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Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle

M. V. Franchi,[1,2] P. J. Atherton,[1] N. D. Reeves,[2] M. Flück,[3] J. Williams,[1] W. K. Mitchell,[1] A. Selby,[1] R. M. Beltran Valls[1] and M. V. Narici[1]

1 School of Graduate Entry Medicine and Health, MRC-ARUK Centre of Excellence for Musculoskeletal Ageing Research, University of Nottingham, Derby, UK

2 School of Healthcare Science, Institute for Biomedical Research into Human Movement and Health, Manchester Metropolitan University, Manchester, UK

3 Department of Orthopaedics, University of Zurich, Balgrist University Hospital, Zurich, Switzerland

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Correspondence: M. Franchi, School of Graduate Entry Medicine & Health and Biomedical Sciences, MRC-ARUK Centre of Excellence for Musculoskeletal Ageing, University of Nottingham, Royal Derby Hospital, Derby, DE22 3DT, UK.
E-mail: m.franchi@nottingham.ac.uk

Abstract

Aim: We investigated architectural, functional and molecular responses of human skeletal muscle to concentric (CON) or eccentric (ECC) resistance training (RT).

Methods: Twelve young males performed 10 weeks of concentric (CON) or eccentric (ECC) resistance training (RT) (n = 6 CON, 6 ECC). An additional 14 males were recruited to evaluate acute muscle fascicle behaviour and molecular signalling in biopsies collected from vastus lateralis (VL) after 30 min of single bouts of CON or ECC exercise. VL volume was measured by magnetic resonance imaging. Muscle architecture (fascicle length, Lf; pennation angle, PA) was evaluated by ultrasonography. Muscle remodelling signals to CON or ECC loading [MAPK/AKT-mammalian target of rapamycin (mTOR) signalling] and inflammatory pathway (TNFαMurf-1-MAFbx) were evaluated by immunoblotting.

Results: Despite the ~1.2-fold greater load of the ECC group, similar increases in muscle volume (+8% CON and +6% ECC) and in maximal voluntary isometric contraction (+9% CON and +11% ECC) were found after RT. However, increases in Lf were greater after ECC than CON (+12 vs. +5%) while increases in PA were greater in CON than ECC (+30 vs. +5%). Distinct architectural adaptations were associated with preferential growth in the distal regions of VL for ECC (+ECC +8% vs. +CON +2) and mid belly for CON (ECC +7 vs. CON +11%). While MAPK activation (p38MAPK, ERK1/2, p90RSK) was specific to ECC, neither mode affected AKT-mTOR or inflammatory signalling 30 min after exercise.

Conclusion: Muscle growth with CON and ECC RT occurs with different morphological adaptations reflecting distinct fibre fascicle behaviour and molecular responses.

Keywords eccentric/concentric loading, muscle remodelling, resistance training.

Skeletal muscles can contract by shortening (concentric) or lengthening (eccentric) (Joyce & Rack 1969, Joyce *et al.* 1969). 'Conventional' resistance exercise training using commercial exercise machines is the most common form of resistance exercise, consisting of lifting and lowering a constant external load. Thus, conventional resistance exercise training combines CON (lifting-phase) and ECC (lowering-phase)

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actions. According to the force–velocity (F-V) relationship, each value of force and velocity on a given curve should belong to the same level of neural activation (Bigland & Lippold 1954, Chow & Darling 1999, Camilleri & Hull 2005). Yet, this requirement is not met by conventional RT as the same external load is displaced during both lifting and lowering phases. Thus, motor units must be de-recruited in the ECC part to enable the load to be lowered (Reeves *et al.* 2009); as such the load used for conventional training is limited by the CON muscle action. Therefore, to ensure that the ECC component of resistance training is not under-loaded, it would be necessary that both shortening and lengthening phases follow the physiological force-velocity curve, that is, the absolute load should be greater for the ECC than the CON contraction (Katz 1939), theoretically involving the same level of neural activation between contraction modes. Nonetheless, to our knowledge, comparisons of pure CON to ECC exercise with such matching to equalize the relative loading stimulus, meeting a fundamental premise of the F-V relation, have not yet been made.

A recent investigation (Reeves *et al.* 2009) provided evidence that distinct loading patterns also lead to distinct architectural adaptations to exercise training, as suggested by Hortobágyi *et al.* (1996). In this previous study (Reeves *et al.* 2009), the architectural responses to muscle loading in older-aged individuals undergoing conventional vs. ECC only training regimes were compared. After 14-week of training, the authors noted a greater increase in muscle fibre (fascicle; Lf) length in the ECC only group compared to the conventional RT group. Conversely, increases in pennation angle (PA) were only evident following conventional RT, but not after ECC only exercise. Furthermore, as conventional RT involves mixtures of both CON and ECC contractions, the architectural responses to 'pure' ECC or CON contractions performed on standard isotonic machines with such matching for relative loading stimulus are unknown.

Distinct architectural adaptations to ECC vs. CON contractions also raise the question as to what could be the molecular basis of this phenomenon. As both human and pre-clinical work has provided evidence of distinct molecular responses to CON vs. ECC contractions, it is likely that similar mechanisms underlie the different architectural adaptations. This hypothesis seems supported by the recent observation that ECC vs. CON growth of cardiomyocytes is regulated via ERK1/2 MAPK signalling (Kehat *et al.* 2011), demonstrating that acute signalling differences in response ECC vs. CON exercise could underlie the ensuing distinct architectural adaptations. In another investigation, using isolated rat muscle Wretman *et al.* (2001) reported greater increases in phosphorylation of ERK 1/2 and p38 MAPKs induced by ECC vs. CON contractions. In addition, Martineau & Gardiner (2001) observed that activation of MAPKs activation was quantitatively related to muscular tension with ECC contraction providing the greater stimulus. Finally, microarray analyses in young men (Kostek *et al.* 2007) demonstrated distinct responses to *acute* CON vs. ECC contractions, suggesting that contraction-specific muscle remodelling results both from distinct signalling and genomic responses to CON vs. ECC exercise. Nonetheless, the relationships between MAPK (or other) signals and that of the distinct architectural basis of skeletal muscle hypertrophy in response to CON vs. ECC exercise, remains unknown.

