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Muscle conduction velocity, strength, neural activity, and morphological changes after eccentric and concentric training

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This study compared the effects of concentric and eccentric training on neuromuscular adaptations in young subjects. Twenty-two men and women were assigned to one of two groups: concentric (CON, n = 11) and eccentric (ECC, n = 11) training. Training consisted of 6 weeks of isokinetic exercise, performed twice weekly, starting with two sets of eight repetitions, and progressing to five sets of 10 repetitions. Subjects were tested in strength variables [concentric, eccentric, and isometric peak torque (PT), and rate of force development (RFD)], muscle conduction velocity (CV), neuromuscular activity, vastus lateralis (VL) muscle thickness, and echo intensity as determined by ultrasonography. There were similar increases in the concentric and eccentric PTs in both the CON and ECC groups ($P < 0.01$), but only the ECC group showed an increase in isometric PT ($P < 0.001$). Similarly, both groups exhibited increased VL muscle thickness, CV, and RFD, and reduced VL echo intensity ($P < 0.05$). Significant correlations were observed among the relative changes in the neuromuscular outcomes and training variables (e.g., total work, average PT) ($r = 0.68$–0.75, $P < 0.05$). The results showed that both training types similarly improved dynamic PT, CV, RFD, and muscle thickness and quality during the early weeks of training.

Recently, eccentric training-induced adaptations have been widely examined due to their positive effects on strength performance, muscle hypertrophy, and injury rehabilitation in athletes as well as in healthy untrained subjects (Tomberlin et al., 1991; Mont et al., 1994; Hortobagyi et al., 1996a, b; Seger et al., 1998; Mjolsnes et al., 2004; Blazevich et al., 2007; Baroni et al., 2013; Oliveira et al., 2013). Eccentric muscle contractions involve unique neuromuscular features that are partly distinct from concentric muscle actions (Enoka, 1996; Carrasco et al., 1999; Guilhem et al., 2011; González-Izal et al., 2013). Some of these differences are greater muscle force production, lower metabolic cost, lower neuromuscular activity required to produce the same workload (Tesch et al., 1990; Proske & Morgan, 2001), lower neuromuscular activity prior to the onset of movement (Grabiner & Owings, 2002), and greater muscle damage (González-Izal et al., 2013). Thus, eccentric and concentric actions provide different stimuli to the muscles and therefore may induce different neural and morphological adaptations (Enoka, 1996; Roig et al., 2009).

Eccentric training induces lower concentric but greater eccentric strength increases compared with concentric training (Tomberlin et al., 1991; Hortobagyi et al., 1996a, b; Seger et al., 1998; Blazevich et al., 2007). In addition, it has been shown that the neuromuscular activity, as assessed by electromyographic (EMG) signaling, increases more during eccentric contractions following eccentric training, whereas increases in the EMG amplitude during concentric contractions often are greater after concentric training (Higbie et al., 1996; Hortobagyi et al., 1996b). With respect to muscle hypertrophy, some studies have shown greater increases in muscle cross-sectional area (CSA) following eccentric training compared with concentric training (Higbie et al., 1996; Hortobagyi et al., 1996b; Seger et al., 1998; Norrbrand et al., 2008), while others have found similar degrees of muscle hypertrophy after concentric and eccentric training (Ben-Sira et al., 1995; Blazevich et al., 2007). However, comparisons between the effects of concentric and eccentric training on both neural and morphological properties (i.e., muscle CSA, thickness, and quality) during the early phases of training (i.e., 4–8 weeks) have been less well investigated. Moreover, possible associations between the neuromuscular adaptations to concentric and eccentric training [i.e., strength performance and muscle thickness (MT) increases] to the training variables (i.e., total work, work per session, maximal and average training PT) have not been investigated, and it would be interesting to determine the influence of such training variables on muscle mass and strength development following a training intervention.

Muscle conduction velocity (CV) depends on the polarization state of the sarcolemma, which is influenced by numerous factors, including the membrane potential, extracellular and intracellular Na^+ and K^+ concentrations, internal and external resistances, and membrane resistance and capacitance (Allen et al., 2008). It had been shown that eccentric exercise induced greater acute impairments in muscle CV (Piitulainen et al., 2011), but a recent study showed that both concentric and eccentric exercises equally decreased muscle CV (González-Izal et al., 2013). Although the acute effects of eccentric and concentric exercises on muscle CV have been assessed previously (Piitulainen et al., 2011; González-Izal et al., 2013), to the best of our knowledge, no longitudinal study has investigated the effects of concentric and eccentric training on the maximal muscle CV. In the only study that has investigated the effect of exercise training on muscle CV, Vila-Chã et al. (2010) observed that 6 weeks of either endurance or traditional resistance training resulted in increases in motor unit CV of 30% of maximal isometric voluntary contraction (MVC). Therefore, whether concentric and eccentric training induce different adaptations in muscle action potential propagation velocity (i.e., muscle CV) remains to be elucidated. This comparison would expand our knowledge of the effects of concentric and eccentric training-induced adaptations on muscle properties.

Muscle quality can be assessed using ultrasound (US) imaging. Enhanced echo intensity is thought to represent changes caused by increases in intramuscular connective and adipose tissues (Pillen et al., 2009; Cadore et al., 2012). In addition, traditional resistance training may improve muscle quality, as suggested by a reduced echo intensity observed after 6 weeks of training in elderly adults (Radaelli et al., 2013). Notwithstanding, to the best of our knowledge, no previous study has compared the adaptations induced by concentric and eccentric training on muscle echo intensity as determined by US imaging, and it would be interesting to investigate whether these distinct types of training induce different changes in muscle quality in young subjects.

