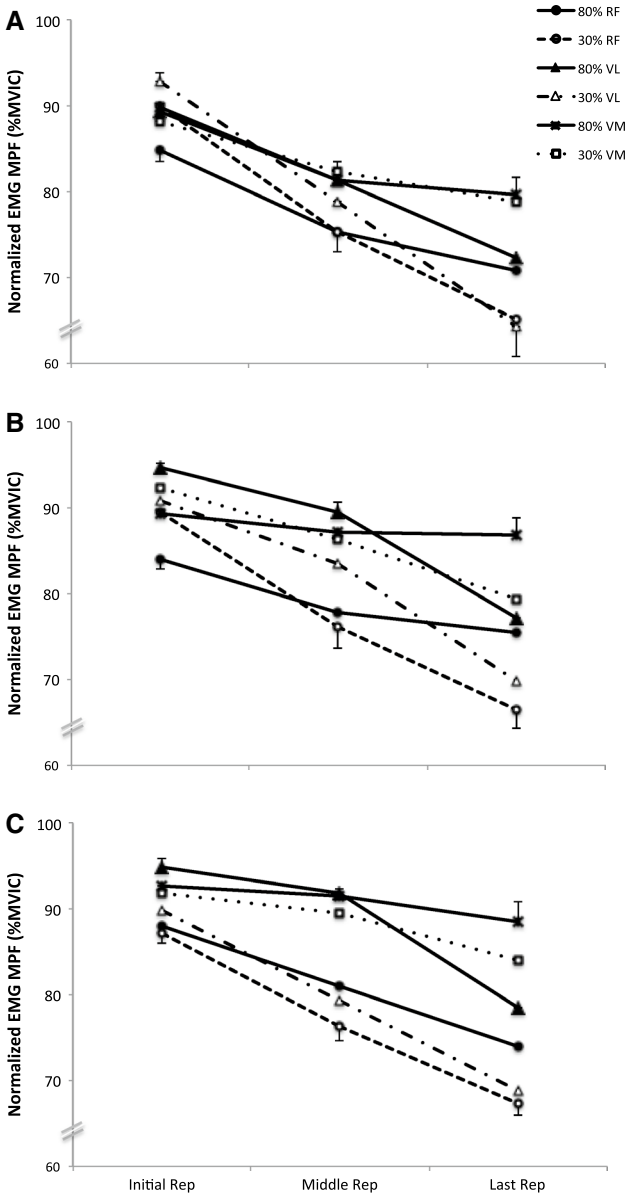

Fig. 6 The mean electromyographic (EMG) mean power frequency (MPF) responses for the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) during **a** Set 1, **b** Set 2, and **c** Set 3. The *error bars* represent the 95 % confidence intervals for the high and low values at each repetition. For the sake of clarity, significant differences are not reported in this figure but are included in the results section

significantly increased from repetition 1 to repetition 4, and EMG AMP (collapsed across rep) was significantly greater for 80 % than 30 % 1RM.

For EMG MPF, there was a load × muscle × rep × set interaction ($p = 0.03$; $\eta_p^2 = 0.77$). With a few exceptions (Fig. 6), EMG MPF remained unchanged from the initial rep to the middle rep, but decreased significantly from the middle rep to the last rep at 30 % 1RM, while EMG MPF decreased significantly from the initial rep to the last rep for the RF, VL, and VM at 80 % 1RM. There were no significant differences in EMG MPF between 80 and 30 % 1RM at the initial reps of sets 1, 2, or 3. However, EMG MPF generally decreased to a greater extent and was significantly lower for the last reps at 30 % than 80 % 1RM (Fig. 6).

