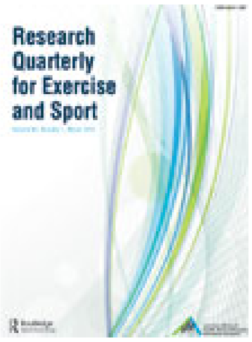

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RESEARCH NOTE

Sex-Related Responses to Eccentric-Only Resistance Training in Knee-Extensors Muscle Strength and Architecture

Giuseppe Coratella,[1,2] Stefano Longo,[1] Emiliano Cè,[1] Eloisa Limonta,[1] Susanna Rampichini,[1] Angela Valentina Bisconti,[1] Federico Schena,[2] and Fabio Esposito[1,3]

[1]University of Milano; [2]University of Verona; [3]IRCCS Don Gnocchi Foundation

ABSTRACT

Purpose: The present study aimed to investigate whether or not eccentric-only training induced different sex-related adaptations in vastus lateralis muscle architecture and knee extensors strength. **Methods**: Thirteen healthy women and 13 healthy men were recruited. Vastus lateralis pennation angle, fascicle length, and muscle thickness, as well as knee extensors eccentric, isometric, and concentric peak torque and one-repetition maximum (1RM) were measured. Both women and men underwent a unilateral iso-load knee-extension eccentric-only training with 120% of the concentric 1RM, consisting of 4 sets × 10 repetitions twice a week for a total of 8 weeks. **Results**: Pennation angle increased in women (+ 14%, 95% CI [10, 17], effect size [ES] = 1.54) but not in men (+ 5%, 95% CI [−1, 11], ES = 0.28), while fascicle length increased in both women (+ 7%, 95% CI [4, 10], ES = 1.02) and men (+ 12%, 95% CI [8, 16], ES = 1.82) and muscle thickness increased in women (+ 13%, 95% CI [8, 18], ES = 1.11) and men (+ 11%, 95% CI [7, 15], ES = 0.89). In both women and men, eccentric (18%, 95% CI [11, 25], ES = 0.96, and 16%, 95% CI [9, 22], ES = 0.82, respectively), isometric (17%, 95% CI [11, 23], ES = 0.53, and 17%, 95% CI [10, 24], ES = 0.62), concentric (12%, 95% CI [7, 16], ES = 0.49, and 9%, 95% CI [5, 13], ES = 0.42) peak torque and 1RM (10%, 95% CI [6, 14], ES = 0.53, and 10%, 95% CI [5, 15], ES = 0.50) similarly increased after the intervention. **Conclusions**: This study showed that the adaptations in strength are not sex-dependent, but the increases in pennation angle only in women suggest that the changes in muscle architecture may depend on sex.

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KEYWORDS
Fascicle length; isokinetic; muscle thickness; pennation angle

Resistance training is well known to induce muscle strength gains and morphological adaptations. Among the several resistance-training protocols (i.e., concentric-only, traditional concentric-eccentric, and eccentric-only exercise; Coratella & Schena, 2016), the effectiveness of eccentric-only training for improving both muscle strength and structure has been largely acknowledged, as already reviewed (Franchi, Reeves, & Narici, 2017; Roig et al., 2009), irrespective of the method (isokinetic or dynamic-constant external load) used (Coratella, Milanese, & Schena, 2015b). Although muscle damage markers have been reported after a single eccentric-only exercise session, a delayed muscle protection occurs thereafter (Coratella & Bertinato, 2015; Coratella, Chemello, & Schena, 2016), making it safe and suitable for training purposes.

Muscle architecture, encompassing pennation angle (PA), fascicle length (FL), and muscle thickness (MT), is a strong determinant used by the skeletal muscle to maximize force production and movement performance (Blazevich, Gill, & Zhou, 2006). Muscles with a large physiological cross-sectional area develop a greater amount of force throughout an increased number of in-parallel sarcomeres, which results in larger PA, while longer fascicles have been related to higher contraction velocity and greater force development at longer muscle length (Blazevich et al., 2006). The arrangement in muscle architecture seems to be sex-dependent, because it has been shown that men have greater MT and PA than women in the *vastus lateralis* (VL) muscle (Kubo et al., 2003; Wu, Delahunt, Ditroilo, Lowery, & De Vito, 2016), while women have relatively longer (Kubo et al., 2003) or similar (Wu et al., 2016) muscle fascicles. Such a sex-dependent muscle architecture may turn into different muscle function, given the greater peak power and muscle efficiency recorded during a jumping task and the concurrent greater gastrocnemius PA and MT in men versus women recently shown in a between-sex comparison (Rubio-Arias et al., 2017).

