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Which regions of the quadriceps femoris muscle thickness best predict muscle strength?

Quais regiões da espessura muscular do quadríceps femoral melhor predizem a força muscular?

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Abstract – The study aimed to investigate the associations between regional muscle thickness (MT) of the rectus femoris (RF) and vastus lateralis (VL) and muscle strength during leg press and knee extension exercises. Twenty-eight men (23 ± 5 years) participated in this cross-sectional study. MT was assessed using ultrasound at the proximal (1/3), middle (1/2), and distal (2/3) regions between the anterior superior iliac spine and the superior border of the patella over the RF muscle, with lateral projection onto the VL. Maximum isotonic muscle strength was assessed using one-repetition maximum (1RM) tests in the leg press and knee extension exercises. Moderate, positive, and statistically significant correlations were observed for most comparisons ($r = 0.408$-0.655, $P < 0.05$), except for the association between leg press 1RM and distal RF MT, which was weak and not statistically significant ($r = 0.366$, $P = 0.056$). Multiple regression analyses indicated that proximal RF and VL MTs explained a greater proportion of the variance in leg press strength ($R^2 = 0.421$, $P < 0.01$), whereas proximal and distal VL MTs explained a greater proportion of the variance in knee extension strength ($R^2 = 0.511$, $P < 0.01$). These findings suggest that regional quadriceps femoris MTs are differentially associated with strength performance depending on the exercise performed in young men. Proximal RF and VL regions best predicted leg press strength, whereas VL thicknesses, particularly at the proximal and distal regions, were more strongly associated with knee extension strength.

Key words: Lower extremity; Musculoskeletal system; Ultrasonography.

Resumo – *O objetivo do estudo foi investigar as associações entre a espessura muscular (EM) regional do reto femoral (RF) e do vasto lateral (VL) e a força muscular nos exercícios de leg press e cadeira extensora. Vinte e oito homens (23 ± 5 anos) participaram deste estudo transversal. A EM foi avaliada por ultrassonografia nas regiões proximal, média e distal entre a espinha ilíaca anterossuperior e a borda superior da patela sobre o músculo RF, com projeção lateral sobre o VL. A força muscular foi avaliada por meio de testes de uma repetição máxima (1RM). Correlações moderadas e significativas foram observadas para a maioria das comparações ($r = 0{,}408$–$0{,}655$; $P < 0{,}05$), exceto para a associação entre o 1RM no leg press e a EM distal do RF, que foi fraca e não significativa ($r = 0{,}366$; $P = 0{,}056$). Análises de regressão múltipla indicaram que as EMs proximais do RF e do VL explicaram uma proporção maior da variância da força no leg press ($R^2 = 0{,}421$; $P < 0{,}01$), enquanto as EMs proximal e distal do VL explicaram uma proporção maior da variância da força na cadeira extensora ($R^2 = 0{,}511$; $P < 0{,}01$). Esses achados sugerem que as EMs regionais do quadríceps femoral estão associadas de forma diferencial ao desempenho de força. As regiões proximais do RF e do VL predisseram melhor a força no leg press, enquanto as espessuras do VL, particularmente nas regiões proximal e distal, apresentaram uma associação mais forte com a força na cadeira extensora.*

Palavras-chave: *Extremidade inferior; Sistema musculoesquelético; Ultrassonografia.*

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INTRODUCTION

Resistance training is widely recognized for promoting morphological adaptations in skeletal muscle, including regional variations in muscle thickness (MT) along the same muscle or muscle group[1]. Several studies have demonstrated regional hypertrophy of the quadriceps femoris (QF), with distinct adaptations between the proximal, middle, and distal regions of MT[2,3]. These findings suggest that regional muscle architecture may influence strength-generating capacity.

Exercise selection, particularly the use of single- versus multi-joint movements, is a key determinant of regional hypertrophy within the QF[4]. Burke et al.[5] reported that the knee extension exercise elicited greater increases in rectus femoris (RF) MT compared with the leg press (8.9% vs. 4.7%), whereas the leg press induced greater MT increases in the vastus lateralis (VL) than the knee extension (8.7% vs. 2.9%). Despite this, most investigations have focused on chronic adaptations[6,7], and the acute relationship between regional quadriceps morphology and dynamic muscle strength during different exercises remains poorly understood.