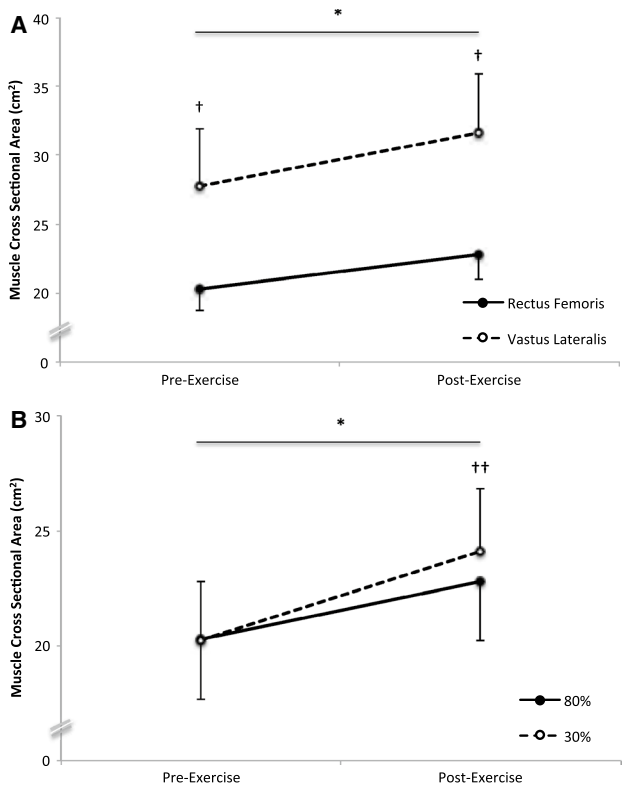

Fig. 7 The **a** muscle × time (collapsed across load), and **b** load × time (collapsed across muscle) interactions for muscle swelling. Values are means ± 95 % confidence intervals. *Pre-Exercise < Post-Exercise for both muscles or loads; †significant difference between muscles; ††significant difference between loads

Muscle cross-sectional area and echo intensity

For mCSA, there were muscle × time ($p < 0.01$; $\eta_p^2 = 0.51$), and load × time ($p < 0.01$; $\eta_p^2 = 0.43$) interactions (Fig. 7). The mCSA was greater for the VL than the RF at pre- and post-exercise. The mCSA increased from pre- to post-exercise for both the RF and VL for 80 and 30 % 1RM for both men and women. However, mCSA increased to a greater degree after the 30 % than 80 % 1RM exercise (Fig. 7).

For EI, there was a muscle × time ($p < 0.01$; $\eta_p^2 = 0.35$) interaction, but there were no differences in EI between the 80 and 30 % 1RM exercise (data not shown). EI was greater in the RF than for the VL at pre-exercise, and EI decreased from pre- to post-exercise in the RF.

Reliability

There was no systematic variability from visit 1 to visit 2 ($p > 0.05$) for any of the variables and all ICC's were greater than zero ($p < 0.05$) according to the 95 % confidence intervals. The ICC, SEM, and CV for the 1RM was 0.97, 5.51 N, and 4.74 %, respectively. The ICCs for EMG AMP and MPF from the RF, VL, and VM during the 1RM were 0.88 and 0.83, 0.94 and 0.78, and 0.90 and 0.68, respectively; the SEMs were 75.29 μV s^{-1} and 2.87 Hz, 45.00 μV s^{-1} and 3.61 Hz, and 114.92 μV s^{-1} and 3.98 Hz, respectively; and the CVs were 21.14 % and 7.61, 11.01 and 9.28 %, and 22.31 % and 11.14 %, respectively. The ICC, SEM, and CV for MVIC force was 0.96, 39.63 N, and 5.48 %, respectively. The ICCs for EMG AMP and MPF from the RF, VL, and VM during the MVIC were 0.81 and 0.86, 0.78 and 0.80, and 0.90 and 0.84, respectively; the SEMs were 24.56 μV s^{-1} and 6.28 Hz, 25.57 μV s^{-1} and 6.56 Hz, and 31.91 μV s^{-1} and 5.76 Hz, respectively; and the CVs were 22.93 % and 8.30, 23.11 and 8.78 %, and 22.84 and 8.23 %, respectively. The ICCs for mCSA and EI of the RF and VL were 0.99 and 0.97, and 0.99 and 0.94, respectively; the SEMs were 0.36 cm^2 and 2.28 au, and 0.94 cm^2 and 3.55 au, respectively; and the CVs were 2.82 and 1.72 %, and 3.47 and 2.83 %, respectively.