Therefore, the aim of the present study was to compare the effects of pure CON vs. ECC exercise training in terms of architecture, morphology and functional outcomes, and relate this to muscle cell signalling responses potentially ascribing the distinct structural and functional adaptations to CON vs. ECC training. The hypothesis put forward was that different mechanical stimulus (shortening vs. lengthening), chronically applied and matched to balance the relative loading inducement, would result in distinct adaptations in muscle morphology, function and architecture: possible underlying mechanical and biochemical mechanisms may be involved in these distinct remodelling processes.

Methods

We recruited 12 young men (25 ± 3 years, height = 182 ± 8.5 cm, mass = 71.9 ± 8.5 kg; means ± SD) not partaking in resistance exercise training to undergo a 10-week resistance exercise-training program. Based on their maximum isometric knee extension torque, they were divided (matched for baseline strength) into two training groups: EG (ECC, $n = 6$, 25 ± 3 years) or CG (CON, $n = 6$, 25 ± 3 years). Resistance exercise training was carried out with a leg-press machine (Technogym, Gambettola, Italy) modified to enable performance of either an ECC only (EG) or CON only (CG) contractions. This was achieved using an electric engine attached to the back of the leg-press (Fig. 1): in the EG, the chair was pulled back with a cable that connected the electric winch to the weight stack via a steel cable, ensuring that subjects did not exert any force with their quadriceps to perform what would otherwise have been the concentric component of the exercise. When the chair was released, it enabled the subject to lower the training load under control through an ECC contraction of the quadriceps. Conversely, the CG performed a CON-only movement consisting of lifting the load. In

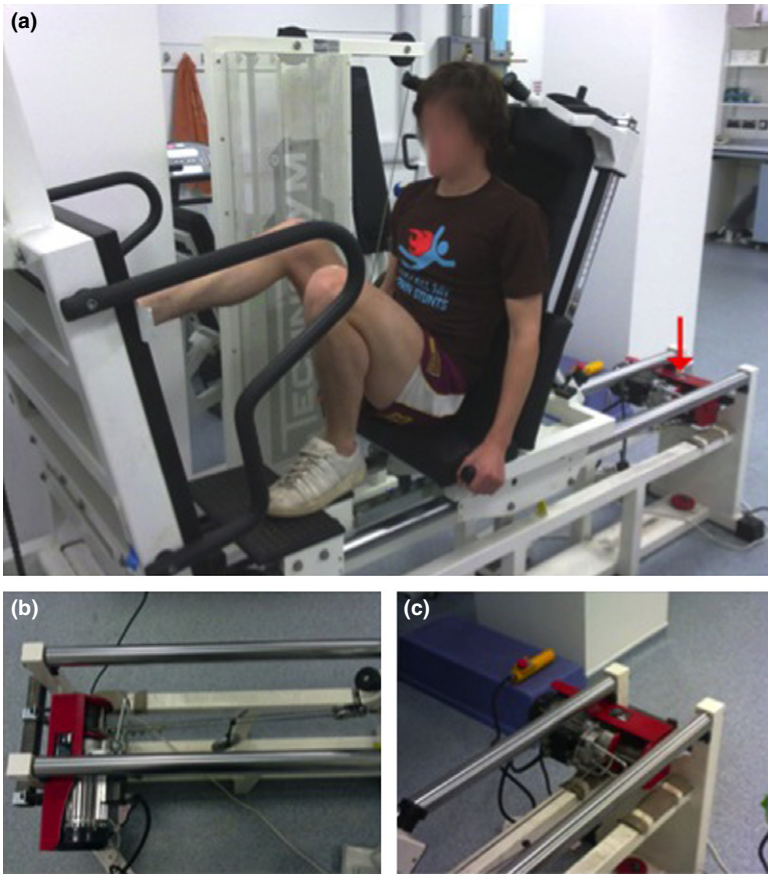

Figure 1 Subject on the Technogym leg press modified ad hoc with the special electric engine visible on the right corner indicated by the arrow (a). The electric winch attached to the chair via steel cable; (b) shows how the winch was connected to the chair (the red arrow indicates a counterweight that prevented the cable from becoming too slack and getting damaged); (c) presents the site where the engine was placed.

this case, the engine operated only during lowering of the load, ensuring that subjects did not exert any force with their quadriceps to perform what would have otherwise been the eccentric component of the exercise. The timing of the contraction was slightly different for the two groups: the CG were asked to complete the contraction in ~2 s, whereas this time period was ~3 s for the EG. This time difference (~2 s CG vs. ~3 s EG) was necessary to ensure that the load was indeed lowered under control in the EG. The training period for the first study was performed, after a familiarization session, three times per week for 10-week and people trained both legs but unilaterally. Both training and acute exercise bouts on the leg-press machine involved the main extensor muscles of the lower limbs. The training load used was of 80% of the concentric (CG) or 80% of the eccentric (EG) 1RM, with four series of a minimum of eight to a maximum of ten repetitions with 1-min rest in between the sets. The 1RM was assessed unilaterally after a warm-up program performed on the leg-press machine using a very light weight that allowed the subject to easily perform eight to ten repetitions either concentrically (lifting of the load phase) or eccentrically (lowering phase). Then, the protocol followed for both contraction phases was the one suggested by Beachle & Earle (1994). This study was approved by the ethical committee of the healthcare science faculty of the Manchester Metropolitan University and conformed to the requirements of the Declaration of Helsinki. Volunteers were informed of the purpose of the study, the experimental design and procedures involved and all the potential risks involved before giving their written consent.

Measurement of electromyographic (EMG) activity

Vastus lateralis-integrated EMG was measured as representative of the knee extensors to provide an indication of neural drive to this muscle group during the tests performed on the Cybex dynamometer. Two surface electrodes (10 mm diameter) were placed next to each other on the lower third of the VL muscle with a 20-mm centre-to-centre electrode distance. These two electrodes were arranged in a 'bi-polar' configuration with a third electrode, the 'ground', placed on a bone area (the patella bone in this case). The skin was shaved and conditioned using a special skin preparation gel (Nuprep™, Unimed, Farnham, Surrey, UK) to reduce skin impedance (using an electrode impedance tester; Oxford medical ltd, Medilog, UK) below 5000 Ohms. To reproduce the same electrode positioning in the

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successive recording sessions, measurements were taken and anatomical spots (bone processes, tendon and muscle insertions) were used to know exactly the right portion of VL for the surface electrodes to be placed. Acquisition of the surface EMG signal was obtained through the Biopac A/D acquisition system at a sampling frequency of 2000 Hz –and filtered through a bandwidth of 10–500 Hz. The root mean square (RMS) was calculated from the raw EMG over a 200 ms time frame where the peak of torque was expressed during the isometric MVC trials. During the 1RM assessment, EMG was monitored to support our assumption that CON and ECC 1RMs would have resulted in similar neural drive: the RMS was calculated over a 200 ms time frame during the mid portion of the contraction phase.