Oranchuk et al.[8] examined the association between QF MT and isometric knee extension strength at different joint angles and reported stronger correlations for VL MT than for RF MT. Similar findings have been reported in studies examining the relationship between muscle mass and isometric knee extension strength[9,10]. However, although dynamic resistance training performed on the knee extension machine appears to preferentially induce RF hypertrophy[11,12], correlations derived from isometric assessments may not adequately reflect strength performance during dynamic contractions. Consequently, uncertainties persist regarding how regional MT contributes to strength production in multi- and single-joint resistance exercises.

Ultrasound-based assessment of QF MT is a valid alternative to magnetic resonance imaging[13] and demonstrates high intra-[14] and inter-rater reliability[15]. Nevertheless, a more detailed understanding of the relationship between regional MT and muscle strength across different resistance exercises is needed to improve exercise prescription and to identify individual predispositions for strength development and hypertrophic responses.

Therefore, the purpose of this study was to investigate the associations between MT of the RF and VL (proximal, middle, and distal regions) and maximal isotonic muscle strength during leg press and knee extension exercises in young men. Additionally, this study aimed to determine which regional MT variables best predicted and explained part of the variance in muscle strength. It was hypothesized that regional MT would exhibit significant, moderate correlations with strength, particularly in the middle and distal regions of the VL. The findings may provide insights into the relevance of regional MT assessment in explaining part of the variance in strength performance and in guiding individualized resistance training interventions for the lower limbs.

METHODS

Sample

The sample consisted of 28 male university students, aged 23 ± 5 years, with a body mass of 74.3 ± 9.4 kg, a height of 176.6 ± 6.3 cm, and a body mass index (BMI) of 23.8 ± 2.5 kg/m^2. For inclusion in the study, participants had to be between 18 and 35 years old, have a BMI of less than 30 kg/m^2, be physically active, have no restrictions on the practice of physical exercise, have prior experience with resistance training, but not be in regular practice in the last six months. Individuals with a history of lower limb injuries or who had used ergogenic aids in the last twelve months were excluded. Eligibility was verified through body mass and height measurements for BMI calculation and by applying the Physical Activity Readiness Questionnaire (PAR-Q) and the International Physical Activity Questionnaire (IPAQ).

All participants were informed about the study procedures and provided written informed consent in accordance with the Declaration of Helsinki and Resolution 466/2012 of the Brazilian National Health Council. The study was approved by the Research Ethics Committee of Pedro Ernesto University Hospital, Rio de Janeiro State University (protocol no. 6.250.363).

Study design

This observational, cross-sectional, exploratory study was conducted over three laboratory visits separated by one week. During the first visit, participants underwent screening procedures, including completion of the PAR-Q[16] and IPAQ[17], as well as measurement of body mass and height according to the International Society for the Advancement of Kinanthropometry guidelines[18]. Following this, the volunteers were familiarized with the leg press and knee extension exercises. During the second visit, ultrasound measurements of QF MT and maximal strength assessments on both machines were performed. During the third visit, all measurements were repeated to assess variability and consistency, allowing calculation of the coefficient of variation (CV) and intraclass correlation coefficient (ICC).

Procedures

Participants rested in the supine position for five minutes to stabilize intramuscular fluid before MT assessment. Anatomical landmarks were identified at the proximal (1/3), middle (1/2), and distal (2/3) portions of the distance between the anterior superior iliac spine and the superior border of the patella. These points were projected laterally to acquire ultrasound images of the RF and VL.