As mentioned above, there is a need to improve the knowledge of the possible different neural and morphological adaptations in the early phases of concentric and eccentric training. In addition, expanding the knowledge of the neuromuscular adaptations during the early phases of concentric and eccentric training may also be useful due to the applicability of shorter periods of training to musculoskeletal rehabilitation programs (Mont et al., 1994; Baroni et al., 2013). Therefore, the purpose of this study was to compare the effects of 6 weeks of concentric and eccentric training on strength variables, neuromuscular activity, MT, muscle CV, and US echo intensity in young men and women. Our hypothesis was that short-term eccentric training would generate greater magnitude of adaptations compared to concentric training on strength, neuromuscular activity, MT, muscle CV, and echo intensity adaptations. In addition, our second purpose was to investigate the possible associations among the training variables, including the total work, average work per session, maximal training peak torque, and average peak torque per session with the magnitude of the increases in the strength variables and MT. Our second hypothesis was that there would be positive associations among these variables within each group.

Methods

Experimental design

To investigate the effects of 6 weeks of concentric or eccentric training on neuromuscular adaptations, the subjects were evaluated using variables related to maximal isometric, concentric, and eccentric PT, as well as maximal neuromuscular activity (i.e., sEMG), muscle CV, MT, and echo intensity. In addition, training variables such as total work (i.e., the sum of the work performed in each session), average work per session, training peak torque, average peak torque per session, and delta training peak torque were assessed in all subjects to investigate the possible associations between these variables and training-induced adaptations. The stability and reliability of the performance variables were assessed in a subgroup of subjects before the start of testing (González-Izal et al., 2013). Each specific test was overseen by the same investigator at the pre- and post-intervention time points and was conducted on the same equipment with identical subject/equipment positioning. The investigator who performed the analysis was blinded to the training modality of the subjects. Each subject performed the tests at the same time of the day throughout the study.

Subjects

Twenty-two healthy physically active volunteers (14 women and 8 men) participated in the study and were randomly assigned to two groups: concentric training [CON, n = 11 (7 women, 4 men)] and eccentric training [ECC, n = 11 (7 women, 4 men)]. All participants were injury free and had some previous experience with strength training, but had not engaged in any regular, systematic training program in the previous 12 months. All of the participants were informed about the possible risks of the experiment and provided written informed consent before taking part in the experiment. The experiment was conducted in accordance with the Declaration of Helsinki and approved by the local Ethics Committee. The exclusion criteria included any history of neuromuscular, metabolic, hormonal, and cardiovascular disease. The subjects were not taking any medications that influence hormonal or neuromuscular metabolism and were advised to maintain their normal dietary intake throughout the study. The physical characteristics of the subjects are shown in Table 1.

Table 1. Physical characteristics (mean ± SD)

	Concentric training group CON, n = 11	Eccentric training group ECC, n = 11
Women/men	7/4	7/4
Age (years)	22.9 ± 7.8	21.3 ± 3.3
Body mass (kg)	66.1 ± 9.5	64.1 ± 12.3
Height (cm)	169.4 ± 7.3	171.0 ± 8.1
% fat mass	20.1 ± 5.7	19.0 ± 6.9

Maximal muscle strength and rate of force development (RFD)

Before and after training, maximal isometric, concentric, and eccentric PTs were obtained using an isokinetic dynamometer (Humac Norm, CSMi Solutions, Stoughton, Massachusetts, USA) in two testing sessions separated by at least 72 h. In one session, the subjects performed concentric maximal contractions (CON), while in the other session they performed eccentric maximal contractions (ECC). The order of the sessions was randomized. In each session, the subjects were seated on the isokinetic dynamometer chair, and their right leg was attached to the isokinetic dynamometer arm so that the rotation axis of their knees was aligned with the rotation axis of the isokinetic dynamometer. The subjects' trunks were fixed to the chair using a belt. Before the strength tests, the subjects warmed up with 10 knee extension/flexion repetitions at an angular velocity of 90°/s, performing at a submaximal effort. After the warm-up, each session consisted of two repetitions of a 4-s MVC at a knee angle of 60° (full extension = 0°). After 5 min of rest, the participants performed two trials of five maximal eccentric or concentric contractions (through knee angles from 0 to 90°) of the knee extensors and flexors at 60°/s separated by 2 min of rest. Two MVCs were also performed for the left leg, and these measurements were used as control values for strength. During all of the maximum tests, the researchers provided verbal encouragement so that the subjects would feel motivated to produce their maximum force. The torque exerted by the knee flexors and extensors was continuously measured using the isokinetic dynamometer, and the data were exported to an A/D converter in the EMG record system and analyzed offline using Matlab software (R2012, The MathWorks Inc, Natick, Massachusetts, USA). Signal processing included filtering with a fourth-order Butterworth low-pass filter at a cutoff frequency of 9 Hz. The PT was defined as the highest value of the torque (N·m) recorded during the unilateral isometric, concentric, and eccentric knee extensions. The maximal rate of force development (RFD_{max}) and RFDs 0–50 ms (RFD50) and 0–100 ms (RFD100) ($N{*}s^{-1}$) were determined from the slope of the force–time curve (Δforce/Δtime) for the isometric contractions over 50 ms time intervals. The maximal RFD values were determined by dividing the force–time curve at successive moving time intervals of 50 ms (i.e., 0–50, 1–51, 2–52) (Häkkinen et al., 2003). The RFD variables were calculated from the force onset, which was considered the point at which the force exceeded 2.5 times the standard deviation of the mean of the force signal at rest, and were determined using the Matlab software. The test–retest reliability coefficients intraclass correlation coefficient (ICC) were over 0.94 for all of the strength variables.

