Research Square

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Muscle architecture and voluntary torque of lower-limb muscles in recreational long-distance runners: a comparison with non-training individuals

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Abstract

Background: Evidence regarding lower-limb muscle architecture in recreational long-distance runners remains inconclusive, largely because previous studies relied on conventional ultrasonography, which estimates rather than directly visualizes muscle fascicles. Extended-field-of-view (EFOV) ultrasonography enables more accurate assessment of muscle architecture and may improve the detection of chronic training-induced adaptations.

Methods: Fourteen male recreational long-distance runners (37 ± 7 years) and thirteen untrained men (29 ± 8 years) underwent EFOV ultrasonographic assessment of the vastus lateralis (VL) and medial gastrocnemius (GM). Fascicle length (FL) and anatomical cross-sectional area (CSA) were normalized to muscle length and body mass, respectively. Maximal voluntary isometric torque and concentric and eccentric peak torque during knee extension and plantar flexion were assessed using an isokinetic dynamometer.

Results: Recreational runners exhibited significantly greater normalized VL fascicle length than controls (approximately 14%; $P < 0.001$), whereas no between-group differences were observed for GM architecture or any isometric or dynamic torque variable ($P > 0.05$). Normalized VL CSA did not differ significantly between groups ($P = 0.172$).

Conclusion: Recreational long-distance runners exhibited longer VL fascicles than untrained men, without corresponding differences in GM architecture, muscle CSA, or maximal voluntary torque. These findings indicate muscle-specific architectural differences that are not necessarily accompanied by greater maximal torque.

INTRODUCTION

Long-distance running is among the most widely practiced endurance activities worldwide and is associated with numerous health and performance benefits [1]. Repeated exposure to cyclic mechanical loading imposes substantial demands on the lower-limb muscles, particularly the knee extensors and ankle plantar flexors, which play essential roles in shock absorption, body support, and propulsion during running [2, 3]. Over time, these repetitive loading patterns may induce structural adaptations within skeletal muscle [4].

Muscle architecture, particularly fascicle length (FL) and cross-sectional area (CSA), is recognized as an important determinant of muscle function because it influences force-generating capacity, shortening velocity, and operating range [5]. Consequently, chronic sport-specific loading has the potential to modify muscle architecture according to the mechanical demands imposed by different training modalities [6]. Understanding these adaptations may provide insight into the mechanisms underlying long-term neuromuscular adaptations to endurance running.

Despite considerable interest in running biomechanics, relatively few studies have investigated muscle architecture in recreational long-distance runners, and the available evidence remains inconsistent. Abe et al. [7] reported that elite sprinters exhibited longer fascicles than long-distance runners and untrained controls, whereas Karamanidis and Arampatzis [8] observed no significant differences in FL or muscle thickness between recreational runners and sedentary individuals. One possible explanation for these discrepancies is the use of conventional single-image ultrasound methods, which rely on geometric extrapolation and may underestimate fascicle length, particularly in muscles with curved fascicles.

In this context, muscle architecture is commonly assessed in vivo using B-mode ultrasonography, a non-invasive and reliable technique for quantifying parameters such as FL and CSA [9–11]. The use of extended-field-of-view (EFOV) ultrasound further enhances measurement accuracy by minimizing geometric assumptions and enabling direct visualization of entire muscle fascicles, thereby facilitating the detection of subtle architectural changes in physically active populations [12, 13]. Importantly, muscle architectural properties are strongly associated with torque-generating capacity at the knee and ankle joints, which are fundamental to shock absorption and propulsion during running [14]

In addition to morphological adaptations, endurance training may influence torque-generating capacity [15]. Sport-specific shifts in torque–angle relationships have been reported in several athletic populations [15, 16], suggesting that chronic exposure to particular movement patterns can alter neuromuscular function. However, whether the architectural characteristics of recreational long-distance runners are accompanied by differences in maximal voluntary torque remains unclear.

Therefore, the purpose of this study was to compare VL and GM architecture, assessed by EFOV ultrasonography, and maximal voluntary torque during knee extension and plantar flexion between recreational long-distance runners and untrained controls. We hypothesized that long-term endurance participation would be associated with muscle-specific architectural adaptations and altered torque characteristics relative to untrained individuals.