Magnetic Resonance images (MRI)

Axial plane scans of the thigh were taken before (1 week) and post-training (4–5 days) using a 0.25 Tesla magnetic resonance imaging (MRI) scanner (Esaote G-scan, Genova, Italy). A T1-weighted Spin Echo protocol was used (repetition time 900 ms, echo time, 26 ms, number of excitation 2, Field of View 200 × 200 mm, slice thickness 10 mm, gap between slices, 1.0 mm). Participants were asked to lie supine on the MRI bed and to insert their leg into a circular coil. Due to the scanning area of the coil, the thigh was imaged in 3–4 separate sections. Markers were placed on the thigh from the patella to the hip to denote different sections and avoid overlap. Axial plane scans along the entire length of the VL were collected; on average, the number of axial scans obtained in each subject was the same for the baseline and post-training periods (~34). From these scans, the contours of the VL muscle of each MRI scan were digitized using the Osirix image analysis software and, subsequently, VL Muscle Volume was calculated as follows:

$$\text{Volume}_{VL}\ (\text{cm}^3) = \Sigma_{ACSA}\ (\text{slice thickness} + \text{gap between slices}).$$

Regional VL hypertrophy was calculated after training by obtaining the baseline and post-exercise average values of the first five axial scans where the VL muscle was visible starting from the hip/knee joint (proximal and distal portions, respectively) and the five scans around the peak of ACSA (muscle mid portion): from these mean values, the percentage increase in ACSA was calculated for the three different regions of the VL muscle.

Muscle (VL) Architecture

Before (1 week) and after training (4–5 days), VL muscle architecture, that is, Lf and PA were measured (by the same investigator) from images obtained *in vivo* at rest using B-mode ultrasonography (Mylab 70, Esaote Biomedica, Genova, Italy), with a 100 mm, 10–15 MHz, linear-array probe. Resting ultrasound images were taken at a specific joint angle (150°), corresponding almost to full knee extension (180°), while the participant was seated on the Cybex Norm dynamometer chair; the transducer was aligned in the fascicle plane to be able to visualize an optimal portion of fascicles on the ultrasound screen. The muscle architectural parameters were quantified from the ultrasound scans using the image analysis software, ImageJ 1.42q (National Institutes of Health, Bethesda, MD, USA). The visible portion of the fascicle length was directly measured using this software. In some instances, a small portion of the fascicle extended off the ultrasound window and it was necessary to estimate this non-visible portion using a linear extrapolation of fibres and aponeuroses (Erskine *et al.* 2009). Pennation angle was measured as the intersection between fascicles and the deep tendon aponeurosis (Fig. 2). The reliability of these ultrasound techniques has been published (Intra-Class Correlation value = 0.99) (Reeves *et al.* 2004);

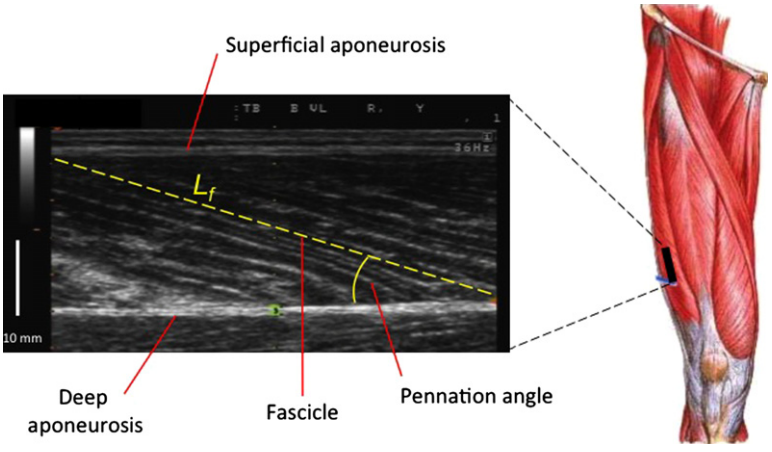

Figure 2 VL ultrasound image captured at rest: pennation angle and the visible part of a muscle fascicle is shown.

images were collected and digitally analysed by the same operator.

Muscle function

Participants were familiarized with all the devices and procedures involved in the study before the actual test sessions: the exercise-training participants were asked to perform contractions in a seated position on the reclining chair of the Cybex Norm dynamometer (hip angle = 85°, hip angle at supine position = 0°). The lower leg was strapped to a pad situated at the end of the Cybex lever arm and the knee joint centre of rotation was aligned with the dynamometer fulcrum. The torque produced on the Cybex dynamometer was sampled into an analogue to digital acquisition system (Biopac System, Inc., Aero Camino Goleta, CA, USA) at a frequency of 200 Hz and displayed on the screen of an Apple computer (Mac. G4, Apple, Cupertino, CA, USA). Maximum isometric torque of the knee extensor muscle group was evaluated by participants performing an isometric maximum voluntary contraction (MVC) at every 10° (0.175 rad) from 90° to 150° (from 1.57 to 2.62 rad) of knee joint angle (180° = full extension). Two MVCs were recorded at each joint angle with 2-min separating each contraction, and the highest torque produced was used to assess MVC changes from pre- to post-training.

Acute behavioural and molecular responses to CON and ECC contraction

An additional untrained 14 men (25 ± 4 years, height = 184 ± 7 cm, mass = 74 ± 4 kg) were recruited and divided into two groups (CG acute, $n = 7$, 26 ± 4 years and EG acute, $n = 7$, 25 ± 4 years) to perform a single bout of ECC or CON exercise, adopting the same design of the training study (same load–repetitions–sets combination). Vastus lateralis (VL) muscle biopsies were collected in these additional volunteers before and 30 min after exercise for signalling purpose: this time was specifically chosen as MAPK activation appears to be transient (Nader & Esser 2001). Ultrasound scans were also acquired during a single CON or ECC contraction performed on the leg-press device. Measures of fascicle length and pennation angle were recorded from screen captures during contractions and analysed in an identical fashion to in the training study.