Muscle CV and maximal neuromuscular activity

Surface electromyography (sEMG) was recorded during the MVC from the vastus lateralis (VL) using a semi-disposable linear array of eight electrodes with a 5-mm inter-electrode distance in a single differential configuration. Prior to electrode placement, the skin was shaved and cleaned with alcohol, and the innervation zone was located using a linear array of 16 electrodes with a 5-mm inter-electrode distance. Then, the array of eight electrodes was placed between the innervation zone and the distal tendon of the VL parallel to the muscle fibers. The sEMG signals were recorded using a 128-channel sEMG amplifier (EMG-USB2, OT Bioelettronica, Torino, Italy) (3-dB bandwidth, 10–500 Hz) and sampled at 2048 samples/s per channel. The sEMG signals were analyzed with Matlab software (R2012, The MathWorks Inc). Each of the EMG channels was filtered using the fourth-order Butterworth band-pass filter with a cutoff frequency between 10 and 500 Hz. Afterward, the EMG records were sliced exactly in 1 s when the peak torque was determined in the force–time curve and the root mean squared (RMS) value was calculated. This value was calculated as the average of the RMS values for each EMG channel in the array during the MVC. The muscle CV was also measured during the MVC using the multidip approach (Farina & Negro, 2007) with channels 3–6 of the electrode array (because this method uses only four consecutive EMG channels). This method is based on the use of a regression analysis of the spatial and temporal frequencies of multiple dips introduced into the EMG power spectrum through the application of a set of spatial filters. The reason behind this approach was that the spatial and temporal frequency domains were linearly related by the CV. Therefore, introducing zeros or dips in the spatial filter transfer function in the power spectrum of the recorded signal, the CV could be estimated from the ratio between the temporal (detected from the power spectrum of the recorded signal) and spatial (imposed through the design of the spatial filter) frequencies at which the dip occurred (Farina & Negro, 2007). The test–retest reliability coefficients (ICC values) of the EMG measurements were 0.85 for both the maximal neuromuscular activity and muscle CV.

Echo intensity and MT

The echo intensity (i.e., muscle quality) and MT were measured using a B-mode ultrasound (MyLab50Xvision, Esaote, Genoa, Italy) following standard procedures described elsewhere (Cadore et al., 2012; Radaelli et al., 2013). A 10.0-MHz scanning head with a width of 10 cm was placed on the skin perpendicular to the tissue interface, and the scanning head was coated with a water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. The subjects were evaluated in the supine position (hip and knee joints fully extended) after 15 min of rest and after 72 h without any vigorous physical activity. After the training period, the US measurements were performed 5 days after the last training session. A line perpendicular to a line between the greater trochanter and the superior side of the patella in the direction of the muscle fibers was marked, and the probe was positioned in this perpendicular line. Three measurements were taken midway between the lateral condyle of the femur and greater trochanter (Kumagai et al., 2000; Cadore et al., 2012; Radaelli et al., 2013). The echo intensity was determined by gray-scale analysis using the standard histogram function in Image-J (version 1.37, National Institutes of Health, Bethesda, Maryland, USA). The region of interest was selected in the VL so that most of the muscle was captured, avoiding any bone or surrounding fascia. For echo intensity analysis, the depth setting was fixed at 5 cm. When this setting was insufficient to display the entire muscle, only the superficial part of the muscle was used for the echo intensity analysis. The echo intensity in the region of interest was expressed as a value between 0 and 255 (0: black; 255: white).

Three MT images were also determined in the VL. The MT was measured at the same position as the echo intensity. The images were digitalized and analyzed in Image-J (version 1.37, National Institutes of Health). The subcutaneous adipose tissue–muscle interface and the muscle–bone interface were identified, and the distance from the adipose tissue–muscle interface to the fascia between the VL and vastus intermedius was defined as the MT. The same investigator made all of the measurements of echo intensity and MT. To ensure that the same testing position was maintained in all of the experimental sessions, the right thigh of each subject was mapped for the position of the electrodes based on moles and small angiomas by marking on a transparent paper (Narici et al., 1989). The echo intensity and MT values were calculated as the mean of the three measurements taken. The test–retest reliability coefficients (ICC) were 0.94 for MT and 0.85 for echo intensity values.

Concentric and eccentric training programs

The training programs in the present study lasted for 6 weeks. Each type of training (i.e., concentric or eccentric) was performed twice weekly. The right leg of each subject was used as the training leg while the left leg of each subject was used as an untrained control leg. The subjects performed two sets of eight repetitions in the first week, progressing to three sets of eight repetitions in the second week, three sets of 10 repetitions in the third week, four sets of 10 repetitions in the fourth week, four sets of 12 repetitions in the fifth week, and five sets of 10 repetitions in the sixth week. During the training, the subjects were advised to perform maximal effort during all of the sets. The angular velocity of training was $60°{\cdot}s^{-1}$. The range of motion during the isokinetic training traveled from 0 to 90° of knee flexion. The researchers provided strong verbal encouragement so that the subjects would feel motivated to produce their maximum force. Before each training session, the subjects warmed up with 10 knee extension/flexion repetitions at an angular velocity of 90°/s at submaximal effort. During the training, the following parameters were recorded in each session for further analysis: total work, the area covered by the torque-joint angle curve; average work per session, the total work divided by 12 (total number of sessions); training PT, the highest PT obtained during the training; average training PT, the sum of the PTs produced in each training session divided by the number of sessions (12); and the delta training PT, the percentage increase in the training PT (Table 2).