METHODS

Participants

Fourteen male recreational long-distance runners (37 ± 7 years, 1.74 ± 0.07 m, 69.9 ± 7.5 kg) and 13 untrained men (29 ± 8 years, 1.70 ± 0.10 m, 66.9 ± 11.8 kg) volunteered for this study. The sample size was determined a priori using G*Power 3.1.9.7 based on the effect size reported by Abe et al. for VL FL differences between runners and controls. Recreational runners included 10 marathon and four half-marathon athletes with more than 10 years of regular endurance training. Controls had not participated in structured physical activity during the previous six months. Exclusion criteria were musculoskeletal injury within the previous six months, use of ergogenic aids, inability to complete testing procedures, positive responses on the Physical Activity Readiness Questionnaire, and a forefoot strike pattern in the runner group. This study was approved by the scientific and ethics committee of the Clementino Fraga

Filho Hospital of the Federal University of Rio de Janeiro, Brazil, number: 52018721.1.0000.5257. All procedures conformed to the standards of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to their inclusion in the study, including consent for participation in the research study and publication of their anonymized data.

Experimental design

Data collection was conducted over two separate days. During the first day, participants underwent anthropometric assessment, ultrasound imaging, maximum isometric contraction tests, and familiarization procedures for dynamic torque evaluation. In the second day, dynamic torque tests were performed by both long-distance runners and control groups.

Ultrasound image acquisition

An experienced examiner utilized B-mode ultrasound (US) (Logic-e, GE Healthcare, USA) operating at a frequency of 10 MHz with a gain of 60 dB, ensuring optimal acoustic coupling with the skin using water-based gel, selected to optimize spatial resolution in superficial muscles. Ultrasound image acquisition procedures followed the protocol proposed by Halmenschlager et al., (2025) [12]. For the VL markings, participants were initially placed in an orthostatic position and subsequently repositioned in the supine posture. The VL length was marked from the midpoint between the lateral femoral epicondyle and the greater trochanter of the femur, allowing the identification of proximal and distal myotendinous junctions [11]. Lengths corresponding to 30%, 50%, and 70% of the VL were measured in the proximal-distal direction (Figure. 1). Similarly, for GM US acquisitions, participants were positioned prone for marking [13], with muscle lengths measured at 30%, 50%, and 70% in the proximal-distal direction (Fig. 1). Transverse orientation at the 50% muscle length enabled the identification for both VL and GM aponeuroses [10], marked for subsequent reference (Fig. 1). Micropore tape markers were placed at predetermined lengths to aid in succeeding ultrasound image identification for both protocols (Fig. 2). During ultrasound image acquisition, the EFOV ultrasound involved continuous transducer movement along the muscle.

Figure 1. Reference landmarks for the acquisition of extended-field-of-view ultrasonographic images of the vastus lateralis (VL) and medial gastrocnemius (GM).

#Insert Fig. 1#

The FL was estimated following the visible fascicle path (not a straight line), and muscle length was measured from the myotendinous junction to the most proximal aponeurosis, allowing normalization. The FL was measured at distances corresponding to 30–50% and 50–70%, proximal and distal, respectively, in both muscles (Fig. 2). The CSA was obtained via EFOV ultrasound at 50% of muscle length (Fig. 2), aided by custom-made rubber molds positioned below the second reference line of the muscles. Two ultrasound images were acquired for FL and CSA measurement of each muscle, with the

average used for successive statistical analysis. Post-acquisition, image analysis was performed using ImageJ 64 software (National Institutes of Health, USA, version 1.53). Muscle architecture parameters were normalized post-processing, with CSA (cm^2) normalized by body mass (kg) and FL of VL and GM by each muscle length (cm).

Figure 2. Extended-field-of-view ultrasonography with the delineations used to measure the anatomical cross-sectional area (ACSA) and fascicle length (FL) of the vastus lateralis muscle (images acquired at 50% and from 50% to 70% of the distal region of interest, respectively).

#Insert Fig. 2#

Knee extension and ankle plantar flexors torque acquisition

Maximal voluntary isometric contractions (MVIC) tests were conducted during the first visit at 70° of knee flexion and neutral ankle position (90°), with two 5-s trials separated by 2 min rest. The highest peak torque was retained [17, 18]. Consistent verbal encouragement was provided during all tests.