Immunoblotting

Post-exercise biopsies were processed in a similar fashion to as previously described (Atherton *et al.*, 2010). Briefly, ~20 mg of muscle was snipped in ice-cold buffer [50 mM Tris–HCl (pH 7.4), 50 mM NaF, 10 mM β-Glycerophosphate disodium salt, 1 mM EDTA, 1 mM EGTA, 1 mM activated Na_3VO_4 (all Sigma–Aldrich, Poole, UK)] and a complete protease inhibitor cocktail tablet (Roche, West Sussex, UK) at 10 μL μg^{-1} of tissue. Homogenates were rotated for 10 min and the supernatant collected by centrifugation at 13 000 × ***g*** for 5 min at 4°C. The supernatant (sarcoplasmic fraction) was used for immunoblot analysis: protein concentrations were determined using a NanoDrop ND1000 spectrophotometer (NanoDrop Technologies, Inc., Wilmington, DE, USA) and adjusted to 1 μg μL^{-1} in 3 × laemmli. Each sample was loaded onto pre-cast 12% Bis-Tris Criterion XT gels (BioRad, Hemel Hempstead, UK) at 15 μg per lane and separated electrophoretically at 200 V for 1 h. Proteins were then wet-transferred at 100 V for 1 h onto polyvinylidene difluoride (PVDF) membranes (0.22 μm), blocked for 1 h in 2.5% skimmed milk in 1 × Tris-buffered saline/Tween-20 (TBS-T), and then incubated in 1° antibodies (1 : 2000 dilution in 2.5% BSA in TBS-T) rocking overnight at 4°C. For phosphorylation of MAPK p38 (Ser189/207), p90RSK (Thr359/Ser363), ERK1/2 (Thr202/Tyr204), p70S6K (Thr389), Akt (Ser473), p65 (Ser536) and pan-actin antibodies were obtained from Cell Signaling Technology, Inc. (Danvers, MA, USA), 4E-BP1 (Ser65/Thr70) from Santa Cruz Biotechnology, Inc. (Santa Cruz, CA, USA) and MAFbx, Murf-1 (C-terminal region) from ECM Bioscience (Versailles, KY, USA). A total amount of TNFα, p65 and IkBα antibodies were obtained from Cell Signaling Technology, Inc. The next day, membranes were washed 3 × 5 min in TBS-T, incubated in HRP-conjugated 2° antibody (New England Biolabs, Hertfordshire, UK; 1 : 2000 in 2.5% BSA in TBS-T) at room temperature for 1 h, before 3 × 5 min washes in TBS-T. Membranes were exposed to chemiluminescent HRP substrate (Millipore Corporation, Billerica, MA, USA) for 5 min and bands quantified by Chemidoc XRS (BioRad). Software measures were taken to prevent pixel saturation; loading anomalies were corrected to Pan-Actin.

Statistical analysis

Differences for group (CG vs. EG, the training groups and CG1 vs. EG1, the acute study groups) and time (baseline vs. post-training/baseline vs. post-exercise) were analysed using a two-way factorial analysis of variance test using GraphPad prism software (version 5.0d; GraphPad software Inc. San Diego, CA, USA). Significant interactions between groups and time were located by Bonferroni post hoc test. The delta (Δ) training values (percentage increases) were statistically tested between groups using an independent t-test that

was also used to compare baseline differences between CG and EG for physiological parameters. A power calculation was performed: our current sample size has a beta level of 0.8 (i.e. power of 80%) for the training study (12 participants) using the parameter of pennation angle and a beta level of 0.9 (i.e. power of 90%) for the acute study (14 participants) using the parameter of p38 MAPK.

Results

EMG of CON-ECC 1-RM, maximum lifting or lowering ability (1-RM) and training load

As mentioned, to test our assumption that both CON and ECC contractions belonged to the same force–velocity curve, EMG activity was measured during performance of a single concentric and eccentric 1-RM in each subject to evaluate whether the two phases correspond to a similar level of neural activation. The means of baseline EMG values for CON and ECC group 1-RM are presented in Table 1. These values represent the mean of the individual rectified EMG activity measured during the entire CON or ECC 1RM and were collected just prior to the training period. In support of our assumption, no significant difference existed in neural activation during the performance of the CON or ECC only exercise. As expected, regarding the maximum lifting or lowering ability data, the baseline and post-training 1-RM was higher in the ECC than the CON group (Table 1), resulting in a higher ECC training load and consequently higher training volume, (132 592 vs. 105 120 kg, $P < 0.01$, calculated as number of sets X number of repetitions X training load for ECC compared to CON exercise in the 10-week period). The pre- to post-training increase in 1-RM was statistically significant in both groups, but with no significant difference in the percentage increase between the ECC and CON group.

Muscle morphology and architecture and maximum voluntary contraction

After training, both groups showed an increase in VL muscle volume but the change was similar between the EG ($6 \pm 0.4\%$, mean ± SEM, $P < 0.0001$) and CG ($8 \pm 0.5\%$, $P < 0.0001$). However, Lf increased significantly more ($P < 0.01$) in the EG ($12 \pm 2\%$, $P < 0.0001$) compared to the CG ($5 \pm 1\%$, $P < 0.01$); conversely PA increased significantly less ($P < 0.01$) in the EG ($5 \pm 1\%$, $P > 0.05$) than the CG ($30 \pm 0.5\%$, $P < 0.0001$) group. Maximum voluntary contraction (MVC) peak amplitude changed in both groups similarly (significant pre-to-post difference, $P < 0.05$) (EG = $11 \pm 8\%$, $P < 0.05$, CG = $9 \pm 6\%$ increase, $P < 0.05$; Fig. 3).

Regional hypertrophy of VL muscle in response to CON or ECC training

Differences in localized hypertrophy were observed in response to 10-week of either CON or ECC resistance exercise (Fig. 4). While both loading modalities induced similar effects on ACSA % increase/decrease in the proximal area (EG = $-1 \pm 1\%$, mean ± SEM, and CG = $-0.5 \pm 1\%$), a significant difference was found in both mid portion (EG = $7 \pm 1\%$, and CG = $11 \pm 1\%$, $P < 0.01$) and distal part of vastus lateralis (EG = $+8 \pm 2\%$ vs. CG = $+2 \pm 1.5\%$, $P < 0.05$) between the two types of training.

Architectural behaviour of VL muscle during performance of CON vs. ECC contractions

Following discovery of such distinct architectural adaptations, we recruited a second cohort to interrogate possible mechanical reasons for these findings, with the aim of determining fascicle behaviour during CON and ECC contractions. Differential behaviour was observed in Lf and PA during CON and ECC resistance exercise performed with leg press (Fig. 5).