Table 2. Training variables (mean ± SD)

	Concentric training group CON, n = 11	Eccentric training group ECC, n = 11
Total work (W)	53 423 ± 16 718	75 767 ± 14 220*
Average total work (W)	4515 ± 1389	6412 ± 1213*
Maximal training peak torque (N·m)	184.2 ± 52.6	281.4 ± 45.6*
Average training peak torque (N·m)	164.5 ± 44.9	233.2 ± 39.6*
Δ training peak torque (%)	11.7 ± 3.7	20.9 ± 6.0*

*Significant differences between groups ($P < 0.001$).

Statistical analysis

The SPSS statistical software package (SPSS Inc., Chicago, Illinois, USA) was used to analyze all of the data. Normal distribution and homogeneity parameters were checked with the Shapiro–Wilk and Levene tests, respectively. The results were reported as the mean ± SD. Comparisons between the groups for the training variables were performed using independent *t*-tests. The training-related effects were assessed using a two-way analysis of variance (group [CON vs ECC] × time [pre vs post]). When the interaction effect was significant, the main factor's group and time were tested again using independent and dependent *t*-tests, respectively. The Pearson product-moment correlation test was used to investigate possible associations between the parameters analyzed. The retrospective statistical power provided by SPSS after analysis was 0.98 for the concentric and isometric PTs, 0.94 for the eccentric PT, over 0.80 for the RFD and EMG variables for which a significant time effect was observed, and 0.74 for the significant time vs group interaction results. Significance was accepted at $P < 0.05$. The effect size (ES) between pre- and post-training for each group was calculated using Hedges' ES, represented by the following formula: $ES = (M_{post} - M_{pre})/SD_{pooled}$, where M_{post} is the mean post-training measure, M_{pre} is the mean pre-training measure for each group, and SD_{pooled} is the pooled SD of the pre- and post-measurements (Hedgess & Olkin, 1985). Threshold values for assessing the magnitude of standardized effects, which are changes as a fraction or multiple of the baseline standard deviation, were 0.20, 0.60, 1.2, and 2.0 for small, moderate, large, and very large, respectively (Hopkins et al., 2009).

Results

Baseline values

The results are presented in Table 3. At baseline, there were no differences between the groups' physical

Table 3. Electromyographic, muscular, and strength parameters pre- and post-training concentric and eccentric training (mean ± SD)

	CON training group (n = 11)		ECC training group (n = 11)	
	Pre-training	Post-training	Pre-training	Post-training
MT (mm)	18.00 ± 1.23	20.19 ± 1.07***	19.04 ± 1.44	21.16 ± 1.23***
MT control (mm)	16.7 ± 0.99	17.48 ± 0.98	17.53 ± 1.38	18.94 ± 1.59
MQ (a.u.)	125.55 ± 7.8	112.76 ± 6.3*	110.76 ± 5.91	99.8 ± 7.95*
MQ control (a.u.)	113.4 ± 8.8	109.4 ± 7.7	100.3 ± 5.0	96.7 ± 7.0
PTiso (N)	210.9 ± 16.6	221.5 ± 19.3	197.9 ± 12.9	229.9 ± 13.2***†
PTiso control (N)	225.2 ± 20.1	227.7 ± 17.8	245.9 ± 20.6	243.1 ± 15.4
PTcon (N·m)	137.9 ± 8.6	164.0 ± 13.6***	133.0 ± 10.6	150.8 ± 10.7***
PTecc (N·m)	196.3 ± 9.7	221.4 ± 18.5**	200.7 ± 15.1	252.4 ± 12.4**
RFD_{max} (N/m/s)	721.2 ± 167.9	959.2 ± 150.4*	584.3 ± 64.0	874.0 ± 131.4*
RFD_{50ms} (N/m/s)	663.1 ± 166.0	935.9 ± 146.0**	578.8 ± 63.7	855.5 ± 136.4**
RFD_{100ms} (N/m/s)	569.1 ± 123.9	808.1 ± 128.8**	509.4 ± 53.8	693.9 ± 77.0**
EMG_{max} (mV)	0.150 ± 0.018	0.163 ± 0.020	0.158 ± 0.018	0.180 ± 0.021
CV_{max} (m/s)	4.16 ± 1.49	4.30 ± 1.12*	4.17 ± 1.62	4.44 ± 1.19*

Significant difference from pre-training values. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.

†Significant time vs group interaction ($P < 0.05$).

CON, concentric; CV_{max}, maximal conduction velocity; ECC, eccentric; EMG_{max}, maximal neuromuscular activity; MQ, muscle quality; MT, muscle thickness; PTcon, concentric peak torque; PTecc, eccentric peak torque; PTiso, isometric peak torque; RFD, rate of force development.

characteristics (Table 1), MT and muscle quality, EMG variables, or strength performance (PT and RFD).

