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ORIGINAL ARTICLE

Influence of full range of motion vs. equalized partial range of motion training on muscle architecture and mechanical properties

Maria João Valamatos[1,2] · Francisco Tavares[3,4] · Rute M. Santos[5] · António P. Veloso[1,2] · Pedro Mil‑Homens[1,2]

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Abstract

Purpose The purpose of this study was to determine the effect of a 15-week partial range of motion (ROM) resistance training program on the vastus lateralis (VL) architecture and mechanical properties, when the time under tension (TUT) was equalized.

Methods Nineteen untrained male subjects were randomly assigned to a control (Control; $n=8$) or training (TG; $n=11$) group. In the TG, the dominant and nondominant legs were randomly selected to be trained with a full ROM (FULL) or a partial ROM (PART) in an isokinetic dynamometer. Training volume was equalized based on the TUT by manipulating sets and repetitions. The VL muscle architecture was assessed by B-mode ultrasonography at rest and during maximal isometric knee extension contractions (MVCs) at ten knee angles. The VL fascicle force and specific tension were calculated from the MVCs with superimposed stimuli, accounting for the moment arm length, muscle architecture, and antagonist coactivation.

Results The FULL training induced changes in fascicle length (FL) (4.9 ± 2.0%, $P<0.001$) and specific tension (25.8 ± 18.7%, $P<0.001$). There was a moderate effect of PART training on the physiological cross-sectional area (PCSA) (7.8 ± 4.0%, $P<0.001$, $d_{av}=0.6$) and torque–angle adaptations (average increase 17.7 ± 3.9%, $P<0.05$).

Conclusions These results provide evidence that crucial architectural and mechanical muscle adaptations are dependent on the ROM used in strength training. It seems that muscle FL and specific tension can be increased by pure concentric training if greater ROM is used. Conversely, restricting the ROM to shorter muscle lengths promotes a greater PCSA and angle-specific strength adaptations.

Keywords Muscle architecture · Muscle size · Regional hypertrophy · Range of motion (ROM) · Vastus lateralis · Resistance training

Abbreviations

1-RM	One repetition maximum
ACSA	Anatomical cross-sectional area
ANOVA	Analysis of variance
BF	Biceps femoris
CIs	Confidence intervals
d_{PT}	Patellar tendon moment arm
FL	Fascicle length
FULL	Full range of motion
ICCs	Intra-class correlation coefficients
MDC	Minimal detectable change
MRI	Magnetic resonance imaging
MVC	Maximal isometric knee extension contraction
MVCs	Maximal isometric knee extension contractions
PA	Pennation angle
PART	Partial range of motion
PCSA	Physiological cross-sectional area

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✉ Maria João Valamatos
mjvalamatos@fmh.ulisboa.pt

[1] Departamento de Desporto e Saúde, Faculdade de Motricidade Humana, Laboratório de Biomecânica e Morfologia Funcional, Universidade de Lisboa, Estrada da Costa, Cruz-Quebrada, Dafundo, 1499-002 Lisbon, Portugal

[2] Faculdade de Motricidade Humana, Centro Interdisciplinar para o Estudo da Performance Humana, Cruz Quebrada, Portugal

[3] Glasgow Warriors, Glasgow, UK

[4] Faculty of Health, Sport and Human Performance, The University of Waikato, Hamilton, New Zealand

[5] Escola Superior de Tecnologia da Saúde de Coimbra, Rua 5 de Outubro-SM Bispo, 3046-854 Coimbra, Portugal

RJMT	Relative joint maximal torque
ROM	Range of motion
SEM	Standard error of the mean
SENIAM	Surface EMG for non-invasive assessment of muscles
SD	Standard deviation
TUT	Time under tension
VL	Vastus lateralis

Introduction

The joint range of motion (ROM) has not been considered a critical resistance training variable (ACSM 2009; Haff and Triplett 2015; Kraemer and Ratamess 2004); however, ROM has been used and manipulated in resistance training programs to improve strength gains and sport performance (Clark et al. 2008). Exercises with a partial ROM have been suggested for specific goals, namely, moving supramaximal loads (> full ROM 1-RM) to obtain the highest level of muscle growth stimulation (Fleck and Kraemer 2014) or limiting the exercise ROM to the phase that is critical for athletic performance to obtain greater training specificity (Clark et al. 2008). However, regarding strength-related adaptations, exercises with a full (or larger) ROM have been associated with greater increases in muscle strength that are usually linked to greater increases in muscle size (e.g., muscle cross-sectional area) (Bloomquist et al. 2013; McMahon et al. 2014a). Differences in muscle size arising from ROM training are suggested to result from the higher mechanical stress and sarcomere lengthening (McMahon et al. 2014a). Despite this conclusion and despite the role of muscle architecture and mechanical properties on general muscle function, there are few reports of the ROM impact on such muscle characteristics. In relation to muscle architecture, greater fascicle length increases are reported at 25, 50, and 75% of the total femur length when training involves a large ROM (McMahon et al. 2014a) or a longer muscle stretch (McMahon et al. 2014b), suggesting that the ROM of muscle action (or muscle excursion) may be the triggering factor for fascicle lengthening. However, in such studies, the impact of ROM resistance training was investigated with an ecologically valid training protocol involving a combination of free, machine and body weights (McMahon et al. 2014a, b). This training regime involves lifting and lowering a constant external load, combining concentric (lifting-phase) and eccentric (lowering-phase) muscle actions. Since increases in fascicle length have also been linked to eccentric muscle actions (Baroni et al. 2013; Franchi et al. 2014; Guex et al. 2016; Timmins et al. 2016), the adaptations previously attributed to the ROM may have been triggered not only by the muscle excursion range but also by the eccentric stimulus. On the other hand, the time that the muscle is under tension is another regulator of hormonal and metabolic muscle responses (Burd et al. 2012; Tanimoto and Ishii 2006) and influences the muscle hypertrophy and strength gains caused by resistance training (Tanimoto and Ishii 2006; Watanabe et al. 2013). Therefore, training with a greater ROM for the same number of sets and repetitions as for a partial ROM will increase the time under tension (TUT) of muscles, allowing greater morphologic adaptations. Consequently, for a deeper understanding of the influences of full vs. partial ROM training on muscle morphology and architecture, both factors—contraction mode and TUT—should be isolated and controlled. Therefore, the primary purpose of this study was to investigate the effect of 15-week concentric partial resistance training on VL architecture and morphology with training that is equalized by TUT. For the aforementioned reasons, we hypothesized that the magnitude of changes in muscle volume would be independent of the training ROM. However, training the muscle with a larger ROM could lead to a superior increase in fascicle length due to the greater tension on the sarcomeres.

Furthermore, the influence of different ROM exercises on muscle mechanical properties is also unclear. It is well known that one of the most important functional properties of skeletal muscle is the length dependence of its force-generating potential. Quite often, force production in sport movements occurs only at a limited portion of the force–length curve studied in isolated conditions (Maganaris 2001). Moreover, quite often (excluding some specific cases, e.g., weightlifter movements), athletic movements are performed in a partial range of the full physiological joint ROM. Therefore, according to the evident adaptability of the force–length properties to specific functional demands (Herzog et al. 1991) and to the accentuation principle (Zatsiorsky 1992), which states that training exercises should be performed within the limited ROM demanded by the specific sport event to improve training specificity (Clark et al. 2008), the second purpose of the present study was to investigate the effect of a 15-week partial ROM training program on the mechanical determinants of the force-generating capacity. These determinants include the torque–angle relationship, the physiological cross-sectional area (PCSA) and the muscle specific tension (maximum muscle force per PCSA). We hypothesized that a partial ROM limited to 60° of knee flexion would shift the torque–angle curve toward its ascending part, which means that the force levels would be increased at smaller fiber lengths corresponding to the critical phase for performance. We also hypothesized that the PCSA and the muscle specific tension would increase after training, independently of the training ROM.