An ultrasound device (GE LOGIQ e, General Electric Healthcare, Chicago, IL, USA) was used in B-mode, with a 38 mm 12L-RS linear transducer, 10 MHz frequency, 80 dB gain, and 80 mm image depth. The transducer was positioned transversely to the thigh, over the marked points, with the aid of a conductive gel and applying minimal pressure to avoid tissue deformation. The images were analyzed using ImageJ software, version 1.53 (National Institutes of Health, Bethesda, MD, USA). MT was determined by the vertical distance between the superficial and deep fascia of each muscle region. The variability and consistency values of the intra-rater muscle measurements were as follows: $RF_{Proximal}$: CV = 1.8% and ICC = 0.959, RF_{Middle}: CV = 1.5% and ICC = 0.980, RF_{Distal}: CV = 1.9% and ICC = 0.984, $VL_{Proximal}$: CV = 1.4% and ICC = 0.984, VL_{Middle}: CV = 1.4% and ICC = 0.986, VL_{Distal}: CV = 1.7% and ICC = 0.980. Accordingly, the MT measurements showed low variability and high consistency[19].

Maximal muscle strength was assessed using one-repetition maximum (1RM) tests on the leg press and knee extension machines. The protocol consisted of a three-minute general warm-up on a cycle ergometer, followed by two specific warm-up sets (eight repetitions at 50% and three repetitions at 70% of estimated 1RM). After three minutes of rest, participants performed successive 1RM attempts with three-minute rest intervals until concentric failure occurred before completing a second repetition. During testing, the knees were initially positioned at 90º. The movement began with the concentric phase, to maximum knee extension of 180º, followed by the eccentric phase, returning to the initial 90º position. The intra-subject variability and consistency of the 1RM measurements were: 1RM in the leg press: CV = 4.4% and ICC = 0.937, 1RM in the knee extension machine: CV = 2.5% and ICC = 0.952. Thus, the 1RM measurements showed low variability and high consistency[20].

Statistical analysis

Normality was assessed using the Shapiro–Wilk test. Descriptive statistics are presented as mean, standard deviation, minimum, and maximum values. Correlations between 1RM tests (leg press and knee extension) and MT (RF and VL – proximal, middle, and distal) were performed using Pearson's correlation coefficient (r), followed by its significance level (P). Correlation magnitudes were interpreted according to Schober et al.[21]. Furthermore, a stepwise multiple linear regression with backward elimination was performed to identify regional MT predictors of strength performance in each exercise. The stepwise approach was adopted due to the exploratory nature of the study and the relatively small sample size, aiming to reduce model overfitting. Model diagnostics included the P-value, coefficient of determination (R^2), standard error of the estimate (SEE), tolerance, variance inflation factor (VIF), and Durbin-Watson test. Statistical analyses were performed using the Statistical Package for the Social Sciences software (IBM SPSS Statistics, v. 25, Chicago, IL, USA), with significance set at $P < 0.05$.

RESULTS

The Shapiro–Wilk test indicated no deviations from normality for any variable. Descriptive statistics are presented in Table 1. Table 2 summarizes the associations between maximal strength and regional MT of the RF and VL.

Moderate, direct, and statistically significant correlations were observed for most comparisons ($r = 0.408$-0.655, $P < 0.05$), except for the association between leg press 1RM and distal RF MT, which was weak and not statistically significant ($r = 0.366$, $P = 0.056$). Multiple regression analysis revealed that proximal RF and VL MT were the strongest predictors of leg press strength, whereas proximal and distal VL MT best predicted knee extension strength, as demonstrated in Equations 1 and 2. Residuals of the final regression models were visually inspected and showed no relevant deviations from normality.

Table 1. Descriptive values of muscle strengths and thicknesses.

Variables	Mean ± Standard Deviation	Minimum - Maximum
1RM Leg Press (kg)	151.0 ± 36.4	85.0 - 215.0
1RM Knee Extension (kg)	100.9 ± 16.5	75.0 - 126.0
MT RFProximal (mm)	24.9 ± 0.34	18.5 - 34.0
MT RFMiddle (mm)	21.1 ± 0.30	14.4 - 25.5
MT RFDistal (mm)	14.8 ± 0.36	5.5 - 22.5
MT VLProximal (mm)	25.6 ± 0.46	18.2 - 38.2
MT VLMiddle (mm)	25.1 ± 0.48	18.4 - 35.6
MT VLDistal (mm)	23.8 ± 0.44	14.8 - 32.9

Note. 1RM = one-repetition maximum; MT = muscle thickness; RF = rectus femoris; VL = vastus lateralis.

