**Acute changes in muscle thickness and pennation angle in response to work-matched concentric and eccentric isokinetic exercise**

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Muscle thickness and pennation angle in concentric and eccentric exercise

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ABSTRACT

Acute changes in muscle architecture influenced by muscle swelling might be associated with chronic adaptations to resistance exercise, including skeletal muscle growth. Concentric (CON) and eccentric (ECC) muscle actions both play a role in hypertrophic processes, but the influence of each on acute indices of muscle swelling [i.e. muscle thickness (MT) and pennation angle PA)] remain relatively unknown. Therefore, this study compared the acute changes in MT and PA in response to work-matched CON versus ECC isokinetic exercise. Twelve university-aged students performed two bouts of maximal isokinetic knee extensions at 120 deg·s⁻¹ on the same day: 50 CON followed by a work-matched ECC bout (~5000 J; 28±5 reps) with the contralateral limb. Ultrasound images were captured from the middle and distal sites of the vastus lateralis before and immediately after each exercise bout. From these images, MT and PA were measured. Middle and distal MT (11-14%, respectively, p<0.001) and middle PA (39%, p<0.001) increased only after CON. Additionally, changes in MT were strongly related to the amount of total work performed (r=0.76) during CON. Our results suggest that when the workload is matched between CON and ECC muscle actions performed at a moderate velocity, CON actions seem to be a more potent stimulus for inducing acute changes in muscle thickness and pennation angle.

Key-words: muscle architecture, muscle swelling, resistance exercise, isokinetic dynamometer, ultrasound.
INTRODUCTION

Resistance exercise (RE) is commonly used to develop functional capacity, preserve health, and improve athletic performance (Ratamess et al. 2009, Garber et al. 2011). To promote optimal training adaptations, acute RE variables such as the type of muscle actions, external load, and amount of total work should be altered (Tan 1999, Gentil et al. 2017) but the optimal manipulation of such RE variables remains a topic of continued investigation (Morton et al. 2016). The current recommendations suggest that RE programs should generally include dynamic repetitions consisting of both concentric (muscle shortening) and eccentric (muscle lengthening) muscle actions. Although implementing concentric and eccentric actions is common during traditional RE, it may be possible that targeted concentric or eccentric actions can be used to elicit certain neuromuscular responses, as each exhibit distinct neuromuscular and morphological responses. For example, eccentric actions produce greater force per unit of muscle size (Gonzalez-Izal et al. 2014), require less motor unit activation per relative load (Linnamo et al. 2000), induce less metabolic stress (Horstmann et al. 2001), and can generate 20-146% greater force than concentric actions (Westing et al. 1991). As eccentric actions are less fatiguing and exhibit greater force outputs, it is possible that eccentric actions can be performed with greater absolute loads for more repetitions, resulting in greater total work: a crucial factor for influencing skeletal muscle hypertrophy (Fry 2004).

Considering the aforementioned attributes of eccentric muscle actions and the fact that one of the most commonly desired RE adaptations is
increasing skeletal muscle hypertrophy, eccentric RE has been advocated as a fundamental stimulus for optimal hypertrophic responses (Walker et al. 2017). However, the process of skeletal muscle anabolism is complex and is not determined by a single variable (i.e. total eccentric work). For example, previous studies have reported that despite greater work performed during eccentric-only RE, concentric and eccentric training induced similar increases in muscular hypertrophy (Schott et al. 1995, Blazevich et al. 2007, Cadore et al. 2014, Franchi et al. 2014). Therefore, it is clear that not only do directly modifiable variables (i.e. exercise choice, external resistance, total work) play a role in skeletal muscle hypertrophy, but their subsequent and indirectly resultant factors also play a role by internally stimulating the anabolic process.