It was recently revealed that eccentric-only training could cause specific adaptations in muscle architecture, involving muscles in a predominant fascicle elongation

CONTACT Giuseppe Coratella giuseppe.coratella@unimi.it Department of Biomedical Sciences for Health, University of Milano, via Giuseppe Colombo 71, Milano 20133, Italy.

with smaller or no changes in PA (Baroni, Silveira Pinto, Herzog, & Aurélio Vaz, 2015). However, some studies have shown that increases in PA occurred in the VL with eccentric-only training (Blazevich, Cannavan, Coleman, & Horne, 2007; Seynnes, De Boer, & Narici, 2007). Nevertheless, while PA did not increase in men (Baroni et al., 2013; Coratella et al., 2015b), it was shown to increase in the studies that included both men and women (Blazevich et al., 2007; Seynnes et al., 2007), leading to sex being considered a possible confounding factor. Furthermore, similar increases were found in blood growth hormone, and greater increases in total testosterone concentration were reported in men versus women (Benini, Prado Nunes, Orsatti, Barcelos, & Orsatti, 2015). These factors may allow men to have greater sensitivity in resistance exercise-induced hypertrophic stimulus, given the greater increments in muscle mass recorded compared with those in women (Hubal et al., 2005). Lastly, between-sex inconsistency in strength gains was also shown in the literature. Indeed, similar (Colliander & Tesch, 1991), greater (Fernandez-Gonzalo, Lundberg, Alvarez-Alvarez, & De Paz, 2014), or lower (Hubal et al., 2005) resistance exercise-induced increases in maximal strength in men compared with women were reported.

However, to date, no study has investigated if the eccentric-only training-induced adaptations in muscle architecture could be sex-dependent. In addition, given the controversy reported in the literature, training-induced strength gains need to be investigated to elucidate the potential influence of sex. Therefore, the aim of the current study was to evaluate the effects of eccentric-only training on quadriceps muscle strength and VL muscle architecture in women versus men.

Methods

Study design

The present study was designed as a two-group, pretest–posttest trial. To calculate the sample size, we assumed a 5% PA change between men and women and considered a variability as standard deviation = 15% (thus resulting in Effect Size = Change / Standard Deviation = 0.33), a two-tailed distribution, an alpha level = .05, and power > .80. Using statistical software (GPower 3.1, Dusseldorf, Germany), the sample size was $n = 11$ per group. To prevent the influence of any possible dropout on the statistical power, 26 participants were enrolled.

Participants

Thirteen healthy men ($M_{age} = 21.2 \pm 2.6$ years, $M_{body\ mass} = 79.4 \pm 4.3$ kg, $M_{stature} = 1.80 \pm 0.10$ m) and 13 healthy women ($M_{age} = 20.8 \pm 3.0$ years, $M_{body\ mass} = 61.1 \pm 3.9$ kg, $M_{stature} = 1.62 \pm 0.07$ m) were recruited for the present investigation. The participants were recreationally active and were not involved in any systematic strength program within 6 months of the present investigation. Throughout the duration of the present study, the participants were not allowed to participate in any other form of strenuous physical activity. People with knee disorders (ligament reconstruction, patella-femoral syndrome, meniscus tears) or muscle injuries (knee extensor or knee flexor strains or contractures) and users of any drug were excluded from the study. All participants signed written informed consent forms before the study, which was approved by the Ethics Committee of the local university. The study was conducted according to the international standards of the Declaration of Helsinki (1975) for studies involving human participants.

Procedures

The present investigation lasted 11 weeks. All participants underwent familiarization testing and training sessions during Week 1. Baseline measurements were assessed at Week 2, the intervention lasted from Week 3 to Week 10 (8 weeks), and the posttraining measurements were assessed at Week 11.

To investigate training-induced strength increments, we measured the concentric, eccentric, and isometric peak torque using an isokinetic dynamometer and one-repetition maximum (1RM) using an isotonic instrument. Muscle thickness, FL, and PA were measured in the VL by ultrasound to estimate architectural adaptations due to the intervention (Coratella, Milanese, & Schena, 2015a).