Discussion

The primary results of the present study indicated that muscle activation, as measured by EMG AMP, remained greater at 80 % than 30 % 1RM across all repetitions and during all three sets for the men and women, despite increases in EMG AMP during each set at 80 and 30 % 1RM exercise (Fig. 4). EMG AMP during the final common repetitions of each set showed the same patterns of response in that muscle activation was greater during 80 % than 30 % 1RM for each repetition, despite increases in EMG AMP, at the ends of sets 1, 2, and 3 (Fig. 5). The cumulative volume (VOL, total work, and TUCL) and muscle activation (iEMG), however, were 18–202 % greater at 30 % 1RM, and the fatigue-induced decreases in EMG MPF were more pronounced during the 30 % 1RM exercise. Furthermore, the acute increases in mCSA (i.e., muscle swelling) that occurred from pre- to post-exercise were greater after the 30 % 1RM exercise. Collectively, these findings suggest that the mechanisms underlying the fatigue that led to failure were unique to the exercise performed at 30 vs. 80 % 1RM. Our findings may help explain the similar adaptations in hypertrophy, but greater adaptations in strength after 80 vs. 30 % 1RM resistance training reported in previous studies (Mitchell et al. 2012; Ogasawara et al. 2013).

Mitchell et al. (2012) and Ogasawara et al. (2013) demonstrated that when performed to failure, 6–10 weeks of chronic resistance training at 30 % 1RM elicited 6–21 % muscle hypertrophy, which was equivalent to the 7–18 % hypertrophy reported after 80 % 1RM training. However, training at 80 % 1RM produced 14–36 % increases in muscle strength, which were greater than the 7–27 % increases observed following training at 30 % 1RM (Mitchell et al.

2012; Ogasawara et al. 2013). Mitchell et al. (2012) hypothesized that, "…as lighter loads are repeated, the point of failure/fatigue ultimately necessitates near maximal motor unit recruitment to sustain muscle tension. Thus, relatively lighter loads lifted to the point of failure would result in a similar amount of muscle fiber activation compared with heavier loads lifted to failure (pg. 75)." However, our results indicate that, when using the same leg extension training protocol as Mitchell et al. (2012), muscle activation was consistently greater for 80 % than 30 % 1RM during all reps and sets performed to failure. Our results also extend the findings of several previous studies (Akima and Saito 2013; Cook et al. 2013; Schoenfeld et al. 2014). For example, Schoenfeld et al. (2014) demonstrated that muscle activation was lower during a single set of 30 % than 75 % 1RM leg press exercise to failure. Although statistical analyses of EMG AMP values at 70 vs. 50 % 1RM were not reported, a qualitative analysis of the data presented (their Fig. 3) by Akima and Saito (2013) suggested that fatigue-induced increases in muscle activation during a single set of 50 % 1RM leg extension exercise to failure were not sufficient to match muscle activation during exercise at 70 % 1RM. When compared to blood flow restriction (BFR) interventions, Cook et al. (2013) demonstrated that muscle activation increased from the first five to the last five repetitions during three sets of leg extension exercise to failure at 20 % 1RM, but muscle activation was still higher at 70 % 1RM. Therefore, our data, in combination with previous studies (Akima and Saito 2013; Cook et al. 2013; Schoenfeld et al. 2014), indicate that muscle fatigue at 30 % 1RM to failure was not sufficient to induce maximal muscle activation as hypothesized by Mitchell et al. (2012) and Burd et al. (2012b). Moreover, our results suggest that stimuli other than maximal muscle activation, as proposed by Mitchell et al. (2012) and Burd et al. (2012b), may have influenced the hypertrophic responses to the low-load (30 % 1RM) resistance training reported in previous studies (Mitchell et al. 2012; Ogasawara et al. 2013).