Methods

Study design

To investigate the hypotheses of the present study, a longitudinal and randomized controlled experimental design was used to investigate the effect of two different resistance training ROMs (the within-subject' independent variable) on muscle volume, muscle architecture, the torque–angle relationship, the PCSA and the muscle specific tension (dependent variables). The participants were randomly assigned to one of two groups: a training group or a nontraining group. The training group performed 15 weeks of isokinetic concentric training, three times per week for a total of 45 training sessions. An attendance of at least 90% of the scheduled sessions, without missing two sessions in a row, was a criterion for participants to remain in the study. For these participants, the dominant and nondominant legs were randomly selected to be trained at either a shorter range of muscle length (partial ROM 0–60° of knee flexion, with 0° corresponding to full knee extension) or at a longer range of muscle length (full ROM 0–100° of knee flexion). As the partial ROM condition allows a shorter contraction time, resulting in a smaller training volume (i.e., total time under tension), the TUT was equalized by adding sets and/or repetitions in the partial ROM training group. Dependent variables were measured at the beginning (pre-training) and the end (post-training) of the intervention. Tests were conducted 4–6 (muscle architecture and strength assessment) and 7–9 (muscle volume) days before and after the first and final training sessions, respectively. For each subject, the pre- and post-training measurements were all performed at the same time of the day to minimize any impact of diurnal variability on muscle function. Eleven subjects completed the training intervention, and eight subjects performed all measurements without carrying out any kind of resistance training between pre- and post-training moments. Two control subjects withdrew from the study as a result of missing the post-training evaluations due to personal reasons (data not included in the analysis).

Subjects

A total of 30 thighs ($n = 30$) of 19 male college students were considered in this study. 19 participants were physically active, but none were specifically trained or had previous resistance training experience. All subjects were over 18 years old (age range 18–32 years old) and free from any pre-existing injuries or musculoskeletal or orthopedic disorders. The subjects were classified into two main groups: the training group ($n = 11$; age 21.6 ± 3.5 years; height 1.75 ± 0.04 m, body mass 71.0 ± 6.9 kg; mean ± SD) and the nontraining group ($n = 8$; age 26.6 ± 5.2 years; height 1.78 ± 0.06 m; body mass 75.7 ± 10.4 kg; mean ± SD). For the training group, the dominant and nondominant legs were randomly selected to be included either in the full ROM group (FULL; $n = 11$) or the partial ROM group (PART; $n = 11$). For the nontraining group, one thigh was randomly selected to be considered the control thigh (control; $n = 8$). During the training intervention, the control subjects maintained their habitual physical activities only.

All subjects were informed of the benefits and potential risks of the investigation prior to signing an institutionally approved informed consent to participate in the study. All procedures were approved by the local Ethical Board and were consistent with requirements for human experimentation.

Resistance training program

The subjects performed maximal concentric knee extensions in a seated position, on a Biodex isokinetic dynamometer (Biodex System 3 research, Shirley, NY, USA) 3 days a week for 15 weeks for a total of 45 training sessions. For all subjects, one thigh was randomly selected to be included in the FULL group, and the contralateral thigh was included in the PART group. The training program was divided into five periodized blocks of 3 weeks, increasing the angular velocity + 30° s^{-1} at every block. The number of sets and/or repetitions was also increased to maintain the TUT throughout the training intervention. To maintain a high-load stimulus (low isokinetic velocity), two sets of six (FULL) or ten repetitions (PART) at 60° s^{-1} were maintained after the first block until the end of the training intervention. One minute of passive rest was allowed between sets for both legs, and the repetitions within a set were performed continuously. The resistance training design (series × reps and angular velocity) is shown in Table 1. Since the angular displacement was lower in the PART, the TUT was equalized by adding sets and/or repetitions for this group (Table 1).

Each training session began with a warm-up consisting of 5 min on a cycle ergometer at a self-selected resistance followed by a general mobilization of the knee joints. All training sessions were supervised, and appropriate verbal encouragement was given with the instruction to "kick as fast as possible". All subjects completed the training intervention without becoming injured and maintained the predetermined attendance (42.7 ± 1.1 training sessions, leading to an adherence level of 94.9 ± 2.5%).

Table 1 Resistance training design—series × reps, angular velocity and time under tension (TUT) for the FULL and PART ROM groups along five blocks of 3 weeks

		Group	Angular velocity	Sets	Reps	TUT (s)
Block I	Weeks 1–3	FULL ROM	$60°\ s^{-1}$	5	6	50
		PART ROM	$60°\ s^{-1}$	5	10	50
Block II	Weeks 4–6	FULL ROM	$60°\ s^{-1}$	2	6	53.3
			$90°\ s^{-1}$	5	6	
		PART ROM	$60°\ s^{-1}$	2	10	53.3
			$90°\ s^{-1}$	5	10	
Block III	Weeks 7–9	FULL ROM	$60°\ s^{-1}$	2	6	53.3
			$120°\ s^{-1}$	5	8	
		PART ROM	$60°\ s^{-1}$	2	10	53.0
			$120°\ s^{-1}$	6	11	
Block IV	Weeks 10–12	FULL ROM	$60°\ s^{-1}$	2	6	52.0
			$150°\ s^{-1}$	6	8	
		PART ROM	$60°\ s^{-1}$	2	10	53.6
			$150°\ s^{-1}$	7	12	
Block V	Weeks 13–15	FULL ROM	$60°\ s^{-1}$	2	6	53.3
			$180°\ s^{-1}$	6	10	
		PART ROM	$60°\ s^{-1}$	2	10	55.0
			$180°\ s^{-1}$	7	15	

Muscle architecture

Vastus lateralis muscle architecture was assessed at rest using B-mode ultrasound imaging with a 9-cm long, 10-MHz linear-array transducer (model EUB-7500, Hitachi Medical Corporation, Tokyo, Japan). Sonographs were taken before and after the training period of both thighs in the training group and in one randomly selected thigh in the control group. Longitudinal images were taken from the mid-belly of the VL muscle, corresponding to 39% of the distance from the proximal edge of the patella to the anterior superior iliac spine (Blazevich et al. 2006). The participants were instructed not to perform any physical activity in the 48 h prior to the lab visit. Before measurements, the subjects laid on a couch for 15 min to restore the normal flow of body fluids. For the measurements, the subjects were seated on the dynamometer chair, with the knees flexed at 10° as measured by a goniometer (0° corresponding to full extension of the knee), the legs supported and the muscles relaxed. This knee bend was selected because it does not cause excessive stretch of the hamstrings in a seated position (Reeves et al. 2009) and helps to reduce the fascicle curvature, improving measurement reliability (Blazevich et al. 2006). To ensure that the probe was effectively placed in both testing occasions, the scanning sites of both legs of all subjects were mapped with a malleable transparent plastic sheet at the pre-training measurements (Blazevich et al. 2007), and the post-training sampling location was also verified by viewing the pre-training ultrasound image.

Muscle fascicle length (FL) was defined as the length of the fascicular path between the superficial and deep aponeuroses. When the fascicles extended beyond the acquired image, the total FL was calculated by linear extrapolation as previously described (Finni et al. 2003) (Fig. 1a). The pennation angle (PA) was determined by measuring the angle between the fascicles and the deep aponeurosis. Both muscle architectural parameters were quantified from the ultrasound scans using image analysis software, ImageJ 1.42q (National Institutes of Health, Bethesda, MD, USA).