Table 2. Association between muscle strength and thickness in different regions.

Muscle Regions	1RM Leg Press	1RM Knee Extension
	r (P)	r (P)
MT RFProximal	0.545 (0.003)	0.558 (0.002)
MT RFMiddle	0.475 (0.011)	0.457 (0.014)
MT RFDistal	0.366 (0.056)	0.408 (0.031)
MT VLProximal	0.582 (0.001)	0.624 (0.000)
MT VLMiddle	0.459 (0.014)	0.631 (0.000)
MT VLDistal	0.524 (0.004)	0.655 (0.000)

Note. 1RM = one-repetition maximum; MT = muscle thickness; r = Pearson's correlation coefficient; P = significance level; RF = rectus femoris; VL = vastus lateralis.

Equation 1:

$$\text{1RM Leg Press} = -20.594 + 35.509 \times \left(\text{MT RF}_{\text{Proximal}}\right) + 32.526 \times \left(\text{MT VL}_{\text{Proximal}}\right) \tag{1}$$

P = 0.001, R^2 = 0.421, SEE = 28.8 kg (19.1%), Tolerance = 0.7, VIF = 1.4, Durbin-Watson = 1.5

Equation 2:

$$\text{1RM Knee Extension} = 28.563 + 12.867 \times \left(\text{MT VL}_{\text{Proximal}}\right) + 16.559 \times \left(\text{MT VL}_{\text{Distal}}\right) \tag{2}$$

P = 0.000, R^2 = 0.511, SEE = 12.0 kg (11.9%), Tolerance = 0.6, VIF = 1.6, Durbin-Watson = 1.5

DISCUSSION

The present study investigated the associations between MT of the RF and VL in their proximal, middle, and distal regions and maximum isotonic muscle strength during leg press and knee extension exercises in young men. The study hypothesis was partially confirmed, as MT of both RF and VL showed weak to moderate and statistically significant correlations with 1RM performance, indicating that regional muscle size explains part of the variability in maximal strength.

These results are similar to those reported by Oranchuk et al.[8], who observed moderate associations between maximal voluntary isometric contraction and MT in the middle and distal regions of the RF and VL across different knee extension angles. In the present study, correlations involving VL MT were consistently higher across all analyzed regions in both leg press and knee extension exercises than in the RF. Similarly, Lanza et al.[9] reported stronger associations between maximal voluntary isometric contraction and VL MT than RF MT, suggesting that, in a cross-sectional context, the VL presents a relatively consistent association with strength production during both dynamic and isometric contractions.

In the knee extension exercise, the distal region of the RF exhibited a weak association with 1RM, whereas the distal region of the VL showed a moderate correlation. Similar results were reported by Voskuil et al.[22], who found a weak association between RF MT and 1RM but a moderate, significant association for VL MT. Despite this, longitudinal resistance training studies consistently demonstrate greater hypertrophy in the distal region of the RF[6,11], possibly due to greater initial muscle lengthening during knee extension, which may favor the length–tension relationship[23]. Therefore, distal RF MT may not be a strong predictor of strength performance during knee extension in the cross-sectional context. However, it appears to be more responsive to chronic training-induced adaptations.

Kojic et al.[24] examined the association between muscle strength during parallel (knee flexion to 90°) and deep squats (knee flexion to 45°) and the average anatomical cross-sectional area of the QF. In that study, RF showed no significant correlations in either squat condition, whereas VL demonstrated moderate and significant associations. Although regional QF analysis was not performed, these findings align with the present results for the leg press, in which RF correlations were lower than those observed for VL, with both muscles showing stronger associations in their proximal regions. This pattern may be explained by the multi-joint and closed kinetic chain nature of the leg press (where the platform is fixed and the chair is mobile), in which distal regions of the QF are relatively more elongated, while proximal regions appear to contribute more substantially to strength generation[25].