Among the many possible internal acute changes that can happen within the muscle, changes caused by muscle swelling, which can be defined as the influx of vascular fluid into the muscle, have been associated with chronic RE adaptations (Schoenfeld 2013, Schoenfeld and Contreras 2014). As this process occurs, architectural changes within the muscle occur. For example, an acute increase in muscle thickness, which provides information regarding the degree of muscle cell swelling, seems to be an important trigger for strength and hypertrophic adaptations (Finan and Guilak 2010, Yasuda et al. 2012). Furthermore, increases in pennation angle seem to be a common finding in hypertrophied pennate muscles as result of strength training protocols (Kawakami et al. 2000, Aagaard et al. 2001) but little is known whether these changes occur as a direct response to exercise, or if these changes only transpire over time.
As such, it is plausible to speculate that acute regional changes in muscle thickness and pennation angle might provide insight into the longitudinal responses to RE. Although previous research indicates that repeated concentric exercise results in a greater number of sarcomeres in parallel and eccentric exercise favors the addition of sarcomeres in series (Franchi et al. 2014), the acute changes in muscle thickness and pennation angle following concentric and eccentric actions remain relatively unexplored. Furthermore, it has been shown that acute and chronic responses to RE are not uniform throughout an entire muscle’s length (Earp et al. 2015, 2016) indicating that multiple measurement sites are required for an accurate representation of the changes occurring within a muscle.

Therefore, the primary purpose of this study was to compare the acute changes in muscle thickness and pennation angle in response to work-matched concentric and eccentric isokinetic exercise. Based on previous research (Blazevich et al. 2007, Franchi et al. 2014), we hypothesized that concentric and eccentric work-matched RE would induce distinct acute changes in muscle thickness and pennation angle. Secondarily, we aimed to determine whether changes in muscle thickness and pennation angle are related to the amount of total work performed. Together, these findings could steer RE practitioners, athletes, and coaches towards modifying the type or number of exercises that focus specifically on concentric or eccentric actions in a RE program.

METHODS

Participants
Twelve university-aged students (8 females = 22±2 yrs, 58±7 kg, 163±5 cm; and 4 males = 21±1 yrs, 74±10 kg, 180±7 cm) volunteered to participate in this study. We conducted a pilot study with five participants to evaluate the effect size for the main dependent variable (MT response following concentric actions), and the sample size was determined *a priori* using G*Power* software with the significance level set at *p*=0.05 and power (1-β)=0.80 in order to detect a moderate effect (*f*=0.25). Based on these a priori calculations and the data from the pilot study, a final sample size of *n*=12 was selected. All participants were apparently healthy and declared that they were free from any chronic disease or orthopedic injury. Participants were not allowed to perform any vigorous physical activities, participate in unaccustomed exercise, take medications, or consume any type of supplement 48h prior to testing. The study was conducted in accordance with the Declaration of Helsinki and the experimental protocol was approved by the Institutional Human Experimental Committee (2.103.261/2016).

**Experimental procedures**

To investigate the effect of concentric and eccentric muscle actions on the muscle thickness and pennation angle of the vastus lateralis (VL), participants performed two bouts of maximal isokinetic unilateral knee extensions at 120°·s⁻¹. Since a large number of repetitions (> 20) would likely promote superior muscle swelling (Jenkins et al. 2015), and consequently promote a more substantial increase in muscle thickness and pennation angle, participants first completed a bout of 50 maximal concentric knee extensions.
(CON) with one leg. Approximately 10-min later, they performed a work-
matched eccentric knee extension (ECC) bout (~5000 J; 28±5 reps) with the
contralateral leg. Although the CON protocol always preceded ECC, the limb
that was chosen to first perform CON was randomly chosen. Before and
immediately after (approximately 1-min was required to move the participant
from the dynamometer to the ultrasound measuring position) each CON and
ECC exercise protocol, ultrasound (US) images were captured from the middle
and distal sites of the VL, from which muscle thickness (MT) and pennation
angle (PA) were determined. All data was collected in a single session lasting
approximately 40 min.