During the second visit, participants performed concentric and eccentric contractions following a standardized warm-up. Knee extension was assessed at 60°/s and 240°/s, while plantar flexion was assessed at 60°/s only [19, 20]. Torque signals were sampled at 100 Hz, filtered with a second-order Butterworth low-pass filter (10 Hz), and normalized by body mass. Peak torque values and corresponding joint angles were extracted using custom MATLAB routines (The MathWorks Inc., version 9.14.0 (R2023a), Natick, Massachusetts, USA)

Statistical analysis

The inter-day reliability of maximal voluntary isometric peak torque (IPT) and ultrasound measurements were assessed using the intraclass correlation coefficient (ICC) and the percentual coefficient of variation. The ICC values were calculated with a two-way mixed-effects model and an absolute agreement definition, interpreted by thresholds [21]. Mean and standard deviation (mean ± SD) described the data, with the Shapiro-Wilk test assessing normality, and the unpaired Student's t-test or Mann-Whitney test were used for the comparisons between groups. The analysis of all data was implemented in GraphPad Prism (v 9.2.0.332; 2021), and the level of significance was set at $p \leq 0.05$. The effect size (ES) was determined between groups as Cohen`s (d), 0.2, 0.5, and 0.8 were considered as small, medium, and large, respectively, as described by Cohen [22].

RESULTS

Reliability analyses demonstrated excellent reproducibility for ultrasound and torque measurements (ICC range: 0.876–0.997; coefficient of variation ≤ 3.98%). Normalized VL fascicle length was significantly greater in runners than in controls in both the proximal and distal regions ($P < 0.001$), corresponding to

approximately 14% higher values. No significant between-group differences were observed for GM fascicle length, VL or GM CSA, or any torque variable ($P > 0.186$).

Figure 3. Comparison of normalized muscle architecture parameters between runners and control group (CG). (A) Vastus lateralis (VL) fascicle length (FL) at proximal and distal regions. (B) Medial gastrocnemius (GM) FL at proximal and distal regions. (C) VL anatomical cross-sectional area (ACSA). (D) GM ACSA. Values are presented as mean ± SD. *Significant difference between groups.

#Insert Fig. 3#

No significant differences were detected between groups for any normalized isometric, concentric, or eccentric torque variable during knee extension or plantar flexion ($p > 0.05$). Moderate effect sizes were observed for some plantar flexion measures, but these did not reach statistical significance (Table 1).

Table 1
Isometric peak torque, concentric and eccentric peak torque and peak torque angle of the knee extensor muscles and ankle plantar flexor muscles at a speed of 60°/s and 240°/s (only for knee extension).

	Torque parameter	Runners	CG	P value	Cohen`s ES (*d*)
Knee extension	NMVIC (Nm/kg)	3.78 ± 0.71	3.54 ± 0.55	0.420	0.38
	$NDPT_{conc}$ 60°/sec (Nm/kg)	2.78 ± 0.43	2.57 ± 0.45	0.295	0.47
	$NDPT_{exc}$ 60°/sec (Nm/kg)	3.68 ± 0.62	3.62 ± 0.67	0.846	0.09
	$NDPT_{conc}$ 240°/sec (Nm/kg)	1.90 ± 0.40	1.89 ± 0.28	0.843	0.03
	$NDPT_{exc}$ 240°/sec (Nm/kg)	3.28 ± 0.37	3.15 ± 0.51	0.903	0.28
	$PTAd_{conc}$ (°)	74.54 ± 11.10	73.86 ± 16.19	0.801	0.05
	PTA_{exc} (°)	54.77 ± 14.01	51.57 ± 9.36	0.984	0.27
Plantar flexion	NMVIC (Nm/kg)	2.29 ± 0.30	2.37 ± 0.34	0.592	0.23
	$NDPT_{conc}$ 60°/sec (Nm/kg)	3.01 ± 0.39	3.27 ± 0.50	0.186	0.58
	$NDPT_{exc}$ 60°/sec (Nm/kg)	3.52 ± 0.49	3.79 ± 0.51	0.237	0.53
	$PTAd_{conc}$ (°)	-15.29 ± 1.33	-16.13 ± 1.36	0.326	0.63
	PTA_{exc} (°)	-14.93 ± 0.73	-14.75 ± 0.46	0.411	0.29

#Insert Table 1#

DISCUSSION

The study aimed to compare the muscle architecture of the VL and GM, as well as torque production during knee extension and plantar flexion, between recreational long-distance runners and untrained individuals (control group). The present findings show structural differences in resting muscle architecture between groups. However, as this was a cross-sectional design, these results should be interpreted with caution.