Training variables and compliance

All of the subjects performed 100% of the training sessions, and there was no difference in the training compliance between the CON and ECC groups. As expected, significant differences were observed in all of the training variables: the ECC group showing greater absolute total work, average work, training peak torque, average peak torque, and delta training peak torque ($P < 0.001$) (Table 2).

Strength performance

After training, there were time effects in the concentric PT (CON: 14.7 ± 9.9%, ES = 0.66; ECC: 15.4 ± 18.6%, ES = 0.49) ($P < 0.001$) and eccentric PT (CON: 13.6 ± 25.9%, ES = 0.56; ECC: 30.3 ± 28.1%, ES = 0.99) ($P < 0.01$), with both the CON and ECC training groups showing similar increases (Fig. 1). In addition, there was a time vs group interaction in the isometric PT ($P < 0.05$). Significant increase was observed in the isometric PT only in the ECC training group (17.2 ± 11.6%, ES = 0.70) ($P < 0.001$), whereas no change was observed in the CON training group (5.6 ± 15.7%, ES = 0.18). Moreover, there were time effects in the maximal RFD (CON: 77 ± 91%, ES = 0.45; ECC: 54.8 ± 63.2%, ES = 0.79) ($P < 0.05$), RFD_{50ms} (CON: 93.4 ± 111.4%, ES = 0.52; ECC: 51.3 ± 62.1%, ES = 0.74) ($P < 0.01$), and RFD_{100ms} (CON: 80.2 ± 92.3%, ES = 0.56; ECC: 42.9 ± 52.1%, ES = 0.78) ($P < 0.01$), with both groups showing similar increases. No changes were observed in the isometric PT of the control leg after the training period (Table 3).

Neuromuscular activity

After training, there was a trend toward a time effect in the maximal VL neuromuscular activity (CON: 14.8 ± 33.9%, ES = 0.22; ECC: 13.8 ± 20.0%, ES = 0.31) ($P = 0.059$) (Table 3).

MT

There was a time effect in the VL MT in the exercised leg ($P < 0.001$) in both groups, with no difference between the groups (CON: 10.9 ± 6.1%, ES = 0.55; ECC: 12.2 ± 8.1%, ES = 0.47) (Fig. 2). No changes were observed in the VL MT in the control leg after the training period (Table 3).

Muscle CV

With respect to muscle CV, both training groups showed increases ($P < 0.05$) with no differences between the groups (CON: 22.2 ± 65.1%, ES = 0.31; ECC: 27.3 ± 73.8%, ES = 0.39) (Table 3).

Muscle quality

There was a time effect in the VL muscle quality (US echo intensity) of the exercised leg ($P < 0.05$), with both groups showing similar decreased intensity (i.e., improved muscle quality) (CON: −6.0 ± 31.5%, ES = 0.53; ECC: −8.8 ± 21.7%, ES = 0.46). No changes were observed in the VL muscle quality of the control leg after the training period (Table 3).

Correlations between training variables and changes in strength and muscular parameters

In the CON training group, positive correlations were observed between the relative changes in the concentric and eccentric PTs and corresponding individual values of

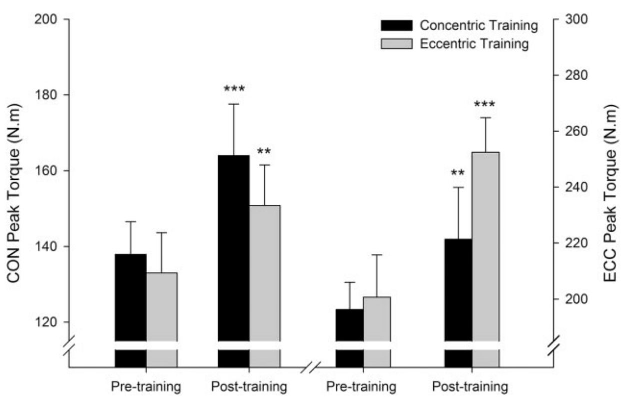

Fig. 1. Concentric (CON, left *y*-axis) and eccentric (ECC, right *y*-axis) peak torques (N·m) (mean ± SD) pre-training and post-training at 6 weeks of concentric or eccentric training. ***Significant difference from pre-training values ($P < 0.001$).

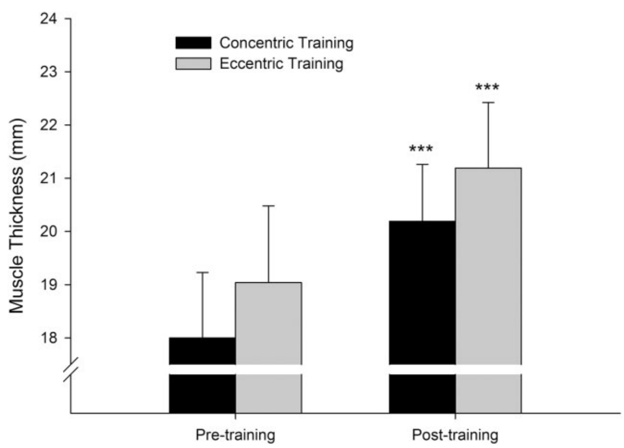

Fig. 2. Vastus lateralis muscle thickness (mm) (mean ± SD) pre and post 6 weeks of concentric or eccentric training. ***Significant difference from pre-training values ($P < 0.001$).