Muscle volume and inter-regional hypertrophy

Axial plane scans of the thighs were taken using a 1.5-T whole-body magnetic resonance imaging (MRI) scanner (Signa HDxT 1.5T, GE Healthcare, USA). A proton density echo protocol (repetition time 4140 ms, echo time 7.5 ms, field of view 512 × 512 mm, slice thickness 4 mm, gap between slices 0.0 mm) was used to continuously scan the thighs from the superior border of the patella to the greater trochanter. Participants were asked to lie supine on the MRI bed and to insert their legs into a circular coil. Due to the scanning area of the coil, the thighs were imaged in two separate sections. On average, the number of axial scans obtained in each thigh was the same for the pre- and post-training periods (≈ 84 axial scans). From these scans, the contours of the VL muscle of each MRI scan (anatomical cross-sectional area—ACSA) were digitized using the OsiriX image analysis software (Fig. 1b) and subsequently, the VL muscle volume was calculated as follows:

$$\text{VL\_volume}\ (\text{cm}^3) = \sum \text{ACSA}\ \times \text{slice thickness}$$

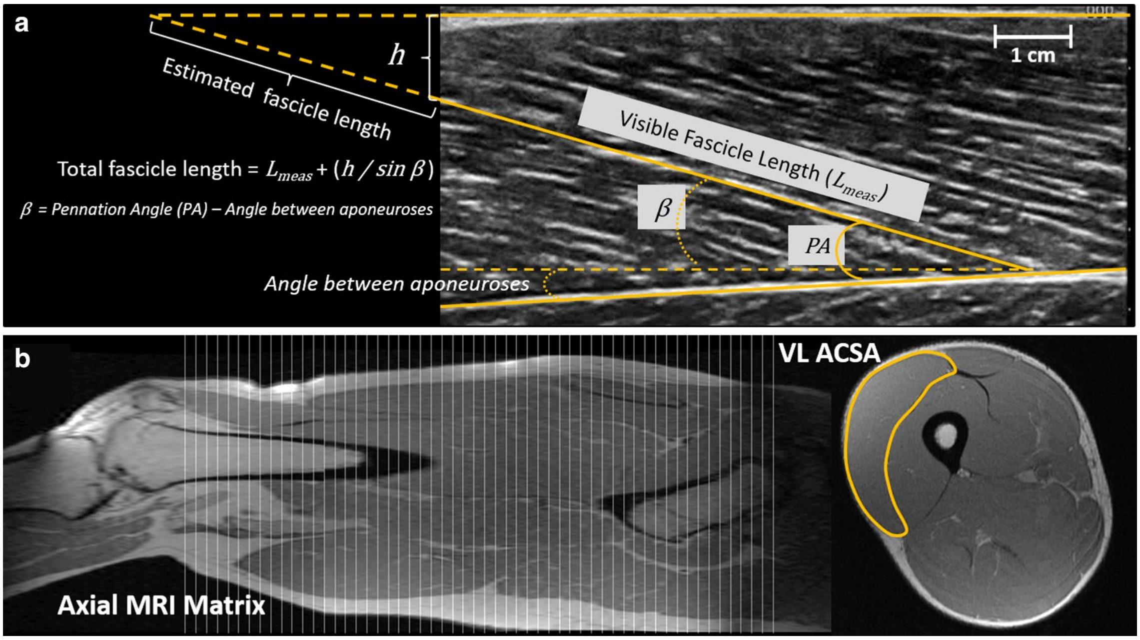

Fig. 1 **a** Muscle architecture measurements: Pennation angle (PA) and fascicle length (FL). When the fascicle was not fully visible within the scan area, the total fascicle length was calculated by linear extrapolation as previously described (Finni et al. 2003). **b** MRI matrix scan of the thigh muscles. The perimeter of the vastus lateralis (VL) is delimited in the right image

Inter-regional VL hypertrophy was calculated after training by obtaining the pre- and post-training average values of five axial scans at 25, 50 and 75% of the total muscle length. From these mean values, the relative increase in ACSA was calculated for the three different regions of the VL muscle (proximal, medial and distal portions, respectively). The total muscle length was defined as the distance between the axial slices where the VL muscle was visible starting from the hip/knee joint (proximal and distal portions, respectively).

Torque–angle relationship

To assess changes in the torque–angle relationship after training, the maximal isometric knee extension torque of both legs was measured on the isokinetic dynamometer at 10 knee joint angles, ranging from 30° to 100° of knee flexion (full extension = 0°), with 5° increments around the expected joint angle for maximal torque (70°; 75°; 80°; 85°; 90°) and 10° around the ascending (30°; 40°; 50°; 60°) and descending parts (100°) of the torque–angle curve. Subjects were seated on the dynamometer chair and firmly strapped at the hip, at the chest and over the thigh to minimize extraneous movement. The knee center of rotation was carefully aligned with the dynamometer axis of rotation, and the lever arm of the dynamometer was firmly attached to the lower leg with inextensible straps. At each knee joint angle, determined by a manual goniometer (MSD, Londerzeel, Belgium), subjects were instructed to perform 1-rapid maximal voluntary isometric knee extension contraction (MVC) and to maintain this maximal effort for ≈ 2 s. The order was randomized, and a minimum of 2 min rest was allowed between contractions to prevent fatigue. The torque signals were A/D converted (MP100—BIOPAC™ Systems, 16-bits) at a sampling rate of 1000 Hz and were filtered with a low-pass filter with a cut-off frequency of 16 Hz. Antagonist muscle coactivation was estimated by determining the electromyographic activity of the biceps femoris (BF) muscle during each MVC. One reference electrode was fixed over the left patella, and two bipolar surface electrodes (Plux—Portugal, Gain: 1000; CMRR: 110 dB, > 100 MΩ input impedance; 25–500 Hz passing band) were placed over the BF muscle belly according to the recommendations of Surface EMG for Non-Invasive Assessment of Muscles (SENIAM) (Hermens et al. 2000). The interpolated twitch technique was used to determine the level of maximal voluntary agonist muscle activation at 90° of knee flexion, as described previously (Erskine et al. 2009). This level of activation was applied to the peak extension torque obtained on each MVC, which, when corrected for antagonist muscle coactivation, provided the relative joint maximal torque (RJMT). The joint angle at which the highest RJMT occurred was considered the optimal knee joint angle (optimal angle) and all subsequent calculations were made at this angle unless otherwise stated.

VL muscle force modeling and specific tension

The VL muscle force was modeled as previously described by Reeves et al. (2004) and Maganaris (2001). Briefly, to calculate the quadriceps forces at the patellar tendon, the highest RJMT was divided by the patellar tendon moment arm (d_{PT}), which was estimated at the peak torque of the MVCs. In the present study, the d_{PT} was determined from sagittal and coronal-plane knee scans obtained with an MRI scanner (Signa HDxT 1.5T, GE Healthcare, USA). The knee was scanned at rest with the participant in the supine position and the joint fully extended. The patellar tendon moment arm was subsequently defined as the length of the perpendicular line between the axis of the patellar tendon and the tibiofemoral contact point (the midpoint of the shortest distance between the two femoral condyles and the tibial plateau). Corrections were made for the difference between d_{PT} at full extension and at the optimal angle (Baltzopoulos 1995) and between rest and MVC (Tsaopoulos et al. 2006), providing the maximal quadriceps force. The relative contribution of the VL muscle to the maximal quadriceps force was estimated from its relative PCSA with respect to the entire quadriceps muscle group, which was based on data from Narici et al. (1992). The force transmitted from the VL fascicle to the tendon was then estimated by dividing the VL muscle force by the cosine of the *PA* measured during MVC. Finally, the specific tension of the VL muscle was calculated by dividing the VL fascicle force by the VL PCSA (Maganaris et al. 2001; Narici et al. 1992), which was calculated by dividing the muscle volume by the optimum FL (measured at optimal angle during MVC). Both FL and PA were measured during MVCs at the same site used for muscle architecture measurements. To ensure that the right region of the muscle was scanned, the probe was held in place using an external device secured by the experimenter and fixed with double-sided adhesive skin interfaces. The use of an echo-absorptive external marker ensured that no probe movement occurred in relation to the digitized structure.