Our main findings revealed that the normalized VL FL was significantly greater in long-distance runners than in the CG ($P < 0.001$), contradicting our initial hypothesis. Although the normalized VL CSA did not differ significantly between groups ($P = 0.172$), the large effect size ($d = 0.80$) was noteworthy. No significant differences in GM architecture were found between groups, although a medium effect size was observed for GM CSA ($d = 0.64$). Furthermore, no significant differences were observed between groups in knee extension and plantar flexion torque parameters.

The greater VL FL observed in runners may reflect long-term adaptations to the specific mechanical demands of running. Rearfoot strikers can experience ground reaction forces up to 2.5 times their body weight during the stance phase [23], requiring substantial eccentric action from the knee extensors. Such loading patterns have been associated with chronic morphological adaptations [2, 24]. Repeated eccentric stress during running could stimulate increases in FL, as supported by previous research [24–26]. Longer fascicle may enhance muscle shortening velocity and functional operating range, however, similar CSA and torque production may indicate that neural or architectural adaptations do not necessarily translate into greater voluntary torque under isometric testing conditions. Although no statistically significant difference in VL CSA was detected between runners and the CG, the large effect size ($d = 0.64$) may indicate a secondary adaptation of the muscle to the increase in FL, consistent with adaptations reported following eccentric training protocols [24].

Only a limited number of studies have investigated muscle architecture parameters in long-distance runners [7, 8]. Abe et al., (2000) [7] observed no significant difference in GM FL, supporting our findings. However, they reported a shorter VL FL among elite long-distance runners, whereas our results based on recreational runners with over 10 years of experience showed longer VL FL. Nevertheless, our findings are consistent with those of Karamanidis & Arampatzis, (2006) [8] who also observed no significant differences in GM FL between young recreational runners and a CG of adults. One potential explanation for the discrepancies between our study and that of Abe et al., (2000) [7] may involve methodological differences in ultrasound imaging techniques. While we used the EFOV to directly assess both FL and CSA, Abe et al., (2000) [7] employed a single-image method with trigonometric estimations, which can introduce errors of up to 14% compared to EFOV [11]. These methodological differences could explain the different results across studies [7]. Additionally, fascicle curvature, particularly in the muscles examined at rest, is well-documented and may not be fully captured by single-image approaches [27]. Another important consideration is that muscle adaptation is non-linear [28, 29], and the anatomical regions analyzed in studies by Abe et al., (2000) and Karamanidis & Arampatzis, (2006) [7, 8] differ from those examined in our study.

In addition, we used EFOV ultrasound imaging to evaluate muscle CSA, which is a key indicator of muscle hypertrophy and strength. Although the statistical analysis did not reveal a significant difference in VL CSA between the groups ($p = 0.172$), the large effect size observed ($d = 0.8$) suggests a trend toward increased CSA in runners. This trend is noteworthy given the chronic mechanical loading associated with running and may reflect the adjustment of the muscle to the increase in FL. The use of EFOV imaging in this study enhanced our ability to detect subtle, yet morphologically meaningful,

changes in muscle architecture that might go missed with less sensitive methods. These findings highlight the importance of considering both statistical and practical significance when interpreting muscle architecture data.

The absence of significant differences in torque production between runners and non-runners deserves further consideration into the specific strength adaptations elicited by long-distance running. It appears that the relatively low intensity and submaximal nature of muscle contraction during running may not provide sufficient neuromuscular stimulus to markedly enhance maximal voluntary torque. Furthermore, morphological adaptations induced by running may not transfer effectively to the isolated and controlled conditions under which torque was measured in this study. This observation is consistent with the findings of Karamanidis & Arampatzis, (2006) [8] who also reported no significant differences in maximal voluntary knee extension and plantar flexion torque between recreational runners and controls. In the present study, normalized peak plantar flexion torque did not reach statistical significance ($p > 0.186$), which aligns with findings by Kubo et al., (2010) [30]. All data were normalized to account for differences in participant height and muscle size across groups.