Table 4. Associations between concentric training adaptations and training variables

	Total work	Mean work	Maximal training peak torque	Mean training peak torque
Δ CON PT	0.63*	0.62*	0.69*	0.70*
Δ ECC PT	0.75*	0.68*	0.68*	0.51
PT CON post-training	0.84**	0.89***	0.95***	0.95***
MT post-training	0.66*	0.66*	0.72*	0.46
PT ECC post-training	0.92***	0.90***	0.87**	0.84**
PT ISO post-training	0.91***	0.94***	0.97***	0.97***

Significant level: *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.
CON, concentric; ECC, eccentric; ISO, isometric; MT, muscle thickness; PT, peak torque.

Table 5. Associations between eccentric training adaptations and training variables

	Total work	Mean work	Maximal training peak torque	Mean training peak torque
Δ ISO PT	0.50	0.51	0.46	0.61*
Δ RFD	0.67*	0.71*	0.68*	0.65*
Δ RFD_{50ms}	0.64*	0.69*	0.65*	0.61*
Δ RFD_{100ms}	0.67*	0.65*	0.71*	0.65*
PT ECC post-training	0.78**	0.78**	0.77**	0.78**
PT CON post-training	0.69*	0.71*	0.67*	0.34
PT ISO post-training	0.81**	0.82**	0.75**	0.71**
RFD post-training	0.65*	0.73*	0.73*	0.67*
RFD_{50ms} post-training	0.62*	0.70*	0.69*	0.63*
RFD_{100ms} post-training	0.72*	0.76**	0.62*	0.54

Significant level: *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$.
CON, concentric; ECC, eccentric; ISO, isometric; PT, peak torque; RFD, rate of force development.

total work, average work, maximal training PT, and average training PT ($r = 0.68–0.75$, $P < 0.05$). In addition, in the CON training group, the training variables also correlated with the post-training isometric, concentric, and eccentric PTs ($r = 0.84–0.95$, $P < 0.001–0.05$) and post-training MT values ($r = 0.66–0.72$, $P < 0.05$) (Table 4).

In the ECC training group, positive correlations were observed between the relative changes in the isometric PT, maximal RFD, RFD_{50ms} and RFD_{100ms}, and corresponding individual values of total work, average work, maximal training peak torque, and average training peak torque ($r = 0.61–0.71$, $P < 0.05$). In addition, in the ECC training group, the values of total work, average work, maximal training peak torque, and average training peak torque also correlated with the post-training values of maximal RFD, RFD_{50ms} and RFD_{100ms}, and isometric, concentric, and eccentric PTs ($r = 0.62–0.82$, $P < 0.01–0.05$) (Table 5).

Correlations between changes in different strength and muscular parameters

In the CON training group, the relative changes in the concentric PT positively correlated with the relative changes in the isometric PT ($r = 0.66$, $P < 0.05$). In addition, the relative changes in muscle quality negatively correlated with the corresponding individual relative changes in the concentric ($r = –0.68$, $P < 0.05$) and eccentric ($r = –0.68$, $P < 0.05$) PTs. In the ECC training group, the relative changes in the eccentric PT positively correlated with the relative changes in the isometric PT ($r = 0.75$, $P < 0.05$).

Discussion

A unique finding of the present study was that both eccentric and concentric training induced similar increases in the muscle CV. In addition, only the eccentric training group experienced increases in the isometric PT, whereas both types of training resulted in marked increases in concentric and eccentric PTs as well as in the RFD variables. Moreover, both training groups experienced similar increases in the MT and muscle quality, suggesting that the eccentric training group had no advantage during the early phase of training (6 weeks) despite performing a greater total workload during the training period. Furthermore, within each group, significant correlations were observed between the training variables and the magnitude of the adaptations in maximal torque, muscle hypertrophy, and RFD.

The concentric and eccentric training groups improved their concentric and eccentric PTs, with no significant differences between groups. However, when analyzing the ES in the strength variables, we observed that this parameter suggested a greater effect of eccentric training in the eccentric PT. Although no significant differences were observed between the groups, the concentric training group increased its concentric PT at ~15% (ES = 0.66) and its eccentric PT at ~14% (ES = 0.56), whereas the eccentric training group increased its concentric PT at ~15% (ES = 0.49) and its eccentric PT at ~30% (ES = 0.99). In general, it has been shown that concentric strength gains are greater in individuals training concentrically while eccentric strength gains are greater in individuals training eccentrically (Tomberlin et al., 1991; Seger et al., 1998; Blazevich et al., 2007; Roig et al., 2009), although similar effects of concentric and eccentric training on concentric strength have also been observed (Ben-Sira et al., 1995; Vikne et al., 2006). The similarity of the increases in eccentric strength after both concentric and eccentric training is not novel and was shown by Blazevich et al. (2007) after 10 weeks of concentric and eccentric training (35–38%). Our study demonstrated increases in maximal concentric and eccentric strength that were similar in magnitude to previous observations following short-term periods of concentric and eccentric training (i.e., 6 weeks) (Hortobagyi et al., 1996a; Baroni et al., 2013). The discrepancies between studies may be related to the different training volumes, intensities (% of MVC), and velocities of training (Blazevich et al., 2007; Roig et al., 2009).