Ultrasound measurements

Internal VL architecture was measured using B-Mode ultrasound
(Philips-VMI, Lagoa Santa, Brazil). For the purposes of this study, the VL was
chosen, as previous research has reported it to be the most homogenous of the
thigh muscles (Blazevich et al. 2006), allowing for more reliable data. Pre- and
post-exercise US images were captured from the middle (39% of the distance
starting from the superior border of the patella to the anterior superior iliac
spine) and distal (22%) sites of the VL before and immediately after each CON
and ECC exercise (Blazevich et al. 2006). For this measurement, participants
were positioned supine on a table with the assessed knee supported from
below to sustain 30° of flexion (extended=0°). They were asked to relax their
limbs during the assessment, and a suitable amount of water-soluble
transmission gel was used to ensure optimal image quality while avoiding
transducer pressure on the skin. The 10 MHz scanning head was placed on the skin perpendicular to the tissue interface, and for the best representation of the bone boundary, the optimal angle was selected for each scan.

The images were analyzed using ImageUJ software (National Institute of Health, USA, version 1.47). From these sonographic images, VL architecture was represented by MT and PA as shown in Figure 1. The MT was defined as the distance between the border of the subcutaneous fascia and the deep aponeurosis, was measured at the longitudinal edges of both sides of the image, and averaged for later analysis. The PA was defined as the angle between the fascicle and its deep aponeurosis (Ando et al. 2014). The same experienced sonographer performed all assessments and analyses. The typical error of measurement was 1.4º for PA and 0.96 mm for MT, and the coefficient of variation was 9.4% for PA and 2.4% for MT.

**Isokinetic dynamometry**

The CON and ECC exercise bouts were performed on an isokinetic dynamometer (Biodex Medical, Inc., Shirley, NY). The device was calibrated according to the manufacture’s recommendations, and participants were positioned on the dynamometer seat with belts fastened across their trunk and pelvis to minimize body movements that could affect torque output. The lateral epicondyle of the femur was aligned to the dynamometer’s axis of rotation, and the lever arm was fixed 3 cm above the lateral malleolus. Before each exercise protocol, participants performed a warm-up routine of 10 isokinetic repetitions at 120 deg·s\(^{-1}\) with a range of motion from 5º to 85º (0º = full knee extension).
During the first 7 repetitions, they were instructed to progressively increase their effort from minimal to maximal, finishing with 3 maximal effort repetitions. Participants received visual feedback of their effort and rested for 1-min before commencing each test protocol.

For CON muscle actions, the participants were asked to fully extend their knee as fast and strong as possible and then to completely relax, allowing gravity to return their limb to the initial position (85° of knee flexion). After completing 50 maximal CON repetitions, the participant was removed from the dynamometer and post-exercise US images were taken. Meanwhile, the total CON work (torque×distance) was calculated in Joules, and the dynamometer was prepared for ECC testing on the other leg. This process took approximately 10-min, and once US measurements were completed, the participant was again secured to the dynamometer.

For ECC muscle actions, participants were instructed to relax and allow the device to passively move their limb to the extended position (5° of knee flexion). Once the knee was at the extended position, participants were instructed to resist as hard as they could throughout the range of motion by pushing against the lever arm as the knee was being flexed. Participants continued to perform maximal ECC repetitions until achieving the same amount of total work as the CON bout.

All participants were verbally encouraged by the same tester to give maximal effort during all repetitions. For each protocol, the cumulative amount of external work was recorded and the greatest torque value of all the torque-time curves was expressed as peak torque. Additionally, the Biodex software
calculated a fatigue index for each protocol by computing the percent change in total work completed during the first third of the test to the total work completed during the final third of the test. All data were calculated using the Biodex software.

**Statistical analysis**

The results are expressed as mean ± standard deviation. The Shapiro-Wilk test was applied to check for data normality, and in the case of a non-normal distribution, a logarithmic transformation was performed. Paired t tests were used to compare total work, peak torque, and the fatigue index between CON and ECC. A two-way repeated measures ANOVA was used to compare the MT and PA between CON and ECC at the middle and distal sites of the VL. Compound sphericity was verified by the Mauchly test, and when the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse-Geisser procedure. Tukey's post-hoc test with a Bonferroni adjustment was applied in the event of a significant difference in the ANOVA. A Pearson's product-moment correlation was used to assess the relationship between the changes in MT and total work based on time×intervention analyses on middle and distal MT and PA, sample size and power were calculated. The observed powers were 1.00 for both middle and distal MT, and 0.630 for middle PA and 0.631 for distal PA. The effect size (ES) calculations were used to evaluate the magnitude of interventions. The power calculations were determined using G*Power version 3.1.3. The other analyses
were performed in SPSS version 20.0 (Somers, NY, USA) with the level of significance being \( p \leq 0.05 \).