We hypothesized that runners would exhibit higher peak isometric and dynamic torque during knee extension and plantar flexion due to the repeated torque production at specific joint angles involved in running. However, this hypothesis was not supported by our findings. Although no statistically significant differences were observed, the effect size for $PTAd_{conc}$ was considered medium ($d = 0.63$), with the CG showing a lower plantar flexion angle. Additionally, the control group exhibited larger effect sizes than runners for peak plantar flexor torque during both concentric ($d = 0.58$) and eccentric ($d = 0.53$) contractions, consistent with the findings of [20].

Sport-specific torque adaptations have been documented in various athletic populations, such as volleyball players versus ballet dancers [16] or runners versus cyclists [15], in which strength gains tend to occur at joint angles that reflect the specific mechanical demands of their respective sports [31, 32]. The specificity of these adaptations likely explains the absence of significant torque differences in our study, suggesting that the neuromuscular responses to long-distance running are highly task-specific and may not translate to generalized strength assessments.

Further research should incorporate direct assessments of additional muscle and tendon properties, alongside muscle architecture, to provide a more comprehensive understanding of the adaptations associated with recreational long-distance running. Only resting parameters were evaluated, which limits inferences about dynamic muscle behavior. Ultrasound provides reliable but localized estimates of architecture, and future research using DTI-MRI or 3D US could provide more comprehensive insights. Additionally, isokinetic testing of the plantar flexors at 240°/s was excluded due to limitations in the range of motion, which compromised measurement accuracy. Another limitation of this study is the absence of a prospective power analysis, which may have affected the ability to detect smaller effects. Although moderate effect sizes were observed for certain parameters, the limited sample size likely

reduced the statistical power. Future studies involving larger cohorts are recommended to validate and confirm these findings.

CONCLUSION

In conclusion, recreational long-distance runners exhibited longer FL in the VL compared with untrained controls, without differences in muscle CSA or torque capacity. These results suggest that chronic endurance participation may be associated with structural variations rather than clear functional differences, although causal relationships cannot be inferred due to the cross-sectional nature of this study. These findings suggest that health professionals, particularly those specializing in sports biomechanics, should take muscle architecture adaptations into account when designing training programs for recreational runners. The use of advanced imaging techniques, such as EFOV ultrasound, enhances the ability to detect subtle yet functionally meaningful changes that may affect performance or injury prevention.

Declarations

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The authors used ChatGPT (OpenAI) solely for language editing and proofreading during the preparation of the manuscript. The authors reviewed and edited all AI-assisted text and took full responsibility for the content of the manuscript.

Statements and Declarations

Author Contributions
Eugenio B. Bacchin: Investigation, Data curation, Formal analysis, Visualization, Writing – original draft. Liliam F. Oliveira: Conceptualization, Methodology, Supervision, Writing – review & editing. Thiago T. Matta: Conceptualization, Methodology, Formal analysis, Supervision, Project administration, Writing – review & editing. All authors read and approved the final version of the manuscript.

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Competing Interests
The authors declare that they have no conflicts of interest related to this study.

Ethical Approval
The study was approved by the Research Ethics Committee of Clementino Fraga Filho University Hospital, Federal University of Rio de Janeiro (protocol No. 52018721.1.0000.5257). All procedures were conducted in accordance with the Declaration of Helsinki.

Consent to Participate
Informed consent was obtained from all participants prior to their inclusion in the study, as described in the appropriate section of the manuscript.

Data Availability
The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Normalized maximal voluntary isometric contraction (NMVIC), normalized peak torque during concentric contraction ($NDPT_{conc}$), normalized peak torque during eccentric contraction ($NDPT_{exc}$), angle of peak torque during concentric contraction ($PTAd_{conc}$), and angle of peak torque during eccentric contraction (PTA_{exc}). NMVIC – Negative values correspond to dorsiflexion position, $NDPT_{conc}$ and $NDPT_{conc}$ were normalized by body mass (kg), and Cohen`s effect size (*d*).