Statistical analyses

All statistics were calculated using the software package SPSS 23 (IBM Corp, Armonk, NY). Descriptive data are presented as the mean ± SD, unless otherwise stated. The assumption of normality was verified using the Shapiro–Wilk test. The changes (Δ) between pre- and post-training for all dependent variables (muscle architecture, muscle volume, VL fascicle force and specific tension) were calculated, and differences between groups (control, FULL and PART) were tested by one-way ANOVA. Significant interactions between groups were determined by the Scheffe post hoc test. Whenever homogeneity of the variances was not observed, a Welch comparison test was performed together with the Tamhane T2 post hoc test. To evaluate the differences between groups in regional muscle hypertrophy (i.e., ACSA @ 25, 50 and 75% of the total muscle length), one-way repeated measures ANOVA was performed; this test was also used to compare the fascicle force between the various joint angles. Cohen's *d* effect-size analysis was used to examine the magnitude of differences between groups (Cohen's d_s) and between pre- and post-training (Cohen's d_{av}) (Lakens 2013). Threshold values of 0.2, 0.5 and 0.8 were used to represent small, moderate and large effects, respectively (Cohen 1988). The effect was deemed unclear if its 90% confidence interval overlapped the thresholds for small positive and negative effects (Hopkins et al. 2009). For all statistical analyses, the level of significance was set at $P < 0.05$. The test–retest reliability of the main assessments of this study was previously measured in a separate sample of active subjects ($n = 10$) (unpublished data). The same experimenter performed these tests on two different occasions, separated by a mean of 2 days. The intra-class correlation coefficients (ICCs) and 95% confidence intervals (CIs) were calculated. To determine the magnitude of change below which there was a greater than 95% chance that no real change occurred, the 95% minimal detectable change (MDC) was also calculated (Weir 2005) as $1.96 \times \sqrt{2} \times$ SEM, where SEM is the standard error of the mean. A summary of the results for inter-day reliability is shown in Table 2. The observed statistical power of our main analyses (averaged to muscle architecture, muscle volume, VL fascicle force and specific tension) was statistically adequate with beta = 0.84.

Table 2 Inter-day measurement reliability

Variables	ICC	95% CI	MDC
Pennation angle (°)—*R*	0.96	0.84–1.00	0.19 (1.3)
Pennation angle (°)—*C*	0.92	0.85–0.96	0.46 (2.3)
Fascicle length (cm)—*R*	0.92	0.71–0.98	0.27 (3.2)
Fascicle length (cm)—C	0.88	0.58–0.97	0.33 (3.7)
MVC torque (N m)	0.89	0.62–0.97	25.0 (8.7)
Optimal angle (°)	0.93	0.74–0.98	1.6 (2.1)
Voluntary activation (%)	0.96	0.33–0.94	2.0 (2.1)
Antagonist co-activation (%)	0.78	0.63–0.97	1.1 (7.6)

Values are expressed as mean (%)

ICC intra-class correlation coefficient, *95% CI* 95% confidence interval, *MDC* minimal detectable change, *R* rest, *C* contraction

Table 3 Resistance training data for the FULL and PART ROM training groups through 15 weeks (five blocks of 3 weeks)

	FULL ROM	PART ROM
Training sessions—adherence level (%)	94.9 ± 2.5	94.9 ± 2.5
Training volume—TUT (s)	2238.6 ± 57.7	2264.2 ± 57.8
Initial torque @ 60° s^{-1} (first session) (N m)	230.5 ± 39.6	187.1 ± 35.1**
Final torque @ 60° s^{-1} (last session) (N m)	265.6 ± 35.4	205.9 ± 49.4**
Total mechanical work (KJ)	435.9 ± 38.5	373.4 ± 38.5***
Mechanical work—block I (KJ)	64.3 ± 20.0	51.8 ± 17.5
Mechanical work—block II (KJ)	75.4 ± 11.1	56.2 ± 15.0**
Mechanical work—block III (KJ)	89.5 ± 8.5	76.6 ± 11.1**
Mechanical work—block IV (KJ)	99.4 ± 8.3	90.5 ± 8.0**
Mechanical work—block V (KJ)	107.2 ± 9.9	98.3 ± 14.7*

Values are means ± SD

TUT time under tension

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$ between groups

Results

Resistance training

Training data related to both the FULL and PART groups are shown in Table 3. Both groups showed a first-to-last session increase in the knee extension torque at 60° s^{-1} (15.3 and 10.1% for FULL and PART, respectively; $P = 0.000$, $d_s = 0.70$), with no differences between groups ($P > 0.05$). The mean training volume (i.e., time under tension) was not significantly different between the groups ($P > 0.05$; Table 3). However, the torque and total- and per-block mechanical work (blocks II, III, IV and V) were higher in the FULL group than in the PART group ($P < 0.01$; Table 3).

Muscle architecture

Significant effects of group were observed from pre- to post-training for PA ($P < 0.001$) and FL ($P = 0.002$). Vastus lateralis PA increased from pre- to post-training in both training groups, but the change was similar between the FULL (9.5 ± 2.4%, $P < 0.001$, $d_{av} = 0.9$) and PART groups (12.2 ± 2.4%, $P < 0.001$, $d_{av} = 1.0$) (Fig. 2). In contrast, FL increased significantly in the FULL group (4.9 ± 2.0%, $P < 0.001$, $d_{av} = 0.7$) with no change in the PART group (− 1.1 ± 3.4%, $P > 0.05$) (Fig. 2). There was no change in PA and FL in the control subjects over the testing period (0.4 ± 3.1 and − 0.5 ± 4.2% for PA and FL respectively; $P > 0.05$) (Fig. 2).

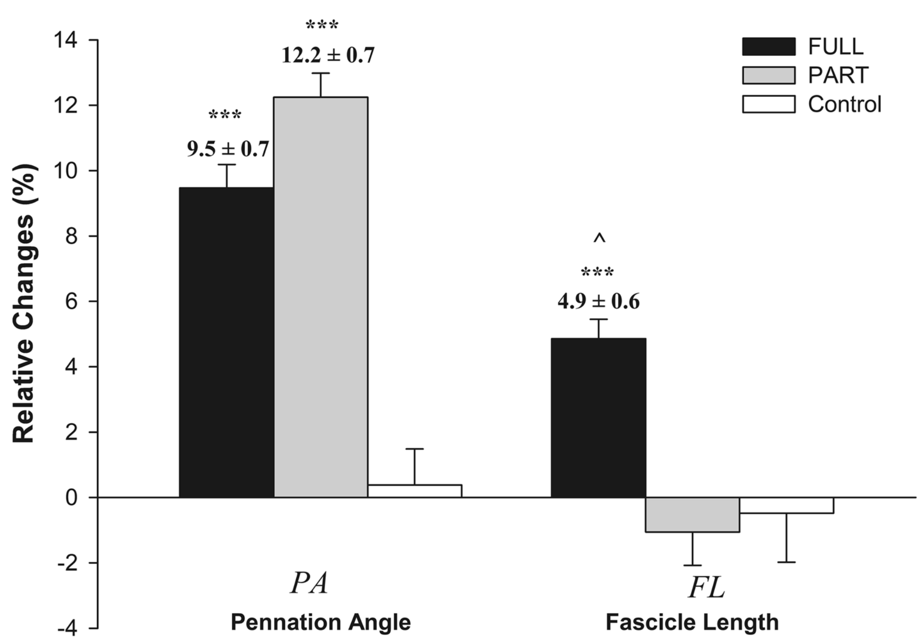

Fig. 2 Relative changes in VL muscle architecture (PA and FL) in the FULL, PART and Control groups over the training period. Values are the means ± SEMs. ***Significant change from pre- to post-training ($P < 0.001$); ^significantly different from the other groups ($P < 0.05$)