RESULTS

Isokinetic variables for knee extension during CON and ECC are presented in Table 1. Peak torque was 33.4% greater \( (p \leq 0.01) \) and the fatigue index was 70.8% less in ECC \( (p \leq 0.01) \) compared with CON. There was no difference \( (p = 0.47) \) in total work between CON and ECC.

Figure 2 shows MT before and after CON and ECC at the middle and distal sites of the VL. For middle VL MT, there was neither a significant time\( \times \)intervention \( [F(1,11)=4.205, p=0.07] \) nor an effect for intervention \( [F(1,11)=0.057, p=0.82] \). However, there was a significant effect for time \( [F(1,11)=18.011, p<0.001; ES=1.28] \). Middle VL MT increased \( (p=0.001; ES=0.58) \) only after CON actions. For distal VL MT, there was a time\( \times \)intervention interaction \( [F(1,11)=10.662, p=0.008; ES=0.98] \), with distal VL MT increasing only after CON \( (p<0.001; ES=0.42) \).

Figure 3 shows PA before and after CON and ECC at the middle and distal sites of the VL. For middle VL PA, there was a time\( \times \)intervention interaction \( [F(1,11)=10.721, p=0.01; ES=0.99] \), but not for the distal VL PA \( [F(1,11)=1.000, p=0.34; ES=0.30] \). Middle VL PA increased \( (p<0.001; ES=1.26) \) only after CON. Although no differences were observed for distal VL PA, CON induced a larger ES than ECC \( (0.63 \text{ vs } 0.13) \).

There was a strong positive correlation between absolute changes in middle VL MT and the amount of total work \( (r=0.76; p=0.004) \) following CON.
No correlations were observed for distal VL MT following CON and no correlations were observed for ECC. No correlations were observed between PA and any other mechanical measurements.

**DISCUSSION**

The main findings of this study were that only CON increased MT (middle and distal sites of the VL) and PA (middle VL). In addition, a strong relationship between changes in MT (mm) and total work (J) was observed. The changes following CON were more pronounced at the middle site of the VL. Therefore, the results of the present study suggest that CON RE results in greater acute cell swelling compared to ECC RE, evidenced by greater changes in muscle thickness and pennation angle.

In the present study, individuals demonstrated an ECC peak torque 33% greater than CON (Table 1). These findings corroborate previous studies that also reported a greater ECC strength capacity (Blazevich et al. 2007, Franchi et al. 2014, Gonzalez-Izal et al. 2014). Although the exact mechanisms that underpin the superiority of eccentric force production remain to be determined, it has been hypothesized that the increased strength capacity might be related to differences in cross-bridge cycling (Douglas et al. 2017, Franchi et al. 2017). One possibility is that the second myosin head interacts with actin during eccentric actions, which would increase the amount of active cross-bridges and consequently force output (Douglas et al. 2017). It is also believed that greater force produced during eccentric muscle actions could be due to a greater stretch of the S2 portions of myosin (Franchi et al. 2017) and/or the storage and
release of elastic potential energy in titin (Nishikawa et al. 2012). Regardless of
the specific mechanisms as play, ECC actions produced more torque than
CON, which allowed the same amount of work to be completed with fewer
repetitions.

The enhanced efficiency of ECC actions was not only evidenced by the
need for fewer repetitions, but was further confirmed by the approximately 71%
less fatigue experienced during ECC (Table 1). Previous studies have also
reported that eccentric actions have less pronounced fatigue compared to
concentric muscle actions (Grabiner and Owings 1999, Baroni et al. 2011). One
possible explanation is that during eccentric actions, cross-bridges seem to
become suspended in an active state (bound to actin), are then forcibly
detached, and then rapidly re-attached, not allowing for a complete contraction
cycle (Douglas et al. 2017). Since a full contraction cycle is not completed, less
ATP is required to maintain force output. In addition to the possible reduced
energy demands of eccentric actions, the greater intrinsic force capacity during
eccentric actions requires fewer active motor units to attain a given absolute
force (Westing et al. 1991). Therefore, fewer active motor units using less ATP
results in less metabolic demand during exercise, which may explain the greater
fatigue resistance in ECC actions (Douglas et al. 2017). On the opposite end of
the spectrum, CON was more fatiguing, and although not measured in the
present study, likely utilized more ATP, resulting in greater lactate accumulation (Kemp 2007).