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Figures

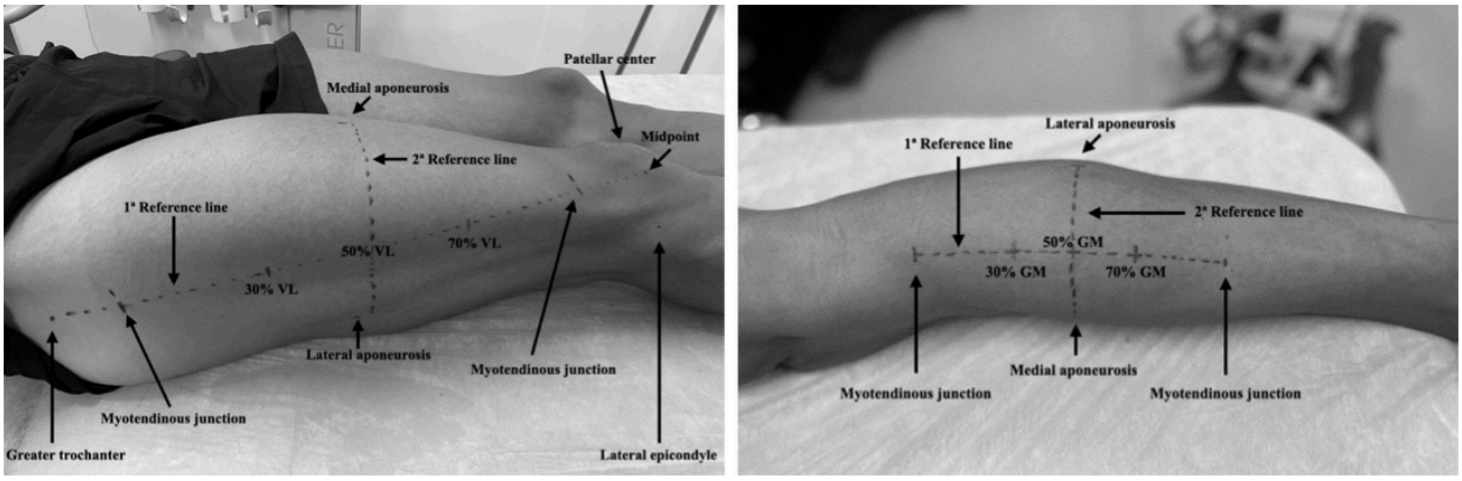


Figure 1

Reference landmarks for the acquisition of extended-field-of-view ultrasonographic images of the vastus lateralis (VL) and medial gastrocnemius (GM).

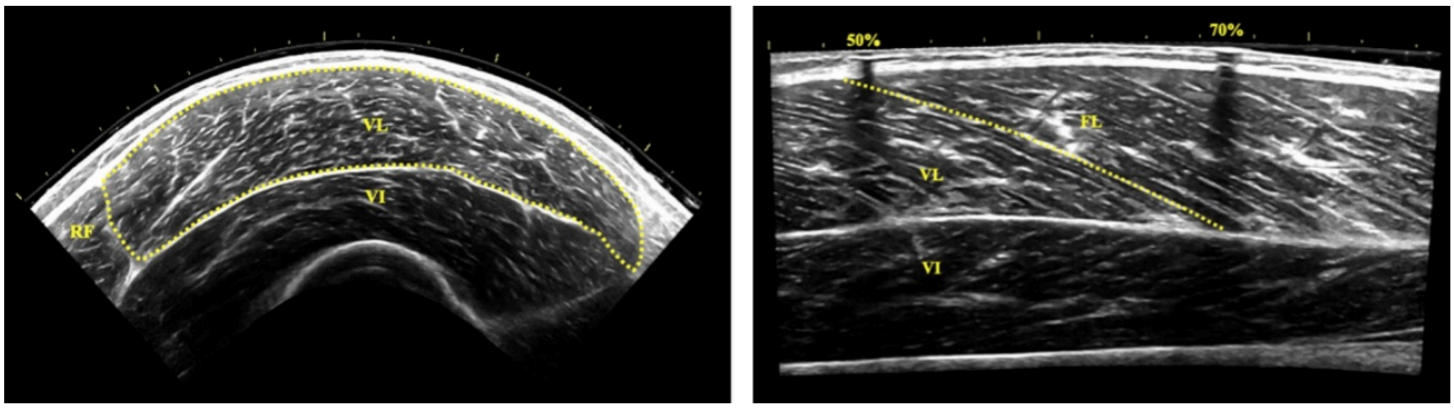


Figure 2

Extended-field-of-view ultrasonography with the delineations used to measure the anatomical cross-sectional area (ACSA) and fascicle length (FL) of the vastus lateralis muscle (images acquired at 50% and from 50% to 70% of the distal region of interest, respectively).