Muscle volume and inter-regional hypertrophy

Significant interactions between groups were observed for muscle volume ($P=0.002$), proximal ACSA ($P=0.001$), medial ACSA ($P=0.003$) and distal ACSA ($P<0.001$). Although no change in VL volume was found for the control subjects (−0.7 ± 3.6%, $P>0.05$), there was a statistically significant increase in the training subjects (Fig. 2). The VL volume increased from 724.8 ± 81.1 to 780.0 ± 87.8 cm^3 ($P=0.001$; d_{av} = 0.6) and from 715.9 ± 83.2 to 763.7 ± 86.4 cm^3 ($P<0.001$; d_{av} = 0.5), for the FULL and PART groups, respectively, leading to a relative change of 7.6 ± 1.6 and 6.7 ± 3.0%, for the FULL and PART groups, respectively (Fig. 2).

The anatomical VL ACSA increased after 15 weeks in all measured regions in both training groups with no significant differences between groups ($P>0.05$) (Fig. 3). As expected, no changes in the control group were found. No differences were found between the distal and medial VL muscle sizes, although both regions were significantly different from the proximal region in both training groups (Fig. 3).

Torque–angle relationship

Although no pre-training torque differences were observed between groups at any knee joint angle ($P>0.05$), significant interactions between groups were observed from pre- to post-training in the torque–angle relationship ($P\leq0.03$). The changes in the FULL and PART groups are shown in Fig. 4. Both training protocols produced a curve upshift (Fig. 4), which was most prominent around the angle of the peak torque, where greater relative changes were found. There was a slight indication of angular specificity in the training in both groups, with PART promoting greater relative increases at 30°, 40°, 50°, and 60° (i.e., knee joint angles within the training ROM), whereas FULL increased the MVCs over the entire knee angle range, except at 30° and 40°. However, the angle of the peak torque did not change after training in either training group ($P>0.05$, Table 4).

VL muscle force and specific tension

Table 4 summarizes the mean ± SD (SEM) of the main parameters of the VL muscle force modeling process. Significant interactions between groups were observed for VL muscle force ($P=0.001$) and specific tension ($P=0.003$). The VL fascicle force increased significantly by 29.7 ± 19.6% ($P<0.001$, d_{av} = 1.6) and 20.1 ± 18.2% ($P<0.01$, $d_{av}=0.9$) after FULL and PART training, respectively, with no significant effect of group. However, there was a moderate effect of PART on the VL PCSA adaptations. The assessment of VL volume and FL before and after training showed a 7.8 ± 4.0% increase in the VL PCSA in the PART group ($P<0.001$; d_{av} = 0.6), in contrast to the FULL group's nonsignificant increments of 2.5 ± 2.9% ($P>0.05$). Consequently, there was also a main effect of group ($P<0.001$) on the VL specific tension (i.e., maximum muscle force per PCSA). The FULL ROM-induced changes in VL fascicle force (29.7%, $P<0.001$) and PCSA (2.5%, nonsignificant) led to a 25.8 ± 18.7% increase in VL specific tension ($P<0.001$; d_{av} = 1.2). Conversely, because the VL fascicle force (20.1%, $P<0.01$) and PCSA (7.8%, $P<0.001$) both increased from pre- to post-training, the VL specific tension remained unchanged in the PART group

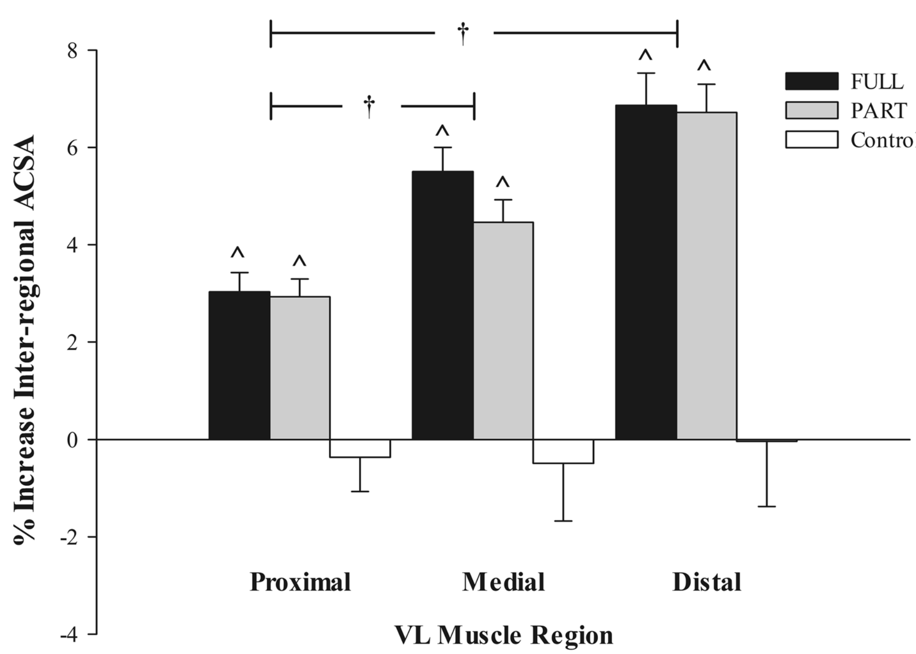

Fig. 3 Inter-regional hypertrophy of the VL muscle for FULL, PART and Control groups on anatomical cross-sectional area (ACSA) measured at 25 (proximal), 50 (medial) and 75% (distal) of the total muscle length. Data are the relative changes [means (%) ± SEMs]. ^Significantly different from the Control group ($P<0.05$). †Significantly different from the proximal region ($P<0.05$). No differences were found between the FULL and PART groups in the proximal, medial and distal regions or between any regions in the Control group