Strength measurements

Isokinetic test assessment

Participants performed the peak torque measurements on an isokinetic dynamometer (Cybex, Lumex, Ronkonkoma, NY). The apparatus was set, and the gravity correction was performed according to the manufacturer's procedures. Participants were locked on the dynamometer seat; two belts secured the trunk and the shoulders. The tested limb was secured, and the knee was properly aligned to the center of rotation of the dynamometer, while an additional lever secured the untested limb. After a standardized warm-up, which consisted of two submaximal concentric and eccentric sets of 10 repetitions, the peak torque was investigated in eccentric (-1.05 rad $\cdot$ s^{-1}, range of motion = 5°–90°), concentric (1.05 rad $\cdot$ s^{-1}, range of motion = 5°–90°), and isometric modalities (60°), while considering 0° equal to the full knee extension (Coratella & Bertinato, 2015). Three maximal repetitions were performed for each modality, and the peak torque was inserted into the data analysis. The operators provided strongly standardized encouragements to participants. At baseline only, the protocol was repeated twice (separated by 3 days) to familiarize participants with the isokinetic dynamometer and to test the reliability of the measurements.

One-repetition maximum

Unilateral knee extension 1RM was measured on an isotonic apparatus (Leg Extension, Technogym, Cesena, Italy). The protocol was based on previous procedures (Coratella & Schena, 2016). The assessment started with a warm-up consisting of two sets of 15 repetitions each using a nonexhaustive intensity. Then, an exhaustive 6- to 8-repetition maximum set was performed to predict a possible 1RM, calculated based on the formula (Brzycki, 1993):

$$\text{Predicted 1RM} = \text{load (kg)}/1.0278 - (0.0278 \cdot \text{number of executed repetition}) \quad (1)$$

Afterward, 90% of the predicted 1RM was used as the first 1RM attempt and loads of 2.5 kg were added until participants were not able to lift the weight stack. Each trial was interspersed with 2 min of passive recovery.

Muscle architecture measurements

Muscle thickness, FL, and fascicle PA were measured at 39% of the distal length of the VL (Blazevich et al., 2006). The participants were seated on a chair with their limbs relaxed at 90° and their muscles fully relaxed (Coratella et al., 2015a). Test–retest reliability was calculated using two images (depth = 5 cm) scanned by a 4.4-cm-length ultrasound scanner (Acuson P50, Acuson Corporation, CA) and analyzed using free software ImageJ (ImageJ, National Institute of Health, Bethesda, MD). The ultrasound transducer was placed longitudinally to the muscle fiber orientation; a water solution gel was used, and minimal pressure was applied to the tissues. Muscle thickness was defined as the distance between the superficial and the deep aponeurosis of the VL. The PA was defined as the angle between the fascicle and the aponeurosis. Lastly, the FL was calculated using the following formula (Blazevich et al., 2006):

$$\text{FL} = \sin(\gamma + 90^\circ) * \text{MT}/\sin(180^\circ - (\gamma + 180^\circ - \text{PA})) \quad (2)$$

where γ is the angle between the superficial and the deeper aponeurosis. The same experienced operator performed the data collection and data analysis.

Eccentric-only training

The intervention consisted of four sets of 10 unilateral eccentric-only knee extensions on the nondominant limb (the limb that is not preferred to kick a ball). The load was set at 120% of the concentric 1RM (Coratella & Bertinato, 2015). The range of motion was approximately 85°, and participants were instructed to maintain a 2-s eccentric phase through visual feedback. From the 5th week to the 8th week, the training load was adjusted by adding 5% of the initial load. An operator lifted the lever to relieve the participants during the concentric contraction, allowing them to perform the eccentric phase only (Coratella et al., 2015b). A standardized warm-up, consisting of three sets of 10 repetitions of weight-free squats, was executed before each training session. Each set was separated by 2 min of passive recovery. The intervention lasted 8 weeks and was performed twice a week (separated at least by 2 days) for a total of 16 training sessions.