Table 1 Maximum lifting or lowering ability changes for the CON Group (CON) and the ECC one (ECC). EMG values were recorded only at baseline during 1RM leg-press for concentric and eccentric phases. Load ratio is also showed and calculated as the ratio of pre- and post-ECC/CON training loads

CON 1RM (kg)			ECC 1RM (kg)			Load ratio	
Pre	Post	Δ%	Pre	Post	Δ%	Pre	Post
192 ± 16 EMG (mV) 0.33 ± 0.1	262 ± 30	36*	233 ± 13 EMG (mV) 0.31 ± 0.1	337 ± 9	44*	1.21	1.29

Values are means ± SEM. Pre, baseline; Post, Post-training.
*$P < 0.05$, pre-to-post difference.

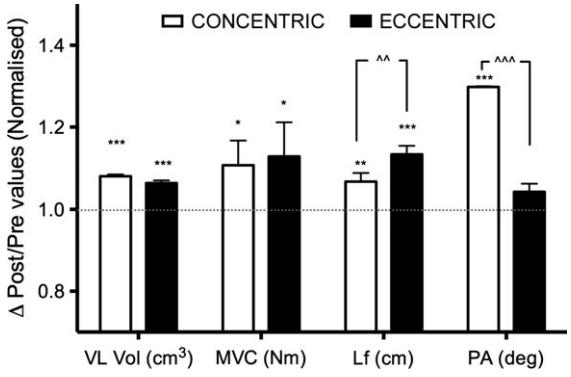

Figure 3 Post-/Pre-training ratios of muscle volume, isometric MVC and muscle architecture in the concentric and eccentric exercise groups. Y = 1 represent the baseline value. Data normalized to pre-values; means ± SEM (*$P < 0.05$ **$P < 0.001$ ***$P < 0.0001$ - ^^, ^^^ = significantly different between groups: $P < 0.01$ and $P < 0.001$, respectively).

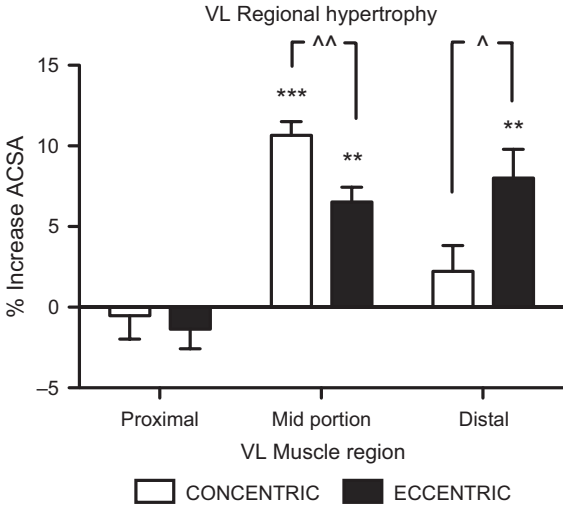

Figure 4 Regional Hypertrophy of VL muscle (ACSA = Anatomical Cross-Sectional Area) after concentric and eccentric training. Data are means ± SEM (**$P < 0.01$ ***$P < 0.001$ - ^, ^^ = significantly different between groups: $P < 0.05$, $P < 0.01$).

During ECC, fibres lengthened during performance of ECC exercise (Lf = +19 ± 2%, mean ± SEM, from start to end of contraction, $P < 0.0001$), whereas during CON, there was a substantial fascicle shortening in Lf (Lf = −19 ± 2%, $P < 0.0001$). Similarly, while PA remained similar from the start to the end of ECC (PA = −3 ± 1%, $P > 0.05$), it showed a substantial increase during CON (PA = +28 ± 1%, $P < 0.0001$).

Acute MAPK, AKT-mTOR and Inflammatory/breakdown signalling responses to a single acute bout of CON vs. ECC exercise

By taking biopsies 30 min following this single bout of CON or ECC, we were also able to interrogate intramuscular signalling purported to be involved in exercise adaptations. Significant increases in phosphorylation of mitogen-activated protein kinases (MAPKs), that is, p-38MAPK, ERK1/2 and p90RSK (Fig. 6) were found 30 min after ECC resistance exercise (p38MAPK = 20 ± 4-fold, ERK1/2 = 2 ± 0.3-fold, p90RSK = 3 ± 1-fold) but not after CON resistance exercise. In contrast, there was no modulation in the phosphorylation of Akt (Ser473) and mammalian target of rapamycin (mTOR) substrate p70S6K 30 min after CON or ECC exercise, although a significant suppression ($P < 0.05$) in activation of 4-EBP1 was found only after CON exercise (Fig. 7). Non-significant changes in the activation of the TNFαMurf-1-MAFbx pathway (TNFα, p-p65, p65, IkBα, p-MurF-1, p-MAFbx) were found 30 min after CON or ECC exercise.

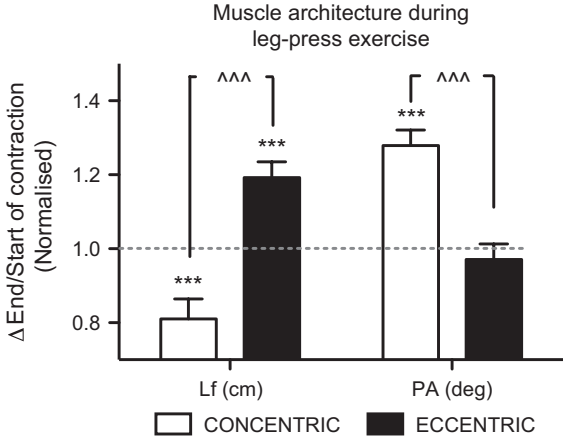

Figure 5 Muscle architectural behaviour during a concentric and eccentric contraction performed on the leg-press device (90°–170° knee joint angle, 180° = anatomical zero). Y = 1 represent the baseline value. Data normalized to pre-values; means ± SEM (***$P < 0.0001$ - ^^^ = significantly different between groups $P < 0.0001$).