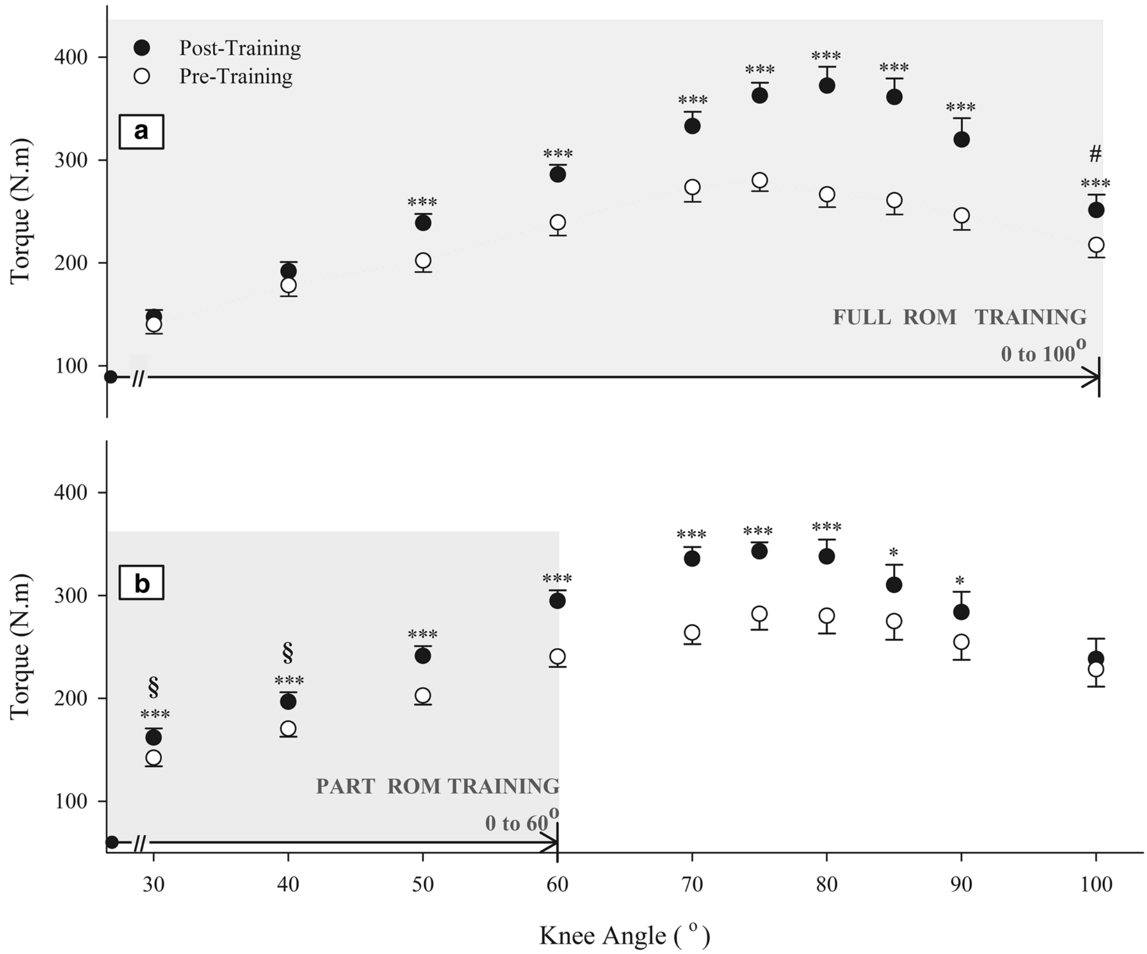

Fig. 4 Changes in the torque–angle relationship from pre- to post-training in the FULL (**a**) and PART (**b**) training groups. Increases were greatest near the optimal knee joint angle and were different between the groups at 30°, 40° and 100° ($P<0.05$). The shaded areas represent the ROM of the FULL (0°–100° of knee flexion; 0°= full knee extension) and PART (0°–60° of knee flexion) groups. Data are the means ± SEMs. *$P<0.05$, ***$P<0.001$ significantly above the pre-training values. #Significantly greater than the PART group ($P<0.05$). §Significantly greater than the FULL group ($P<0.05$)

(10.9 ± 18.3%, $P>0.05$), although this value also tended to increase.

There was no change in VL fascicle force, PCSA and specific tension in the control subjects (−3.1 ± 6.6, −0.4 ± 2.5 and −3.3 ± 6.6%, $P>0.05$, respectively) over the 15-week testing period.

Discussion

The first purpose of our study was to investigate the effect of a 15-week concentric resistance training program with different ROMs on VL architecture and morphology, with training that is equalized between the conditions. We have compared, for the first time, the structural and architectural remodeling of human skeletal muscle in response to resistance concentric training over a longer (FULL) vs. shorter (PART) range of muscle length with equalized muscle contraction time. Moreover, to the best of our knowledge, only study by Guex et al. (2016) has analyzed the influence of ROM resistance training under isokinetic conditions, which is an effective strategy to regulate muscle excursion range (i.e., joint range of motion), therefore, controlling the real time of muscle contraction and allowing pure concentric muscle contractions. As smaller ROM training allows a shorter contraction time and, therefore, a smaller training volume (i.e., time under tension), we equalized the TUT by adding sets and/or repetitions for the PART training group. Given that the TUT strongly influences the anabolic response (Burd et al. 2012), it was hypothesized that while the magnitude of morphological changes would be independent of the training ROM, the architectural adaptations would not. Our findings support the initial hypotheses: (1) there were similar increases in muscle volume in both training groups;

Table 4 Pre- and post-training torque–angle relationship and force modeling parameters for the FULL, PART and Control groups

	Pre-training	Post-training	Δ %
Maximal MVC torque (N m)			
FULL ROM	290.7 ± 45.0 (13.6)	383.8 ± 56.1 (16.9)***	32.0 ± 16.8 (5.6)###
PART ROM	292.3 ± 54.6 (16.5)	365.4 ± 44.9 (13.5)***	25.0 ± 20.4 (6.1)##
CONTROL	298.0 ± 28.9 (10.2)	296.0 ± 30.2 (10.7)	− 0.7 ± 2.3 (0.8)
Optimal angle (°)			
FULL ROM	78.6 ± 6.1 (1.9)	79.1 ± 5.1 (1.6)	0.0 ± 8.9 (2.7)
PART ROM	75.0 ± 6.7 (2.0)	76.8 ± 5.3 (1.6)	2.4 ± 6.4 (1.9)
CONTROL	73.8 ± 4.2 (1.5)	73.1 ± 5.0 (1.8)	− 0.9 ± 3.8 (1.4)
Voluntary activation (%)			
FULL ROM	94.0 ± 2.5 (0.8)	95.7 ± 1.7 (0.5)	1.8 ± 2.2 (0.7)
PART ROM	93.8 ± 1.9 (0.6)	96.0 ± 1.4 (0.4)*	2.3 ± 2.3 (0.7)^
CONTROL	93.7 ± 1.9 (0.6)	93.5 ± 1.8 (0.6)	− 0.3 ± 2.1 (0.8)
Antagonist co-activation (%)			
FULL ROM	13.4 ± 1.7 (0.5)	11.2 ± 1.6 (0.5)	− 16.0 ± 12.7
PART ROM	13.0 ± 1.1 (0.3)	10.9 ± 2.1 (0.6)	− 16.2 ± 15.7 (4.7)
CONTROL	15.2 ± 3.1 (1.1)	15.2 ± 2.3 (0.9)	− 0.1 ± 18.4 (6.5)
Patellar tendon moment arm (cm)			
FULL ROM	3.7 ± 0.2 (0.05)	3.7 ± 0.2 (0.05)	0.6 ± 1.4 (0.4)
PART ROM	3.6 ± 0.2 (0.05)	3.7 ± 0.1 (0.04)	0.7 ± 2.8 (0.8)
CONTROL	3.8 ± 0.2 (0.1)	3.8 ± 0.2 (0.1)	0.0 ± 1.8 (0.6)
Quadriceps force (KN)			
FULL ROM	7.38 ± 1.22 (0.37)	9.44 ± 1.33 (0.40)***	27.79 ± 19.34 (5.83)###
PART ROM	7.46 ± 1.55 (0.47)	8.78 ± 1.33 (0.40)***	17.77 ± 17.71 (5.34)##
CONTROL	7.29 ± 0.77 (0.3)	7.04 ± 1.00 (0.36)	− 3.29 ± 6.61 (2.34)
VL PCSA (cm^2)			
FULL ROM	86.6 ± 11.6 (3.5)	88.7 ± 10.9 (3.3)	2.5 ± 2.8 (0.8)
PART ROM	84.9 ± 10.5 (3.2)	91.5 ± 10.7 (3.2)***	7.8 ± 4.0 (1.2)###††
CONTROL	87.2 ± 9.1 (3.2)	86.8 ± 8.9 (3.1)	− 0.4 ± 2.5 (0.9)
VL fascicle force (KN)			
FULL ROM	2.71 ± 0.47 (0.14)	3.51 ± 0.53 (0.16)***	29.73 ± 19.63 (5.92)###
PART ROM	2.74 ± 0.59 (0.2)	3.29 ± 0.53 (0.16)***	20.16 ± 18.20 (5.49)##
CONTROL	2.72 ± 0.32 (0.11)	2.64 ± 0.43 (0.15)	− 3.08 ± 6.56 (2.32)
VL specific tension ($N\ cm^{-2}$)			
FULL ROM	31.8 ± 6.8 (2.0)	40.0 ± 6.7 (2.0) ***	25.8 ± 18.7 (5.7)###
PART ROM	32.6 ± 7.4 (2.2)	36.2 ± 5.5 (1.7)	10.9 ± 18.3 (5.5)†
CONTROL	31.6 ± 4.9 (1.7)	30.5 ± 4.7 (1.7)	− 3.3 ± 6.6 (2.3)