Statistical analysis

Statistical analysis was performed using Statistical Package for Social Science (SPSS) 20.0 (IBM, Armonk, NY). Test–retest reliability was measured using an intraclass correlation coefficient (ICC; Cronbach's α coefficient) and the standard error of measurement (SEm). The sphericity's assumption was analyzed using the Mauchly test. The normality of the distribution was analyzed using the Shapiro–Wilk test. The variations of the dependent parameters (1RM; isokinetic eccentric, concentric, and isometric peak torque; and FL, MT, and PA) were analyzed by a two-way (Time × Sex) repeated-measures analysis of variance. Post-hoc analysis using Bonferroni's correction was then performed to calculate the main effects for group (two levels: men and women) and time (two levels: baseline and posttraining). An additional analysis of covariance was run using baseline level as a covariate to investigate the difference in pretest–posttest changes in women versus men. Correlations using Pearson's coefficient were then performed to investigate whether the training-induced changes were correlated with baseline values. Significance was set at $p < .05$. Data are reported as mean ± standard deviation. The differences over time were reported as changes in percentage with 95% confidence interval (95% CI). The effect size was calculated and interpreted according to Cohen's recommendations as follows: 0.2 to 0.49 = *small*; 0.5 to 0.79 = *moderate*; 0.8 to 0.99 = *large*; > 1 = *very large* (Cohen, 1988).

Results

High scores of test–retest reliability between the familiarization session and baseline were found for isometric (ICC = .965, SEm = 8.2 N), concentric (ICC = .951, SEm = 9.5 N·m), and eccentric (ICC = .948, SEm = 10.7 N·m) peak torque and 1RM (ICC = .976, SEm = 1.2 kg). Similarly, VL MT (ICC = .951, SEm = 0.6 mm), PA (ICC = .927, SEm = 0.6º), and FL (ICC = .905, SEm = 2.0 mm) showed high scores of test–retest reliability. At baseline, irrespective of the testing modality, men had higher quadricep strength than women ($p < .05$). Similarly, greater PA and MT were found in men compared with women (Table 1), while there was no difference for FL.

No Time × Sex interaction was found for 1RM, $F(1, 25) = 0.822$, $p = .371$, or eccentric, $F(1, 25) = 0.333$, $p = .569$, concentric, $F(1, 25) = 0.198$, $p = .822$, and isometric peak torque, $F(1, 25) = 1.784$, $p = .186$. A significant Time × Sex interaction was found for PA, $F(1, 25) = 7.457$, $p = .011$, but not for FL, $F(1, 25) = 2.991$, $p = .096$), or MT, $F(1, 25) = 1.435$, $p = .237$. *Moderate* to *large* increases in quadriceps strength occurred in both men and women (Table 1) by a similar extent (Figure 1). *Very large* increases in PA occurred only in women (Table 1) by a greater extent compared with the *small* changes shown in men (Figure 1). *Very large* increases in FL occurred in both men and women (Table 1), although men showed a greater but not a significant extent (Figure 1). *Large* and *very large* increases in MT occurred in men and women, respectively (Table 1).

No correlation was found between the baseline strength values and the eccentric-only training-induced changes in 1RM ($r = .313$, $p = .111$) or eccentric ($r = -.303$, $p = .124$), concentric ($r = -.171$, $p = .393$), and isometric ($r = -.105$, $p = .603$) peak torque. Baseline muscle architecture values showed *moderate* correlations with the changes in PA ($r = -.417$, $p = .030$), FL ($r = -.477$, $p = .012$) and MT, ($r = -.588$, $p = .001$).

Discussion

The present study aimed to investigate the effects of eccentric-only training on quadriceps strength and muscle architecture in men versus women. The novelty of the current results is that in women but not in men, PA increased after the training intervention, while similar FL and MT were observed in both men and women. Additionally, irrespective of the testing modality, quadriceps strength similarly increased after training for both men and women.

The present results showed that PA eccentric-only training-induced adaptations occurred in women but not in men. The increments in PA reflected the increases in in-parallel sarcomeres, which increased the physiological cross-sectional area, leading to greater muscle strength (Blazevich et al., 2006). However, the increases in PA after eccentric-only training protocols have been quite controversial in the literature. No adaptation in VL PA was found after 4 weeks (Franchi et al., 2015), 6 weeks (Coratella et al., 2015b), or 12 weeks of eccentric-only training in young men

Table 1. Training-induced adaptations in the trained limb.