In the present study, EMG MPF decreased by 25, 26, and 11 % at 30 % 1RM compared to 14, 18, and 6 % decreases at 80 % 1RM in the RF, VL, and VM, respectively. Decreases in EMG MPF during fatiguing exercise are caused by shifts in the EMG power spectrum toward lower frequencies (Basmajian and De Luca 1985; Hermens et al. 1992). Fatigue-induced shifts in the EMG power spectrum have been attributed to decreases in action potential conduction velocity (Brody et al. 1991), changes in action potential shape (Hermens et al. 1992), and reduced relaxation rates of muscle (Marsden et al. 1983), which in turn, have been attributed to increased inorganic phosphate (Pi) concentrations, decreased intramuscular pH, and altered sarcolemmal ion gradients (Brody et al. 1991). Therefore, the greater percent decreases in EMG MPF observed during the 30 % 1RM exercise in the present study may have reflected greater metabolic byproduct accumulation.

Exercise-induced cell hydration and/or swelling may influence cellular functions such as proteolysis (Haussinger et al. 1990) as well as glycogen (Low et al. 1997) and protein synthesis (Fumarola et al. 2005) through the regulation of anabolic signaling (Hoffmann et al. 2009). It has been hypothesized that acute muscle swelling in response to exercise may occur due to an increase in intracellular osmotic concentration secondary to an increased rate of glycolysis, byproduct accumulation, and altered ion concentration gradients (Hoffmann et al. 2009; Sjogaard et al. 1985). Hoffmann et al. (2009) suggested that decreases in intracellular pH may also cause muscle swelling through the activity of ion exchange pumps. In the present study, the acute increases in mCSA from pre- to post-exercise were 5–11 % greater after the 30 % than 80 % 1RM exercise. Combined with the greater decreases in EMG MPF at 30 % 1RM, these findings support the hypothesis of Hoffmann et al. (2009) regarding the inverse relationship between intramuscular pH and acute muscle swelling and provide further indirect evidence of greater metabolic byproduct accumulation during the 30 % 1RM resistance exercise.

The hypertrophic adaptations reported after chronic resistance training at 30 % 1RM with limited strength increases (Mitchell et al. 2012; Ogasawara et al. 2013) compared to 80 % 1RM training, may be related to the accumulation of metabolic byproducts that occurs during prolonged peripheral fatigue (Popov et al. 2006, 2015). In the present study, the 30 % 1RM resistance exercise required 59 % greater volume, 202 % greater time under load, and 18–45 % greater total muscle activation (iEMG) than the 80 % 1RM exercise. Furthermore, the decreases in EMG MPF were more pronounced, while the acute muscle swelling was greater, for 30 % than 80 % 1RM. Therefore, resistance exercise at 30 % 1RM may prolong the exposure to metabolites, which may act as a stimulus for muscular hypertrophy. For example, Popov and colleagues (Popov et al. 2006, 2015) showed that performing continuous contractions (i.e., no relaxation between repetitions) to failure at 50–54 % 1RM increased lactate concentrations to a greater extent than exercise at 74–80 % 1RM (discontinuous contractions) to failure, and enhanced anabolic signaling, decreased myostatin expression, and increased growth factor-1, and growth hormone (GH) concentrations, all of which promote hypertrophy. Burd et al. (2012a) demonstrated that prolonged time under load, compared to resistance training at a normal cadence (1 s concentric, 1 s eccentric), also enhanced muscle protein synthesis. Terzis et al. (2010) showed greater mammalian target of rapamycin (mTOR) responses after resistance training with five sets of 6RM than after one or three sets of 6RM. Therefore, the prolonged exposure to metabolic byproduct

accumulation, as indirectly indicated by the results of the present study, may contribute to the hypertrophy reported after chronic training at 30 % 1RM despite lower muscle activation than training at 80 % 1RM.