Values are means ± SD (SE)

MVC maximal isometric knee extension contraction, *PCSA* physiological cross-sectional area, *VL* vastus lateralis

^$P < 0.05$ significantly different from others groups

†$P < 0.05$; ††$P < 0.01$ significantly different from FULL group

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$ significantly above pre-training values

##$P < 0.01$; ###$P < 0.001$ significantly different from Control group

and (2) there were significant differences in muscle architectural parameters between the groups (Fig. 2). As hypothesized, there was a significant main effect of training on the VL muscle volume with no significant differences between FULL and PART. Partial ROM training has been generally viewed as a strategy to accommodate a larger external load in the joint range that provides a greater mechanical advantage (near the peak force production) (Massey et al. 2004), with the belief that lifting heavier loads will induce greater adaptations (owing to the higher mechanical stress). In our study, the ROM restriction to the last 60° of knee extension under isokinetic conditions led to a difference in mechanical stress between the FULL (higher torque) and PART (lower torque) groups. The training loads (mean torque) were an average of 13.2 ± 3.3% lower in the PART group, leading to a FULL/PART training load ratio of ≈ 1.15. However, mechanical stress is not the only factor promoting muscle hypertrophy (Schoenfeld 2010). Data in the literature suggest that maximum gains in muscle hypertrophy are achieved by training regimens that produce significant metabolic stress while maintaining a moderate degree of muscle tension (Schoenfeld 2010; Tanimoto and Ishii 2006). For instance, a previous study has shown that low-intensity resistance training (≈ 50% 1RM) with slow movement and tonic force generation causes similar increases in muscular size and strength to those after high-intensity training (≈ 80% 1RM) at normal speed (Tanimoto and Ishii 2006). These results suggest that a sustained contractile force and repeated movements probably optimize the intramuscular environment that may be associated with hypertrophy, i.e., a hypoxic condition and the accumulation of metabolic subproducts (Takarada et al. 2000). Furthermore, there is some evidence that when there is TUT equivalence, protocols performed with a higher repetition number and shorter repetition durations led to increased levels of fatigue (Tran and Docherty 2006) and blood lactate concentration (Lacerda et al. 2016). If such intramuscular conditions are crucial to the development of muscle strength and hypertrophy, then it is possible that the similar increase in VL muscle volume found after PART training was due to the metabolic stress caused by the same TUT but higher training repetitions.

Because of the nonlinear changes in regional muscle hypertrophy previously reported (Franchi et al. 2014; Housh et al. 1992; McMahon et al. 2014a), we calculated the mean ACSA for 25, 50 and 75% of the total VL muscle length. Significant increases in regional VL ACSA compared to that at baseline were found at all measured sites, with no differences between training groups (Fig. 3). Although no significant differences were observed between the distal and medial measured sites, there was a trend for a greater increase in VL ACSA from the proximal to the distal region. Similar results were found by Housh et al. (1992), who verified increases of 1.1, 8.0 and 13.4% in the VL ACSA measured at a proximal, medial and distal levels, respectively, after 8 weeks of isokinetic concentric leg extension/flexion training. With regard to the training ROM, we found no significant differences in any of the muscle size measurements between FULL (3.0, 5.5 and 6.9% for the proximal, medial and distal VL regions, respectively) and PART (2.9, 4.5 and 6.7% for the proximal, medial and distal VL regions, respectively), providing evidence that muscle mass adaptations are independent of ROM training. These findings are in contrast with previous literature that analyzed the influence of ROM dynamic training on lower body muscle adaptation (Bloomquist et al. 2013; McMahon et al. 2014a, b). Bloomquist et al. (2013) observed a greater increase in all portions of the front thigh muscle CSA in the group that trained via squats with a greater ROM. When comparing the effect of lower body isoinertial ROM resistance training, McMahon et al. (2014a, b) reported that a greater ROM (McMahon et al. 2014a) and longer muscle lengths (McMahon et al. 2014b) promote greater hypertrophy at the distal portion of the VL muscle, concluding that alterations in muscle length may influence the stress–strain relationship along the muscle length, promoting a discrepancy in the mechanical stress between muscle regions. Our results show that when the lower tension and the smaller muscle fascicle excursion of PART training are compensated by an increase in mechanical work (increasing the training repetitions), similar muscle mass adaptations can be expected. Consequently, we found no significant differences between full or limited ROM training in any muscle mass parameter. Nevertheless, interesting differences in muscle architecture were found as a result of the different training ROMs. There was a significant increase in FL in the FULL group (4.9 ± 2.0%, $P < 0.001$, $d_{av} = 0.7$) with no changes in other groups (PART and Control). This finding is in line with previously reported gains after resistance training using an identical range of muscle action (≈ 100° ROM) (Franchi et al. 2014; Reeves et al. 2004, 2009) and suggests the addition of sarcomeres in series in response to the muscle excursion range used in the FULL group. However, a major finding of this study was that there was no significant effect of PART on FL adaptations, confirming that the greater ROM concentric training may be a superior loading stimulus for increasing the FL, as previously suggested by McMahon et al. (2014b). Since the PART thigh was trained through a knee joint range of motion of 60° (0°–60° of knee flexion), which is closer to the functional demands chronically imposed on the muscle in the usual daily activities, that training stimulus was within the accommodation zone and was probably not enough to disturb the muscle fiber lengthening integrity. Conversely, for the FULL thigh, the muscle excursion range (ROM = 100° of knee flexion) was greater than the normal ROM and could be considered a training load stimulus, supporting previous animal (Koh and Herzog 1998) and human (Blazevich et al. 2007; McMahon et al. 2014a, b) research evidence indicating that muscle excursion range is a possible stimulus for increasing the FL. Although some studies have already shown that muscles undergoing different amounts of stretching and shortening have the ability to adapt to their new functional lengths by adding or removing sarcomeres in series (Tabary et al. 1972; Williams and Goldspink 1973), only the investigations of McMahon et al. (2014a, b) measured the FL changes in response to dynamic strength training at different muscle lengths. Although the gains were higher with a greater ROM (23 ± 5%) and longer muscle length training (24 ± 3 mm), the authors also found significant increases in the VL FL with short muscle length training (10 ± 2%). Moreover, the relative increases reported by the authors are much greater than those found in the present study (4.9 ± 2.0% for the FULL group). It should be noted, however, that the aforementioned studies (McMahon et al. 2014a, b) used an ecologically valid protocol (i.e., eccentric, isometric and concentric phases) and that the discrepancy between the two sets of results could arise from differences in these training protocols (combined isoinertial and isometric vs. pure isokinetic concentric). As mentioned previously, eccentric contractions lead to greater FL increments than do concentric contractions (Franchi et al. 2014). Therefore, the eccentric component of movement (lowering-phase) and the 2-s sustained contraction at the deepest joint angle (isometric phase) used by McMahon et al. (2014a, b) may have produced the differences in FL gains between the studies.