	Baseline Mean (*SD*)	Posttraining Mean (*SD*)	Change % [95% CI]	*p* value	Effect size
1RM (kg)					
Men	56 (11)*	62 (12)	10 [5, 15]	.001	0.50
Women	34 (6)	38 (7)	10 [6, 14]	< .001	0.53
Eccentric peak torque (N·m)					
Men	294 (59)*	335 (47)	16 [9, 22]	< .001	0.82
Women	208 (38)	244 (38)	18 [11, 25]	< .001	0.96
Concentric peak torque (N·m)					
Men	231 (52)*	253 (54)	9 [5, 13]	.002	0.42
Women	151 (35)	168 (36)	12 [7, 16]	< .001	0.49
Isometric peak torque (N					
Men	228 (49)*	269 (58)	17 [10, 24]	< .001	0.62
Women	178 (41)	208 (35)	17 [11, 23]	< .001	0.53
Fascicle length (mm)					
Men	85.8 (6.2)	97 (6.5)	12 [8, 16]	< .001	1.83
Women	89.4 (7.1)	96.5 (8.6)	7 [4, 10]	.038	1.02
Pennation angle (degree)					
Men	15.2 (3.3)*	16.0 (3.8)	5 [−1, 11]	.134	0.28
Women	10.8 (1.1)	12.4 (1.2)	14 [10, 17]	< .001	1.54
Muscle thickness (mm)					
Men	26.2 (3.4)*	29.1 (3.1)	11 [7, 15]	.002	0.89
Women	21.5 (2.3)	24.3 (2.9)	13 [8, 18]	< .001	1.11

Note. 1RM = one-repetition maximum. Changes are shown as percentage with confidence interval 95% CI. *$p < .05$ compared with women at baseline.

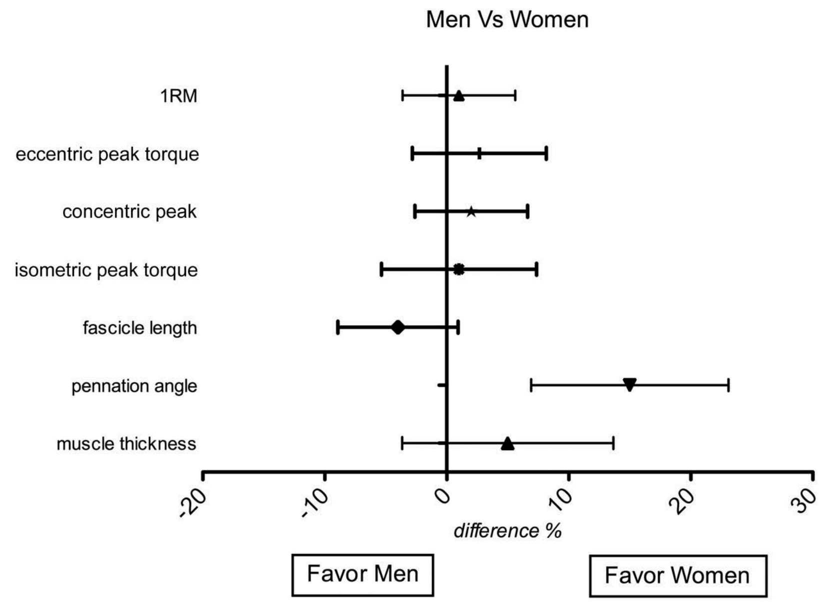

Figure 1. A direct women-versus-men comparison of the differences in training-induced adaptations is shown as mean difference (%) with 95% confidence intervals. The results are based on the analysis of covariance, with the baseline values considered the covariate, the posttraining values considered the dependent variable, and the group considered a fixed factor.

Note. 1RM = one-repetition maximum.

(Baroni et al., 2013; Franchi et al., 2014). Similarly, no difference in VL PA occurred in older men and women after 14 weeks of enhanced eccentric training (Reeves, Maganaris, Longo, & Narici, 2009) nor was there a difference in *biceps femoris* after 8 weeks of eccentric-only training (Potier, Alexander, & Seynnes, 2009), even though the authors provided no indication about the sex of the participants. On the contrary, eccentric-only training-induced increases in VL PA were observed in men after 9 weeks (Guilhem, Cornu, Maffiuletti, & Guével, 2013) or in men and women after 5 weeks in the VL but not in the *vastus medialis* (Blazevich et al., 2007). Similarly, enhanced eccentric training led to early increases in VL PA in young men and women (Seynnes et al., 2007) as well as conventional concentric-eccentric training in older men and women (Reeves et al., 2009). The negative correlation observed between the baseline values and the changes in PA may lead one to argue that the major stimulus for increasing PA in women may depend on their lower baseline PA values, as consistently shown with previous findings (Kubo et al., 2003). Among the complex and multiple mechanisms that rule the protein synthesis, it has been reported that suppression of the expression of 4E-BP1 (a gene that downregulates the protein synthesis) was concurrent with increases in muscle volume via specific increases in PA (Franchi et al., 2014). However, it is acknowledged that such a speculation needs to be proven.