Combined, increased energy expenditure and increased intramuscular
lactate concentrations have been linked to increased muscle cell swelling,
which was apparent only in CON in the present study. Specifically, MT increased at the middle and distal sites of the VL (14% and 11%, respectively), and PA increased on the middle site of the VL (39%). On the contrary, ECC did not result in any significant changes in VL architecture (Figure 2 and 3). These results agree with previous studies describing changes in architecture following dominant-concentric exercises. Brancaccio et al. (2008) reported an increase of 9% in MT and 13% in PA following an incremental cycle ergometer test to exhaustion, and another study reported increases in MT of 5% and PA of 11% following 50 isometric contractions (Kubo et al. 2001). Similarly, Csapo et al. (2011) also showed that the conventional leg press exercise resulted in 7% and 10% for MT and PA, respectively.

As previously mentioned, the greater increase in VL architecture observed in CON is probably a result of greater metabolic demand associated with concentric muscle actions compared to eccentric actions (Horstmann et al. 2001). The greater metabolic demand of concentric actions results in more metabolic byproducts (e.g. lactate, H+, P_i, etc.) (Kraemer et al. 2006), generating an osmotic pressure in favor of the muscle cell (Sjogaard and Saltin 1982). This greater pressure results in fluid movement from the vascular space into active muscle (Ploutz-Snyder et al. 1995) due to the dilatation of arterioles and an increased capillary pressure, favoring the osmosis of water from capillaries to the interstitial space (Sjogaard and Saltin 1982). It is proposed that changes in extracellular osmolality can modify cell volume, and therefore, the concentration of intracellular molecules by altering the function of internal structures such as cellular nucleus (Finan and Guilak 2010). Therefore,
evidence suggests that muscle swelling would be an important trigger for protein synthesis and skeletal muscle anabolism. Ultimately, these multifaceted responses to muscle swelling and muscle cell functioning may partially explain the hypertrophic response induced by concentric exercise (Loenneke et al. 2012, Yasuda et al. 2012).

As hypothesized, the changes in VL MT following CON exercise were strongly related to the total work performed (Figure 4). This result indicates that individuals with a greater concentric work capacity may experience a greater increase in cell swelling. Interestingly, the relationship between total work and the change in MT was only observed at the middle site of the VL. This result is consistent with previous reports of intramuscular architecture variation (Blazevich et al. 2006). Such variations are probably required in pennate muscles in order to achieve mechanical stability, and potentially to allow a muscle to have both ‘force-generating’ and ‘force-transfer’ regions. Since CON induced greater changes in MT, it could be hypothesized that acute response would predict region-specific hypertrophy. Although further studies are warranted to confirm this hypothesis, a previous study agreed with our data (Franchi et al. 2014), demonstrating that concentric-only muscle actions induced muscle hypertrophy only at the middle VL, while eccentric-only RE promoted hypertrophy at the distal site.

Although this study indicates that concentric actions may provide a superior internal stimulus for anabolism, this study is without limitations. It has to be mentioned that although total work was equated between CON and ECC, the isokinetic nature of the design and greater strength expressed during ECC
(i.e. fewer repetitions performed at the same speed) resulted in unequal time under tension between the protocols, which might also play a role in acute exercise responses. Moreover, considering that ECC was always performed 10-min following CON, it might be speculated that a residual central fatigue might have reduced the muscular performance during ECC. However, the decrement in muscular performance as effect of fatigue would have indeed increased the total number of repetitions to complete the ECC workload, which would reduce the potential interference on results. Additionally, the results observed in the present study are specific for moderate isokinetic velocity (120 deg·s\(^{-1}\)). Further studies are necessary to investigate whether similar results would be found using slower or faster velocities. Lastly, although regional changes were present at the middle site of the VL during this study, which is consistent with previous research (Franchi et al. 2017), it is important to note that a more dynamic exercise (e.g. squats or lunges that involve simultaneous hip and knee movements) may result in different regional changes compared to those observed following isokinetic exercise in the present study. However, any further comments on that topic would be outside of the scope of the present study, and future research may wish to investigate that possibility.