Further architectural adaptations included a significant increase in the VL PA in both training groups, with no significant effect of group (Fig. 2). According to our expectations and in agreement with previous literature evidence that a concentric stimulus tends to increase the amount of sarcomeres in parallel (Kawakami et al. 1995), a significant increase in the VL PA was observed in both the FULL (9.5 ± 2.4%, $P < 0.001$, $d_{av} = 0.9$) and PART (12.2 ± 2.4%, $P < 0.001$, $d_{av} = 1.0$) training groups, whereas no significant changes were observed in the control group. Our data show that an equal TUT also promotes similar PA increases between FULL and PART training, even when the fascicles are exposed to lower tension (PART). Because the fibers of pennate muscles rotate during contraction (Fukunaga et al. 1997), it is possible that when working with a shorter ROM the fascicles are mechanically stressed at greater pennation angles. This argument may justify, at least partly the slightly nonsignificant differences in VL PA observed between the PART and FULL groups, with respective values of 12.2 ± 2.4 and 9.5 ± 2.4%.

The second purpose of this work was to investigate the effect of PART training on mechanical determinants of the force-generating capacity. According to the evident adaptability of the force–length properties to specific functional demands (Herzog et al. 1991), it was hypothesized that PART training would provide a change in the torque–angle curve, i.e., a leftward shift of the optimal angle toward the trained ROM. This shift would mean that the muscle could become more functionally adapted to the trained ROM, being able to apply higher force in the critical ROM for performance. Our findings partially support this hypothesis, as although the angle of peak torque did not change after PART ROM training, there was a slight indication of angular specificity of the training in both the FULL and PART groups. The moderate to large effect size for the relative changes at 30°, 40°, 50°, and 60° confirms a solid effect of PART training ($0.6 < d_{av} > 1.1$). Similar findings had already been reported for knee extensor muscles in a study (Graves et al. 1989) that compared the effect of full extension exercises (0°–120° of knee flexion) and two partial ROM exercises (60°–120° and 60°–0° of knee flexion), with greater improvements in isometric strength for the groups with limited ROM training. Other authors have also reported this angular specificity of training (Bloomquist et al. 2013; Clark et al. 2008; Massey et al. 2005; McMahon et al. 2014a; Pinto et al. 2012). As mentioned, a decrease in the training ROM allows a higher load (> full ROM 1-RM); however, minor adaptations to the untrained angles are expected. Our results showed no relevant constraints on the use of partial concentric ROM training, suggesting that this training could be a complementary component to free-weight exercises to promote improvements in sport-related tasks. However, we would like to emphasize that in the present study, the specific tension only increased significantly in response to the muscle excursion range used in the FULL group. To our knowledge, such a result has not been reported previously. Although increases in specific tension after high-intensity resistance training have been reported previously (Erskine et al. 2010; Reeves et al. 2004), this is the first study reporting differential adaptations to full vs. partial ROM. As PART ROM training-induced changes in the VL PCSA (7.8%) and fascicle force (20.2%), the VL specific tension remained unchanged in the PART group. Conversely, because FULL training increased both the FL and muscle volume (4.9 and 7.6% increase, respectively), the PCSA remained unchanged in the FULL group. Consequently, FULL training induced an increase in the VL specific tension (i.e., maximum muscle force per PCSA), as a result of a disproportionate increase in the fascicle force relative to the PCSA (29.7 and 2.5% increase, respectively). This discrepancy between the increase in muscle strength and size often reported following resistance training (Erskine et al. 2010) is commonly explained by the neural adaptations being greater than the muscle hypertrophy (Staron et al. 1994). However, the voluntary quadriceps muscle activation in the FULL group increased only 1.8% (nonsignificant, Table 4), which is quite similar to previous reports of increased muscle activation after resistance training (Erskine et al. 2010; Reeves et al. 2004). Furthermore, although there was a trend toward decreases, there was no significant change in the level of antagonist muscle coactivation following training (− 16%, without statistical significance, Table 4). Therefore, correcting MVC for voluntary muscle activation, antagonist muscle coactivation and d_{PT} (which remained unchanged after training) gave a 27.8% increase in the maximal quadriceps force (Table 4), thus demonstrating that training-induced changes in voluntary activation, coactivation and d_{PT} contributed little (4.2%) to the increase in MVC torque. Although we cannot deduce the source for the VL specific tension increase in the FULL group from the present results, some explanations have been presented as being able to cause the change in whole-muscle specific tension (Erskine et al. 2010). Among the factors that may explain this phenomenon are the increase in the number of thick myofilaments per unit area (packing density) (Pansarasa et al. 2009), a change in muscle fiber-type composition and/or preferential muscle fiber hypertrophy of type II fibers (Campos et al. 2002), and/or a possible change in the quality of attachment between the contractile muscle fibers and the surrounding connective tissue through which force is transmitted to tendons and bones (Erskine et al. 2010).

Given the within-subject design of our study, we cannot rule out the possibility that either of the protocols exerted contralateral effects. Although, to our knowledge, there has been no attempt to quantify this effect when both limbs are trained with different protocols, we have had some findings suggesting that the cross-education effect may have been minimal or non-existent in our study: (1st) we found a correlation between muscle volume and force gains ($r=0.55$, $P=0.002$); (2nd) no correlations were observed between muscle forces gains in FULL and PART legs ($r=0.41$, NS); and (3rd) the training-induced changes in voluntary activation and antagonist coactivation were minimal and contributed little to the increase in muscle force. These points suggest that if such a phenomenon did in fact occur, it was not sufficient to counteract the specific loading effects of our protocols.

Conclusions

Resistance training exercise ROM is frequently manipulated to reach specific training goals and obtain gains that can better transfer to sport movements. The results of the present study have highlighted that when the muscle is subjected to equalized isokinetic concentric training, similar increases in muscle size and maximal strength can be expected between full and partial ROM training. Partial ROM exercises have shown joint angle-specific gains in strength, with greater relative increases around the trained joint angles. This finding means that as long as the number of repetitions is increased, the training routines can emphasize specificity by decreasing the ROM to that required for the sport tasks without compromising the strength and muscle mass gains. Likewise, partial ROM training can also be selectively prescribed in rehabilitation to improve strength and muscle hypertrophy in patients with articular limitation or muscle atrophy.

However, we have shown that even when equalizing the TUT between FULL and PART training, the use of full ROM exercises has greater benefits to overall strength gains (i.e., along the entire ROM), with quite good transfers to partial ROM strength. Moreover, the adherence to a greater ROM is also a determinant of crucial architectural and mechanical muscle adaptations. Our findings have shown that to increase the FL and the specific tension, training with an ROM greater than the ROM normally used in daily activities or sport tasks is required. Since the muscle FL has a critical role in the muscle shortening velocity, allowing rapid and powerful muscle actions, the full ROM should be privileged in the training of athletes of explosive sports. The reason for the increase in specific tension after FULL training remains unknown but it is possible that this type of training may cause a change in the muscle fiber-type composition or an increase in the lateral force transmission between muscle fibers and connective tissue.

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Author contributions MJV, APV and PM-H conceived and designed research. MJV, FT and RMS conducted experiments. MJV and PM-H analyzed data. MJV wrote the manuscript. All authors read and approved the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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