Regarding isometric PT, there was an increase only in the eccentric training group, which was in agreement with previous studies (Hortobagyi et al., 1996a, b). It has been suggested that the greater effect of eccentric training on isometric force is due to eccentric training that may increase the stiffness of the passive elements, which could account for the greater increases in both eccentric and isometric forces (Hortobagyi et al., 1996a). Thus, it could be speculated that this result is related, at least in part, to the positive stimulus that ECC resistance training may have on connective tissue as described by Cavagna (1977).

The similar increases observed in the RFD variables (i.e., RFD_{max}, RFD_{50ms}, and RFD_{100ms}) suggested that both training types could improve the RFD in short-term periods, although the ES was greater in the eccentric compared with the concentric group (ECC: ranging from 0.74 to 0.79 vs CON: ranging from 0.45 to 0.56). Our results were in agreement with Blazevich et al. (2008), who observed similar increases in the RFD over several time intervals (0–30 to 0–200 ms) after concentric and eccentric training with no differences between the groups. Interestingly, the RFD variables increased in the CON training group despite the absence of changes in the isometric PT. Along with the absence of a correlation between the RFD and the isometric PT, this finding suggested that improvements in the RFD may occur independently of increases in maximal strength.

Regarding the maximal neuromuscular activity, there was only a trend toward significant increase following concentric and eccentric training (~15%, $P = 0.06$), and a small ES was observed in both groups (0.22 and 0.33 in the concentric and eccentric groups, respectively). Adaptations in the EMG amplitude are often observed in the early phases of resistance training, suggesting greater motor unit recruitment and/or a higher firing rate among the motor units (Narici et al., 1989; Higbie et al., 1996; Hortobagyi et al., 1996b; Häkkinen et al., 2003; Cadore et al., 2010; Guilhem et al., 2013). However, some authors have failed to demonstrate increases in the EMG amplitude after resistance training (Garfinkel & Cefarelli, 1992; McCarthy et al., 2002). In a study investigating neural adaptations to concentric and eccentric training, Higbie et al. (1996) observed similar increases between the ECC and CON training groups in EMG amplitude during eccentric action, whereas only the concentric groups increased in maximal EMG during concentric action. In the present study, maximal neuromuscular activity was assessed only in the isometric MVC, which may explain the absence of changes in this variable because increases in EMG variables often occur in parallel with increases in the corresponding peak torque (Narici et al., 1989; Hortobagyi et al., 1996a; Häkkinen et al., 2003; Cadore et al., 2010), and the isometric PT only increased in the eccentric training group.

The VL MT increased similarly between the training groups (CON: ~11%, ES = 0.55; ECC: ~12%, ES = 0.47). Our results were in agreement with Blazevich et al. (2007), who observed similar changes in VL MT and CSA after 10 weeks of eccentric and concentric training. In contrast, some studies have shown that eccentric training induces greater increases in muscle mass as determined by the CSA of the whole quadriceps (Higbie et al., 1996; Norrbrand et al., 2008) or fiber CSA (Hortobagyi et al., 1996b). However, it appears that eccentric training induces greater CSA increases in individual type II fibers (Hortobagyi et al., 1996b), but the difference between training types is small when the whole quadriceps CSA is assessed (Higbie et al., 1996). In the present study, because we used ultrasonography to assess the muscle adaptations, we were not able to detect potential differences at the fiber level. Interestingly, in the present study, the greater total work and average work per session in the eccentric group did not provide additional stimulus to increase the MT. It is possible that the subjects' initial characteristics (i.e., untrained) and the short training period influenced this result. In addition, although mechanical tension alone can produce muscle hypertrophy, it is unlikely to be solely responsible for the hypertrophic gains associated with exercise (Hansen et al., 2001). One could suggest that changes may have occurred in other regions of VL, which might not be detectible with one measurement by US. Therefore, potential differences in overall muscle size between the ECC and CON training groups might be detected assessing more regions of VL or using imaging techniques with better spatial resolution (e.g., magnetic resonance image, computerized tomography). However, a high correlation has been shown between morphological adaptations observed using muscle thickness with those observed using imaging techniques with better spatial resolution (Bemben, 2002; Ahtiainen et al., 2010). The MT increases observed after only 6 weeks were similar to increases that have been observed after a greater period of traditional resistance training (e.g., 10–12 weeks) (Tanimoto et al., 2008; Ronnestad et al., 2012; Guilhem et al., 2013). The possible explanation for this increase may be that the subjects exerted maximal strength during the whole range of motion throughout all of the repetitions during the isokinetic concentric and eccentric training, whereas in traditional resistance training, strength levels that are near maximal are only exerted at the sticking point (Drinkwater et al., 2007).

The effects of resistance training on muscle CV have been poorly investigated. In the present study, both concentric and eccentric training induced increases in the muscle CV. These changes are in accordance with the findings of Vila-Chã et al. (2010), who observed that 6 weeks of either endurance or strength training resulted in increases in the motor unit CV at 30% of MVC, suggesting that physical training induces changes in the excitability and conduction properties of the fiber membrane independent of the type of exercise. Notwithstanding, comparison between the present results and the results of

Vila-Chã et al. (2010) is difficult due to differences in the methods used to assess the CV. First, Vila-Chã et al. (2010) investigated CV in individual motor units using intramuscular EMG signals instead of the sEMG used in the present study. Second, we assessed the muscle CV during an MVC instead of the 30% of MVC used by Vila-Chã et al. (2010). The muscle CV depends on the polarization state of the sarcolemma, which is influenced by numerous factors, including the membrane potential, extracellular and intracellular Na^+ and K^+ concentrations, internal and external resistances (i.e., an indication of the ability of the intracellular and extracellular medium to conduct the transmembrane voltage), and membrane resistance and capacitance (Allen et al., 2008). It has been found that eccentric and concentric exercise protocols can produce similar acute changes in the muscle CV (González-Izal et al., 2013), and therefore it can be speculated that they could induce similar adaptations in the CV after training. From a practical point of view, this result may suggest that both training types are equally effective stimuli to increase the velocity of action potential propagation in muscle fibers.