Discussion

In the present study, we compared, for the first time, the structural remodelling of human skeletal muscle in response to pure CON and ECC loading while attempting to link this with the molecular signalling pathways implicated in muscle remodelling (MAPKs, mTOR etc.). Furthermore, while previous investigations focused on morphological and architectural responses to CON and ECC resistance training matched for work-load (Higbie *et al.* 1996, Blazevich *et al.* 2007, Moore *et al.* 2012), no study has yet, to the best of our knowledge, matched the CON and

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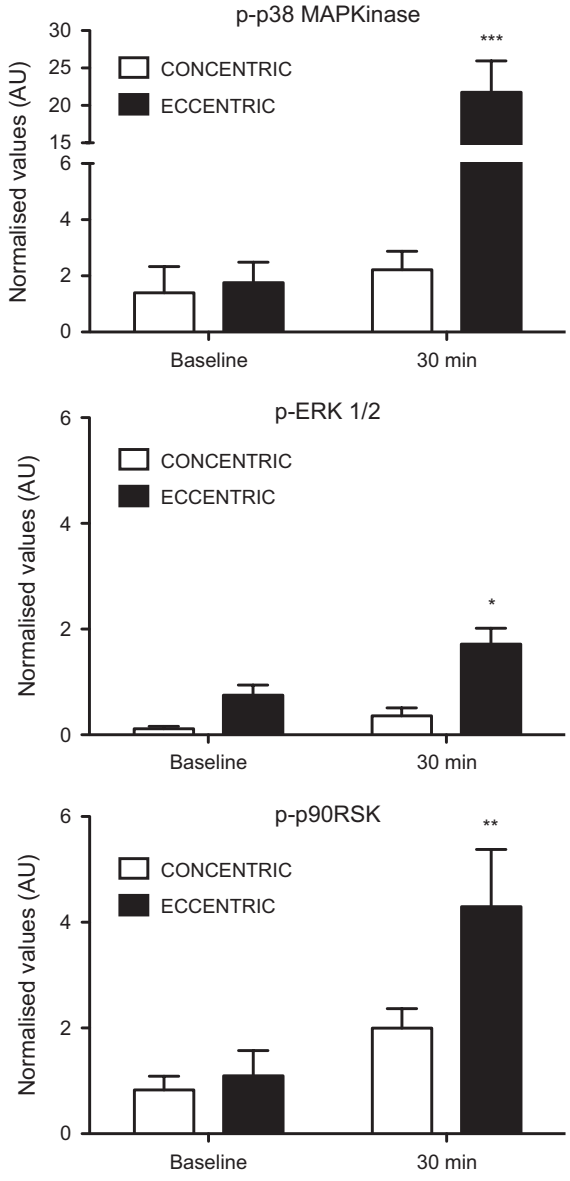

Figure 6 MAPK Molecular responses (phosphorylation) at 30 min after either a single concentric or eccentric training session. Data are means ± SEM. (*$P < 0.05$, **$P < 0.01$, *** $P < 0.001$).

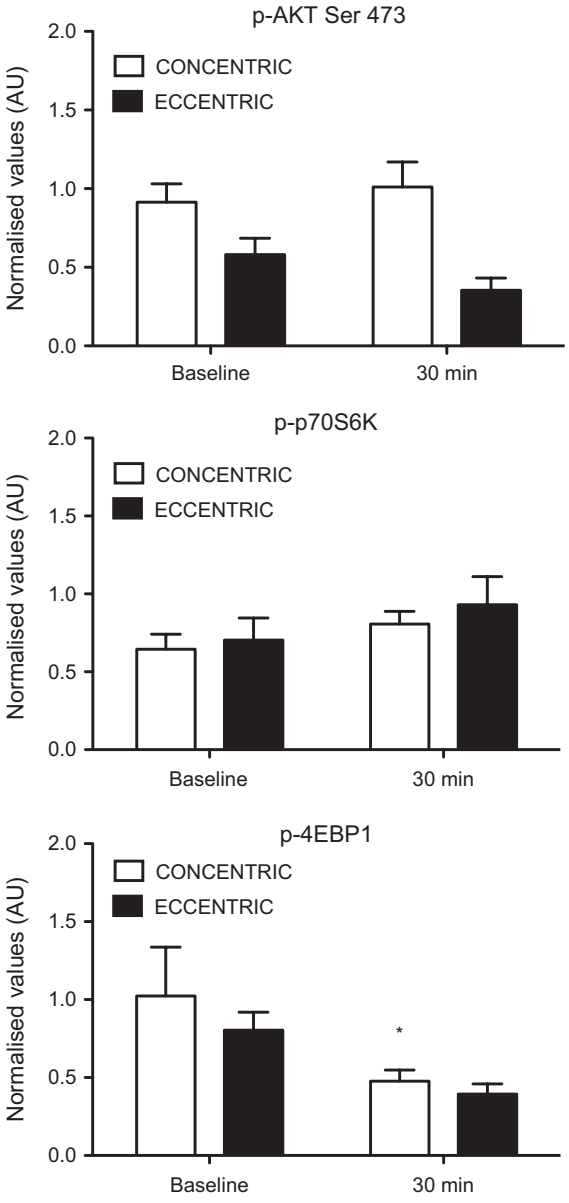

Figure 7 Akt, p70S6K and 4EBP1 molecular responses (phosphorylation) at 30 min after either a single concentric or eccentric training session. Data are means ± SEM (*$P < 0.05$).

ECC phases for the same relative load while monitoring neural drive to meet one of the fundamental requirements of the F-V relationship (Bigland & Lippold 1954, Chow & Darling 1999, Camilleri & Hull 2005). Hence, our training loads were matched to the same percentage of the CON and ECC repetition maximum (i.e. CON 1RM and ECC 1RM) and EMG values revealed similar levels of neural activation for both CON and ECC 1-RM (Table 1). The ECC group/CON group training load ratio remained between the 1.21 to 1.29 range (Table 1), this confirms previous observations of the greater forces associated with ECC than CON *in vivo* (Westing *et al.* 1988, Aagaard *et al.* 2000). These findings support our contention that both shortening and lengthening phases of our resistance exercise paradigms belonged to the same F-V curve. Although 1RM assessment is a sort of an 'unrefined' method, the fact remains that 1RM is still recognised as 'gold standard' in training studies. Furthermore, the best available technique to assess neural drive *in vivo* is still EMG. In this investigation, integrated EMG (i.e. result of recruitment and rate coding) was similar in the two

different conditions. The authors would like to emphasise that in the present study, the load was not matched for neural activation but rather, EMG was recorded in relatively equal external loads and similar EMG values were found.