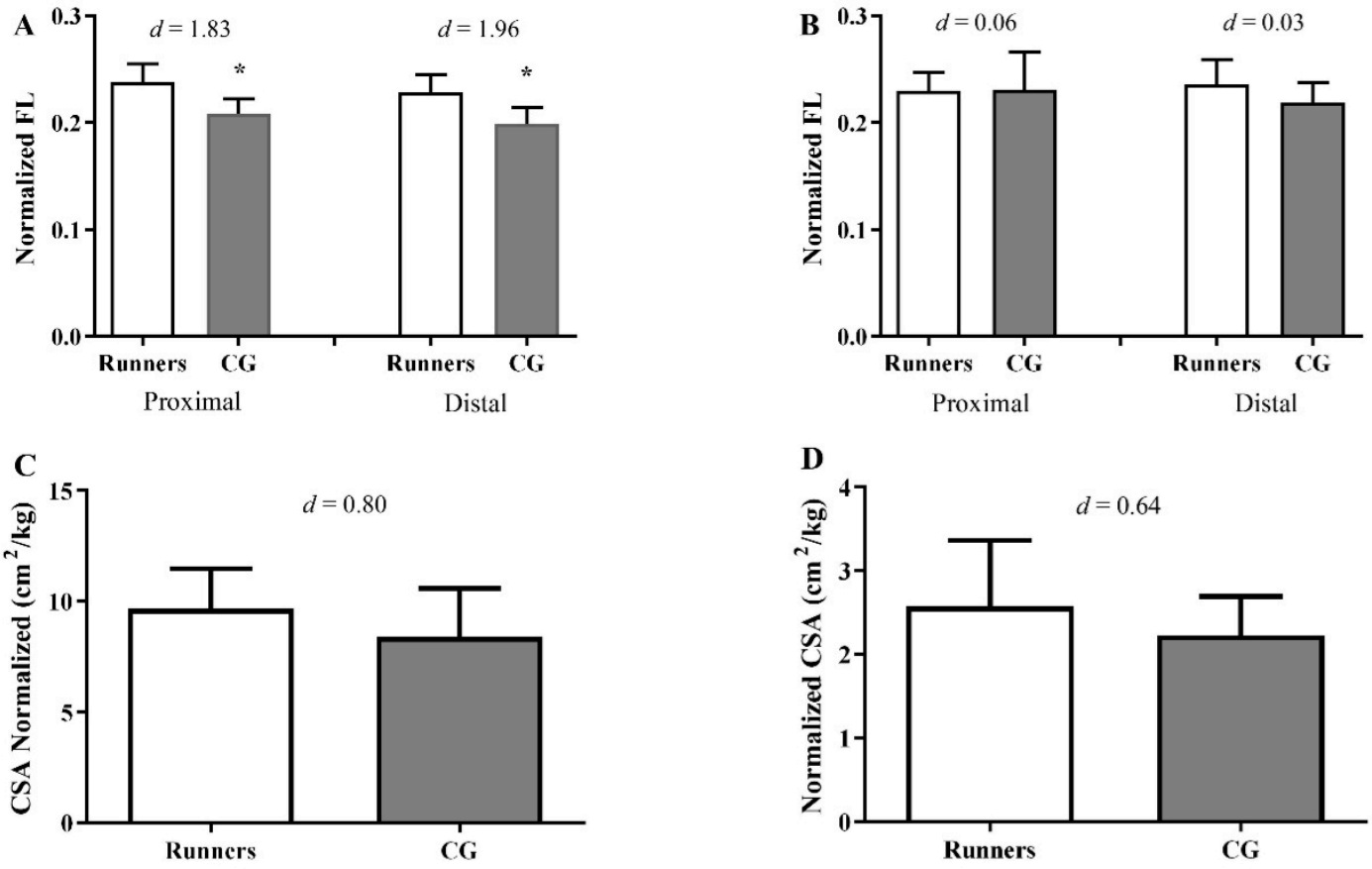


Figure 3

Comparison of normalized muscle architecture parameters between runners and control group (CG). (A) Vastus lateralis (VL) fascicle length (FL) at proximal and distal regions. (B) Medial gastrocnemius (GM) FL at proximal and distal regions. (C) VL anatomical cross-sectional area (ACSA). (D) GM ACSA. Values are presented as mean ± SD. *Significant difference between groups.