It has been suggested that muscle quality can be assessed using US because enhanced echo intensity represents changes caused by increased intramuscular connective and adipose tissues (Pillen et al., 2009; Cadore et al., 2012). Indeed, echo intensity values have been inversely associated with PT in elderly men (Cadore et al., 2012). Nevertheless, little is known about the effects of resistance training in the muscle quality assessed by echo intensity. In a study by Radaelli et al. (2013), both low (one set per exercise) and high (three sets per exercise) volumes resulted in decreased echo intensity values in elderly women after only 6 weeks of training, suggesting a greater muscle quality after the interventions. Nevertheless, to the best of our knowledge, no study has compared the echo intensity adaptations to concentric and eccentric training. A unique finding in the present study was that both concentric and eccentric training induced a reduction in the echo intensity values after 6 weeks, suggesting an improvement in the muscle quality in the young men and women investigated. As observed for the MT, it appears that the greater absolute total work performed by the eccentric training group did not represent an additional stimulus to improve muscle quality. However, this result may also be a consequence of the short term (i.e., 6 weeks) of the exercise intervention and the initial training status of the subjects (i.e., untrained). In addition, it is possible that the greater metabolic demand during concentric actions (González-Izal et al., 2013) could compensate for any possible disadvantage of the lower workload performed during concentric training compared with eccentric training. Indeed, the echo intensity reflects the intramuscular adipose tissue (Pillen et al., 2009), which could be more affected by a type of exercise with greater metabolic demand. However, whether US echo intensity reflects muscle quality in young populations to a similar extent as in elderly adults remains to be elucidated, and caution, therefore, is necessary when interpreting the present results.

As mentioned above, the greater total work and average work per session in the eccentric group did not provide additional stimulus to increase neuromuscular adaptation. However, curiously, within each group, there were associations between the training performance (i.e., total work, average work per session, maximal training peak torque, and average peak torque per session) and the neuromuscular gains observed. It has been postulated that the product of volume and intensity (i.e., total workload) is an important stimulus to induce muscle hypertrophy and muscle strength gains, although there may be a threshold stimulus for hypertrophy above which accomplishing greater total work does not result in additional stimulation (Schoelfeld, 2010). In the concentric group, the participants who exerted greater torque during the whole range of motion, which resulted in a greater average work per session and consequently a greater total work in the training period, had more increases in their concentric, eccentric, and isometric PTs. One could suggest that these associations could be due to the subjects who were able to generate more strength during the training program were also those who were able to increase their strength. However, the same association was not observed in the eccentric training group, in which the training performance was only associated with RFD gains. Another interesting finding in the present study was the association between the isometric PT gains and the PT in each specific test for each group (i.e., concentric or eccentric), which suggested that those subjects who most increased their strength in the specific test (i.e., concentric or eccentric) were also those who were able to transfer the strength gains to the nonspecific test (i.e., isometric).

It should be mentioned as a limitation of the present study that only the VL was assessed. Thus, although the investigation of other knee extensor muscles would not change the strength results, it is possible that differential neural and morphological adaptations could be observed in other muscles (e.g., vastus medialis, VL, and rectus femoris) after concentric and eccentric training, which remains to be further investigated.

In summary, short-term eccentric and concentric training induced similar increases in maximal concentric and eccentric muscle strength, as well as in the isometric RFD, whereas isometric muscle strength increased only with eccentric training. In addition, morphological adaptations such as MT and muscle quality were also similar between the groups. These similar adaptations occurred even though the eccentric group performed significantly greater total work, average work, training maximal PT, and average PT during the training period. Moreover, eccentric and concentric training resulted in comparable increases in maximal muscle CV, which may suggest similar electrophysiological adaptations in the polarization conduction capacity of the sarcolemma.

Perspectives

Concentric training may induce greater concentric strength gains, whereas eccentric training may result in greater eccentric strength gains and greater muscle hypertrophy (Roig et al., 2009). However, some studies have shown that concentric and eccentric training both induce similar changes in concentric and eccentric strength and hypertrophy (Ben-Sira et al., 1995; Vikne et al., 2006). In the present study, the greater total work performed during eccentric training did not provide additional stimulation of muscle hypertrophy (MT), muscle quality, or dynamic strength gains. In addition, adaptations in the polarization conduction capacity of the sarcolemma (i.e., the muscle CV) induced by concentric and eccentric training were similar in the previously untrained subjects. From a practical standpoint, short-term twice-weekly concentric and eccentric training induces the same magnitude of changes in the dynamic PT (i.e., eccentric and concentric), RFD, muscle hypertrophy, and muscle quality. Moreover, it should be mentioned that the training adaptations observed were induced using resistance exercise programs starting with a very low volume (i.e., two sets of eight repetitions) and then progressing to a higher volume at the end of 6 weeks (i.e., five sets of 10 repetitions) with all repetitions performed at maximal effort.

Key words: Muscle hypertrophy, training periodization, electromyography, early-phase adaptations.

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