The *very large* fascicle elongations found in both men and women are consistent with the findings of several previous studies (Baroni et al., 2013; Blazevich et al., 2007; Coratella et al., 2015b; Franchi et al., 2014, 2015; Guilhem et al., 2013; Reeves et al., 2009). Such a typical eccentric training-induced adaptation depends on the level of mechanical constraint that muscle fascicles underwent during the repetitive eccentric contractions (Franchi et al., 2014; Reeves et al., 2009). In turn, it would result in an in-series sarcomeres addition (Blazevich et al., 2006). Fascicle elongation allows the muscle to shorten at a higher velocity with a positive consequence on sprint performance because longer VL fascicles were negatively correlated with the 100-m sprint time (Kumagai et al., 2000). In addition, the repetitive strain due to the eccentric-only training may have accounted for the shift of the longer muscle toward the point at which the passive tension occurs, thereby facilitating the increment of the muscle range of motion (Potier et al., 2009). Finally, eccentric-only training has been shown to move the muscle length–tension relationship rightward, thereby decreasing the strain-injury risk (Brughelli & Cronin, 2007). Although no significant women-versus-men difference in FL was found at baseline, the negative correlation between the baseline values and the changes in FL suggests that people with shorter fascicles could be more sensitive to the lengthening stimulus. Therefore, eccentric-only training seems to effectively promote fascicle elongation equally in women and men.

Very large and *large* increases in MT were found in women and men, respectively. Although the increases were not different, the negative correlation with the baseline values may indicate that women were more sensitive to the eccentric-only stimulus. The increases in MT could have been derived from increases in the PA, FL, or both (Blazevich et al., 2006; Coratella et al., 2015b). Therefore, it seems that women and men may have gained greater MT through different mechanisms. In the only previous direct women-versus-men comparison of the enhanced eccentric training-induced adaptations, similar increments in thigh muscle mass were reported (Fernandez-Gonzalo et al., 2014), consistently with the present results. Similarly, enhanced eccentric training led to increases in quadricep muscle volume in both women and men (Norrbrand, Fluckey, Pozzo, & Tesch, 2008; Tesch, Ekberg, Lindquist, & Trieschmann, 2004). However, generic resistance exercise seems to induce greater muscle mass gains in men (Hubal et al., 2005). The same authors suggested that the results should be interpreted with caution due to the large variability in muscle mass gains in both women and men.

Eccentric-only training was shown to be a great stimulus to increase muscle strength (Roig et al., 2009). Particularly, the authors of the meta-analysis emphasized the role of eccentric-only training to increase total strength (i.e., the sum of the concentric, eccentric, and isometric peak torque). Accordingly, the present results showed increases in quadricep peak torque in all the testing modalities, with greater strength gains in the eccentric versus concentric modality in line with the training/testing specificity (Baroni et al., 2015). In addition, both women and men experienced similar moderate increases in 1RM, as already shown in the literature (Coratella et al., 2015b; Coratella & Schena, 2016). Enhanced eccentric training led to greater increases in strength in men than in women (Fernandez-Gonzalo et al., 2014), although similar protocols did not result in sex-dependent strength gains (Norrbrand et al., 2008; Tesch et al., 2004). In addition, it must be noted that strength gains depend on both neural and morphological factors, which could act together or independently (Hubal et al., 2005).

It is acknowledged that the current investigation comes with some limitations but also with interesting perspectives. No data on changes in muscle activity were recorded, which might have provided further insight into the strength gains. Furthermore, although the VL is largely used to represent quadricep muscle architecture, different measurements (e.g., dual-energy X-ray absorptiometry or magnetic resonance imaging) may result in more comprehensive muscle mass analysis.

What does this article add?

The current eccentric-only training induced strength gains and changes in muscle architecture differently in women versus men. The lower baseline PA values in women could be related to the increases in PA shown only in women, suggesting that this process may be sex- or baseline-dependent. Typically, eccentric-only training lengthened muscle fascicles and led to increases in MT, which seems to depend on the different responses in the PA and VL in men and women. Finally, strength gains were not sex-dependent and were characterized by the greater increases in eccentric versus concentric strength.

ORCID

Stefano Longo http://orcid.org/0000-0001-5806-8305
Emiliano Cè http://orcid.org/0000-0003-0691-3153
Eloisa Limonta http://orcid.org/0000-0001-7246-2819
Fabio Esposito http://orcid.org/0000-0002-4420-2611

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