Muscle hypertrophy *per se* was an expected consequence of our resistance training protocols. However, muscle volume showed similar changes after both training modes (ECC = +6 and CON = +8%, non-significant difference between groups). Although both concentric and eccentric exercise programs have shown to induce gains in muscle mass, there seems to be insufficient evidence of the superiority of either these two types of contraction (Wernbom *et al.* 2007). Nevertheless, the similar changes in muscle volume in the present study were considered unexpected, as not only ECC training load was higher, but also because ECC training has been suggested to produce greater hypertrophy and strength than CON training (increase in muscle fibre size, Hortobágyi *et al.* 1996) and associated trends towards whole muscle greater CSA (Roig *et al.* 2009). If the predominant promoter of muscle hypertrophy were the mechanical stimulus, one would expect to find a greater hypertrophy in the ECC group due to the higher training load (i.e. higher mechanical stimulus). However, this was not the case, indicating that the intensity of mechanical stimulus may not be the sole determinant for muscle hypertrophy; rather, this might be governed by the type of contraction performed (ECC/CON) and also that other factors blunting muscle hypertrophy may be at play in ECC contractions.

Interesting differences in muscle architecture using ultrasound were also found as result of the different training regimens. Although Lf increased in both groups, the ECC group showed a significantly greater gain in Lf compared to the CON one, while training produced an increase in PA after both types of training but the increase in pennation angle in the ECC group was much lower than in the CON one (Fig. 3). These findings suggest that addition of serial sarcomeres occurs in response to muscle lengthening scenarios (e.g. Holly *et al.* 1980, Seynnes *et al.* 2007, Reeves *et al.* 2009), and herein mainly, as a result of the ECC component. Instead, increases in PA occur to bundle more contractile units along the tendon aponeurosis (Gans & Bock 1965, Kawakami *et al.* 1993) primarily reflecting muscle shortening, principally as a result of the CON component. Finally, while these findings of distinct architectural responses are allied with those reported by Reeves *et al.* (2009) in older individuals after ECC vs. conventional training, our current evidence for distinct architectural adaptations to *pure* CON vs. ECC in younger individuals is the first report of its kind and reveals that adaptations following conventional RT are dominated by the concentric component (at least in older men), perhaps reflecting the greater loading stimulus of the CON phase compared to the ECC one, when applied using standard gym equipment.

Intriguingly, while both groups showed a similar overall increase in VL muscle volume, the regional morphological patterns of muscle hypertrophy induced by the two loading modes differed substantially. For instance, while ECC exercise promoted greater muscle hypertrophy (as measured by changes in ACSA by MRI) in the distal portion compared to CON, increases in the mid VL muscle were greater for CON than ECC (Fig. 4). We contend that evidence of these differences in the regional distribution of hypertrophy along the muscle belly reflects a differential addition of sarcomeres in series and in parallel. Pennation of muscle fibres allows greater packing of sarcomeres in parallel along the tendon aponeurosis (Gans & Bock 1965). Hence, the finding that CON training promoted a large increase in pennation (30%), with little increase in fascicle length (5%), strongly suggests that CON training leads to hypertrophy mainly through addition of sarcomeres in-parallel. As indicated by the increase in ACSA, this phenomenon seems to mainly occur in the central region of the VL, which, because of the bell-shaped distribution of muscle ACSA, comprises a large portion (~ 60%) of the whole VL volume. Instead, when training involved muscle stretch, that is, with ECC training, hypertrophy occurred mainly through an elongation of fascicles (12%) and with little increase in pennation angle (5%), suggesting preferential addition of sarcomeres in-series. The increase in ACSA over a larger portion (about 2/3) of the muscle belly (central and distal regions) associated with preferential increase in fascicle length suggests that the addition of new sarcomeres in series occurred over a large portion of the muscle belly. It remains to be established where along muscle fibres sarcomere were added but it is probable that this occurred at the periphery since early (Williams & Goldspink 1971) as well as recent (Allouh *et al.* 2008) observations showed (directly or indirectly), preferential addition of sarcomeres in series at the periphery of muscle fibres in response to stretch overload, and in response to developmental growth, as satellite cell frequency and concentration seems particularly high at the ends of muscle fibres (Allouh *et al.* 2008). Although this accordance between architectural and morphological adaptations to training seems reasonable, a limitation of the present study is that ultrasound scans were taken just from the middle of the muscle belly with the assumption that changes in architecture observed in this region would be representative of changes along the whole muscle. This may not be the case, as

pennation angle might have increased more closer to the myotendineous junction after ECC exercise (i.e. causing the greater VL distal hypertrophy). However, although in principle it could be argued that limiting the ultrasound scans to a single muscle site may not also be representative of other changes occurring in other muscles, it must be acknowledged that Vastus Lateralis presents a more uniform architecture throughout its length compared to other heads of the quadriceps (i.e. Vastus intermedius (VI) anterior and lateral portions present inhomogeneous architecture, Blazevich *et al.* 2006). Moreover, a very recent publication investigating the changes in muscle architecture between different sites of the four heads of the quadriceps observed how the adaptations in muscle CSA, thickness and PA were quite consistent between the Vasti and only significantly different if compared to Rectus Femoris (RF) changes size and architecture (Ema *et al.* 2013). These results could be explained by the fact that RF is a bi-articular muscle, differing from the vasti anatomically and biomechanically. The region of VL investigated in the present study (VL mid length) coincides with the site in which the largest CSA value was observed. Furthermore, our aim is to show different responses brought by the two different loading paradigms: the choice of the muscle site is supported by the study by Ema *et al.* (2013) in which VL is the muscle that showed less inhomogeneous changes between CSA and architecture throughout the muscle; hence, we have reason to believe that this site could still be the best representative of the whole quadriceps.

Blazevich *et al.* (2007) similarly reported an increase in Lf in response to ECC exercise in the first 5 weeks of training but it could be argued whether the architectural adaptations of the present study do continue overtime, as it appears that in Blazevich's study these adaptations did not occur beyond the 5-week period. Thus, while Blazevich and colleagues confirmed the early architectural adaptations phenomenon previously reported by Seynnes *et al.* (2007), our present work suggests that these changes are still detectable after 10 weeks of RET. Further investigation is needed to assess whether these architectural responses will be observed of different magnitude (i.e. similar or milder) after 5 weeks of RET.

Despite the distinct global (i.e., whole-muscle volume) hypertrophy responses between CON and ECC training groups, functional (strength) adaptations revealed similar increases in isometric MVC for both groups (CON 9%; ECC 11%). Although this similarity in the strength increase seems paralleled by the changes in muscle volume, it does raise the question of why, despite the greater training load (1.2-fold) of the ECC group, VL hypertrophy was similar. Possible causes of this finding and of the different architectural adaptations to ECC and CON training may be linked to muscle damage caused by ECC contractions and to distinct signalling pathways involved in ECC and CON.