Multiple regression analysis indicated that proximal RF and VL MT explained a greater proportion of the variance in leg press strength. In contrast, proximal and distal VL MT accounted for a larger proportion of the variance in knee extension strength. All statistical assumptions were satisfied, including absence of multicollinearity (Tolerance > 0.1; VIF < 10) and independence of residuals (Durbin–Watson = 1.5). These findings complement those of Monte and Franchi[10], who identified the middle RF and VL regions as the primary predictors of maximal voluntary isometric contraction during knee extension. However, their analysis was restricted to the initial angle of 90°, a condition in which strength production is angle-specific[26].

Previous electromyographic studies demonstrate greater VL activation during multi-joint exercises and greater RF activation during single-joint exercises when muscles are compared with themselves[27,28]. The biarticular nature of the RF may reduce its activation during the leg press, increasing the neuromuscular demand placed on the VL[27,28]. Nevertheless, proximal RF MT showed meaningful explanatory capacity for leg press strength, suggesting that acute neuromuscular activation does not necessarily reflect the structural contribution of specific muscle regions to strength production. Consistent with this interpretation, Wakahara et al.[12] demonstrated that early training-induced muscle activation patterns are associated with intramuscular heterogeneity, and that identical training stimuli may result in distinct neuromuscular and hypertrophic adaptations over time.

Voskuil et al.[22] further demonstrated that muscle quality, assessed via echo intensity of the RF and VL corrected by subcutaneous adipose tissue thickness, has a moderate association with knee extension strength, reflecting the relative proportion of contractile and non-contractile tissue. Beyond muscle quality and thickness, additional architectural factors such as pennation angle and fascicle length are important determinants of strength[6]. Increases in pennation angle may expand intramuscular packing and contribute to hypertrophy and strength-generating capacity[29], whereas fascicle length appears to play a greater role in contraction velocity and strength production during fast or large-amplitude movements[30]. Thus, although MT is a relevant morphological indicator, strength performance is influenced by a combination of complementary morphofunctional characteristics.

Several limitations should be acknowledged. The anatomical reference points used for RF imaging may not correspond precisely to the proximal, middle, and distal regions of the VL due to differences in muscle origins and insertions, as well as interindividual anatomical variability. Additionally, electromyographic data were not collected, precluding direct analysis of regional activation patterns. Other relevant morphological variables, such as whole muscle architecture (anatomical cross-sectional area, pennation angle, and fascicle length) and muscle quality, were also not assessed. Although all assumptions for multiple regression were met, the sample size (n = 28) was relatively limited given the number of potential predictors, and the regression models should therefore be interpreted as exploratory. Finally, the cross-sectional design precludes causal inference regarding the relationship between regional MT and maximal strength.

In summary, the association between strength and muscle mass indicates the presence of inter- and intramuscular functional differences that may influence strength performance and contribute to regional adaptations, reinforcing the importance of considering specific morphological characteristics when examining the determinants of muscle strength in applied settings. Therefore, future studies could benefit from the results presented here and propose a training routine to determine the effects of different exercises, isolated or combined, on muscle strength and regional hypertrophy of the QF.

CONCLUSION

Regional QF MT exhibits weak-to-moderate associations with maximal isotonic muscle strength during leg press and knee extension exercises in young men. Proximal RF and VL MTs were the primary predictors of leg press strength, whereas proximal and distal VL MTs showed greater predictive capacity for knee extension performance. These findings indicate that the regional contribution of QF muscles to strength output is exercise-specific, reinforcing the relevance of regional morphological assessments when investigating the determinants of muscle strength.

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COMPLIANCE WITH ETHICAL STANDARDS

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Ethical approval

Ethical approval was obtained from the Research Ethics Committee with human subjects at the Pedro Ernesto University Hospital of the Rio de Janeiro State University, and the protocol was written in accordance with the standards established by the Declaration of Helsinki.

Conflict of interest statement

The authors have no conflict of interests to declare.

Author Contributions

Conceived and designed experiments: ALCS, LSB, PSCG; Performed experiments: ALCS, LSB; Analyzed data: ALCS, PSCG; Contributed with reagents/materials/analysis tools: ALCS, PSCG; Wrote the paper: ALCS, LSB, PSCG. All authors read and approved the final version of the manuscript.

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