Metabolic stress is a term that has been used to describe prolonged exposure to metabolic byproduct accumulation as an underlying factor for muscle hypertrophy (Loenneke et al. 2011; Schoenfeld 2010). For example, previous studies have shown that resistance exercise at 20 % 1RM in combination with BFR is capable of stimulating acute increases in muscle protein synthesis (Fry et al. 2010), while chronic resistance exercise at 20 % 1RM with BFR is capable of eliciting significant hypertrophy (Takarada et al. 2004). It has been suggested that the increase in muscle protein synthesis following BFR exercise at 20–40 % 1RM occurs as a result of fatigue-related metabolic byproduct accumulation, or "metabolic stress" (Loenneke et al. 2011). In support of this hypothesis, Takarada et al. (2004) demonstrated increases in leg extensor muscle strength and muscle size following resistance training at 20 % 1RM with BFR. In addition, acute increases in GH were observed following training at 20 % 1RM with BFR. The authors (Takarada et al. 2004) postulated that metabolic stress influenced the acute GH responses and chronic hypertrophic adaptations. Therefore, it is possible that metabolic stress is also an underlying mechanism of the hypertrophic adaptations observed following chronic low-load resistance training without BFR (Loenneke et al. 2011; Schoenfeld 2010; Takarada et al. 2004).

Our results indicate that EMG AMP was 84–127 % higher during the 80 % than 30 % 1RM resistance exercise. Consequently, exercise at 80 % 1RM theoretically required greater recruitment of high-threshold, type II motor units and/or greater motor unit firing rates than exercise at 30 % 1RM. Previous studies have demonstrated that high-intensity resistance training (6–8 RM; 80–85 % 1RM) stimulates hypertrophy of all three major fiber types (i.e., type I, type IIa, and type IIb), however, hypertrophy was greatest in the high-threshold, type II motor units (Staron et al. 1990). Interestingly, Mitchell et al. (2012) reported a non-significant 7 % greater increase in VL type I fiber size after 10 weeks of training at 30 vs. 80 % 1RM, while Netreba et al. (2013) observed a greater increase in VL type II fiber size following 8 weeks of training at 85 vs. 25 % 1RM. These findings tentatively suggest that there may be fiber type-specific adaptations that occur dependent on the load used during resistance training. Specifically, it is possible that greater type II fiber hypertrophy occurs with training at 80 % 1RM, while a greater reliance on lower-threshold motor units may result in greater type I fiber hypertrophy with training at 30 % 1RM. Moreover, it has been suggested that mechanical stress (i.e., high intra-muscular forces) can also increase anabolic signaling and muscle hypertrophy (Schoenfeld 2010). Collectively, therefore, these factors may be acting to influence the hypertrophic and strength adaptations observed during chronic training at 80 % 1RM. Recently, Herda et al. (2010) hypothesized that the mechanomyogram is capable of distinguishing between type I and type II fiber-related differences in motor unit activation strategies, which may implicate mechanomyography as an attractive non-invasive method to examine the potential fiber type-specific adaptations to high- (80 % 1RM) vs. low-load (30 % 1RM) resistance training.

To our knowledge, this is the first study to quantify and compare EMG AMP, EMG MPF, acute muscle swelling, and total volume during high-load, 80 % 1RM vs. low-load, 30 % 1RM resistance training exercise. Our results demonstrated that muscle activation was 38–62 % lower for the superficial quadriceps femoris muscles during resistance exercise at 30 % than at 80 % 1RM, despite fatigue-induced increases in EMG AMP at both 80 and 30 % 1RM. However, the cumulative volume and muscle activation, time under load, and increases in mCSA from pre- to post-exercise (i.e., muscle swelling) were greater, while the decreases in EMG MPF were more pronounced for 30 % 1RM. These fundamental differences in fatigue manifestations may help explain the unexpected chronic adaptations in hypertrophy vs. strength observed in previous studies (Mitchell et al. 2012; Ogasawara et al. 2013), independent of the differences in muscle activation. Future studies are needed to further examine the acute and chronic neuromuscular responses to high- vs. low-load resistance training.

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Conflict of interest The authors have no perceived conflicts of interest to declare.

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