Following such intriguing findings in the adaptive features of VL muscle after 10 weeks of CON vs. ECC, we chose to investigate the acute changes in muscle architecture in response to single CON or ECC exercise bouts by recruiting a second subject group. As expected, based upon the behaviour of the muscle-tendon unit, during CON contractions fascicles shortened (by −19%) and lengthened (+19%) during ECC contractions. We speculate that the contraction-specific VL fascicle length change (i.e. marked fascicle shortening during CON and marked fascicle lengthening during ECC) is a primary cause of the differential architectural adaptations and that such adaptations start from the first training session after CON and ECC bouts, as suggested by Seynnes *et al.* (2007) who showed that such differences in muscle architecture can be detected at very early stages of training.

Although distinct cell signalling responses to CON and ECC in humans have yet to be established, in the present study we observed increases in phosphorylated MAPK, for example, p-38 MAPK, ERK 1/2 and p90RSK in the ECC but not CON. Similarly, reputed differences in the signalling response of muscle cells have been observed in animal models (Martineau & Gardiner 2001, Wretman *et al.* 2001). Furthermore, ERK1/2 expression was previously shown to regulate CON vs. ECC growth pathways in cardiomyocytes, suggesting MAPKs are involved in regulating architectural remodelling processes in muscle tissue (Kehat *et al.* 2011). In this latter study, cardiomyocytes isolated from mice lacking ERK showed an increase in length of the cardiomyocytes (ECC growth), whereas cardiac cells isolated from mice over-expressing MEK1 (a MAPK-Kinase, ERK1/2 up-regulator) showed a preferential growth in myocyte thickness (CON growth). Recruitment of this second study group allowed us to interrogate the effects of an acute bout of CON or ECC upon intramuscular signalling proteins associated with adaptation to exercise, with particular focus on MAPK's. In doing this, we observed a specific MAPK activation only in response to ECC (which lead to a preferential increase in Lf), although a similar and simple relationship between ERK1/2 and determination of architectural adaptation in human skeletal muscle could not be confirmed, unless it is the reverse of the mechanisms occurring in cardiac muscle. Further work is needed to define this.

Another clue as to why these architectural differences may exist is that ECC leads to a greater degree of damage than CON (Byrne *et al.* 2004), with greater myofibrillar disruption occurring with ECC

(Schoenfeld 2012). However, we found no significant increases in TNFαMurf-1-MAFbx pathway (p-TNFα, p-p65, p65, IkB, p-MurF-1, p-MAFbx) 30 min after exercise. This supports the notion that activation of MAPK in response to ECC occurred independently of muscle damage/inflammation, acting through MAPK (Kramer & Goodyear 2007, Murton *et al.* 2008) and more likely through mechano-transduction mechanisms (although we cannot exclude the likely onset of muscle damage/inflammation phenomena after our single biopsy time point). Furthermore, despite the fact that we observed no differences in whole-muscle hypertrophy between ECC and CON (despite the marked architectural adaptive differences), we measured activation of growth signalling (mTOR substrates). Apart from suppression of 4EBP1 30-min post-CON only (Atherton *et al.* 2005), no other signals were modulated by 30-min post-CON or ECC. Clearly, the energy stress after exercise, which governs the latency in muscle protein synthesis responses (Cuthbertson *et al.* 2006), may have prevented us from evaluating MAPK and AKT-mTOR cross-talk. However, no further biopsies were taken, which represents a study limitation. It must be acknowledge that performing acute and chronic studies in different groups precluded interrogation of correlative links, for example, between MAPK phosphorylation and architectural adaptations. Nonetheless, the acute exercise data revealing substantial contraction-dependent divergence in mechanical and molecular responses and the chronic data revealing divergent architectural/morphological adaptations are highly robust. It could also be argued that one limitation of this study is the different time under tension curve found in the two types of contractions: as stated, the greater time under tension in the eccentric mode was specifically chosen to enable to perform the lengthening/lowering of the load phase in safety. Nevertheless, as previous studies have shown (Burd *et al.* 2012), the greater time under tension curve is associated with increased anabolic response. If this was the case in this study, we should have observed differences in hypertrophic response (i.e. ECC Vol > CON Vol), which did not occur. Burd and colleagues investigated the anabolic responses to different time under tension comparing 1 s contractions vs. 6 s ones (6-fold greater), whereas the present investigation used 2 s vs. 3 s (0.5-fold difference): it is likely that this relatively smaller difference in time under tension was not sufficient to trigger different hypertrophic adaptations, as the morphological data are much more reflecting the findings presented by Adams *et al.* (2004) that showed same increase in muscle size to ECC, CON and isometric training of the same duration. Moreover, although the greater time under tension could reflect/suggest a likely increased physiological blood flow restriction occurring during the ECC phase, which should therefore result in a higher stimulation of hypertrophic signalling and/or greater muscle volume (Meyer 2006), in this study no differences have been found in terms of anabolic signalling between the two training regimes. Hence, we may conclude that this difference in time under tension was not sufficient to modulate a differential anabolic response.

Conclusions

This study has shown that CON and ECC training paradigms lead to divergent structural adaptations, supported by different myogenic responses. ECC training leads to a marked increase in fascicle length (~1.5-fold) with no significant change in pennation angle, while CON training induces a 3-fold increase in pennation angle, with little (<1-fold) change in fascicle length. These results suggest that ECC training seems to promote the addition of sarcomere in series, whereas CON training favours the addition of sarcomere in parallel. This differential pattern of sarcomere addition induced by the two types of training, as inferred by the increase in fascicle length and pennation angle, seems also reflected by the distribution of muscle hypertrophy along the VL muscle belly, predominant in the mid to distal regions for ECC training and predominant in the mid belly region for CON training. The different muscle remodelling induced by CON and ECC training may be associated with distinct MAPK responses to the two contraction modes. The similar hypertrophy with ECC and CON RT may be explained by the greater myofibrillar disruption caused by ECC loading, followed by possible activation of inflammatory pathways likely antagonizing muscle hypertrophy.

Conflict of interest

There is no conflict of interest to declare.

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Author's contribution

MVN PJA NDR MF conceived and designed the experiments. MVF NDR WKM performed the experiments. MVF AS RMBV analysed the data. MVN PJA MF JW contributed reagents/materials/analysis tool. MVF MVN PJA NDR MF wrote the paper.

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