In conclusion, only CON isokinetic exercise performed in moderate velocity promoted acute changes in muscle thickness and pennation angle during work-matched isokinetic exercise. The changes were more pronounced in the middle site of VL, indicating that region-specific changes are likely to occur as a result on concentric actions. These results seem to have some practical importance to RE practitioners and coaches. The findings of this study
might steer RE practitioners, athletes, and coaches towards placing a larger
focus on concentric actions in a RE program if the desired outcome is acute
muscle swelling, which has been linked to skeletal muscular growth. However,
further studies should investigate whether such acute changes do in fact translate into chronic regional neuromuscular adaptations.

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CONFLICT OF INTEREST
The authors have no conflicts of interest.

REFERENCES


Baroni, B.M., Stocchero, C.M., Santo, R.C. do E., Ritzel, C.H., and Vaz, M.A.


Fry, a C. 2004. The role of resistance exercise intensity on muscle fiber


Jenkins, N.D.M., Housh, T.J., Bergstrom, H.C., Cochrane, K.C., Hill, E.C.,


FIGURE LEGENDS

Figure 1. Representative ultrasound image from one subject. Vastus lateralis architecture is represented by muscle thickness (vertical lines) and pennation angle (angle between the fascicle and its deep aponeurosis).

Figure 2. Middle and distal VL muscle thickness before and after concentric and eccentric actions. *p ≤ 0.05 vs PRE for concentric actions. Values are presented as mean ± SD.

Figure 3. Pennation angle before and after concentric and eccentric exercises in the middle and distal sites of the vastus lateralis (VL). *p ≤ 0.05 vs PRE for concentric exercise; † p ≤ 0.05 between concentric and eccentric exercises. Values are presented as mean ± SD.

Figure 4. Pearson's product-moment correlation between middle VL muscle thickness changes (post-pre) and concentric work volume.
Table 1 – Isokinetic variables for knee extension during concentric (CON) and eccentric (ECC) muscle actions

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<th>Variable</th>
<th>CON</th>
<th>ECC</th>
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<td>Peak torque (N·m⁻¹)</td>
<td>173.0 ± 47.6</td>
<td>259.9 ± 60.1*</td>
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<td>Repetitions</td>
<td>50.0 ± 0.0</td>
<td>28.4 ± 4.8*</td>
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<tr>
<td>Work (J)</td>
<td>5122 ± 1354</td>
<td>5060 ± 1358</td>
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<td>Fatigue index (%)</td>
<td>61.0 ± 8.7</td>
<td>17.8 ± 12.4*</td>
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*p ≤ 0.05 between ECC and CON. Fatigue index is the percent change in total work completed during the first third of the test (i.e. the first third of the total number of repetitions) to the total work completed during the final third of the test (i.e. the final third of the total number of repetitions).
Representative ultrasound image from one subject. Vastus lateralis architecture is represented by muscle thickness (vertical lines) and pennation angle (angle between the fascicle and its deep aponeurosis).

188x181mm (300 x 300 DPI)
Middle and distal VL muscle thickness before and after concentric and eccentric actions. *p ≤ 0.05 vs PRE for concentric actions. Values are presented as mean ± SD.
Pennation angle before and after concentric and eccentric exercises in the middle and distal sites of the vastus lateralis (VL). *p ≤ 0.05 vs PRE for concentric exercise; † p ≤ 0.05 between concentric and eccentric exercises. Values are presented as mean ± SD.

220x123mm (300 x 300 DPI)
Pearson's product-moment correlation between middle VL muscle thickness changes (post-pre) and concentric work volume.

$r = .760$
$p = .004$