MLTJ
Muscles, Ligaments and Tendons Journal

ORIGINAL ARTICLE

DEVELOPMENT OF PREDICTIVE EQUATIONS FOR ESTIMATING REGIONAL CROSS-SECTIONAL AREAS OF THE QUADRICEPS FEMORIS IN UNTRAINED YOUNG WOMEN USING ANTHROPOMETRIC MEASUREMENTS

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Received: 22/08/2025
Accepted: 22/12/2025
Published: 17/09/2026

Conflict of interests: The Authors declare that there are no competing interests.
Aknowledgment: The Authors would like to thank the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) and the Pro-Rectory of Research of the Universidade do Estado de Minas Gerais (UEMG) for their financial and institutional support, which made this study possible.
Fundings: This study was supported by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) and the Pro-Rectory of Research at the Universidade do Estado de Minas Gerais (UEMG).
Data availability: Data are available upon reasonable request from the corresponding author.
Contributions: LTL: funding, conceptualization, data analysis and manuscript writing. IHAL: data analysis and manuscript writing. IHAL, IJSR, GP, KCP: study execution. IHAL, IJSR, GP, FDT, LTL, FDT: manuscript reviewing.
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LEVEL OF EVIDENCE: 3

ABSTRACT

Background: The assessment of muscle cross-sectional area (CSA) is widely used in both clinical and performance contexts, as it reflects morphological changes associated with strength training-induced hypertrophy and muscle atrophy in conditions such as sarcopenia. Although imaging techniques such as computed tomography, magnetic resonance imaging, and ultrasonography provide accurate analyses of CSA, their high cost and the need for specialized professionals limit their routine application. In this context, low-cost indirect methods, such as anthropometric measurements, emerge as viable alternatives.

Aim: This study aimed to develop predictive equations to estimate the CSA of the quadriceps femoris (QF) muscle and its respective portions, rectus femoris (RF), vastus lateralis (VL), vastus intermedius (VI), and vastus medialis (VM), using thigh circumference and skinfold measurements taken at 50% and 70% of femur length, with ultrasonography as the reference method.

Materials and methods: Thirty-six untrained young women participated (body mass: 56.08 ± 17.79 kg; height: 1.60 ± 0.05 m; age: 21.00 ± 2.16 years). Circumference and skinfold thickness measurements were taken at both 50% and 70% of femur length (FL) for each muscle. Muscle CSA was assessed using panoramic-view ultrasonography.

Results: Ten multiple linear regression equations were developed, six of which showed relative errors ranging from 7.2%

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to 19.9%, which are comparable to or lower than values reported in existing models, given the equations 50% of CF for VL r^2 = 0.351; SEEr = 12.4%, VI r^2 = 0.5046; SEEr = 13.5%, VM r^2 = 0.190; SEEr = 12.9% and QF r^2 = 0.356; SEEr = 12.4% and at 70% of CF for VI r^2 = 0.200; SEEr = 17.8% and QF r^2 = 0.356; SEEr = 12.4%.
Conclusions: The results presented indicate that, although some equations have moderate coefficients of determination, the error levels found demonstrate potential for application, as they approach the precision of already established equations.

KEYWORDS
Cross-sectional area, anthropometric measurements, prediction equation, ultrasound, strength training

INTRODUCTION

The cross-sectional area (CSA) is a variable used to assess muscle hypertrophy induced by strength training[1] and is associated with the capacity for muscle force production[2]. Additionally, CSA is also used to evaluate muscle atrophy, such as that occurring in sarcopenia due to aging[3] and physical inactivity[4]. In this context, reductions in both muscle mass and muscle strength performance may be associated with an individual's functional incapacity, consequently leading to an increased incidence of non-communicable chronic diseases and a higher risk of mortality[5]. Considering the information presented above, CSA is a relevant diagnostic parameter for distinguishing an individual's level of health and physical fitness[6,7].

However, there are different techniques capable of quantifying skeletal muscle CSA that can adequately assess an individual's body composition and monitor its changes over time[8]. These techniques, which can accurately measure CSA, include imaging exams such as ultrasound, computed tomography, and magnetic resonance imaging[1,9-12]. However, these methods are costly and often inaccessible to most healthcare professionals, thus hindering the monitoring of physical training programs, injury prevention, and rehabilitation[13]. Furthermore, for image acquisition to be reliable in the assessment of CSA, a trained and experienced evaluator is required[14]. This represents a limiting factor for healthcare professionals who do not have adequate training to operate such equipment.

Developing indirect and low-cost methods can assist professionals in measuring muscle CSA more affordably and with adequate precision[1,13]. Anthropometric measurements (e.g. circumference and skinfold thickness) are low-cost, non-invasive quantitative methods[15] primarily used to estimate changes in body segment composition[1]. Previous studies have used equations based on circumference and skinfold measurements to estimate muscle CSA[16-18]. Therefore, the use of these measurements emerges as a strategy to estimate CSA through predictive equations based on anthropometric data[10]. Furthermore, some studies have developed predictive equations to estimate the CSA of different muscles. However, they assessed only a single point along the muscle length[10,16]. It has been reported that resistance training induces a heterogeneous hypertrophic response along the length of the muscle[19-22].

Thus, developing predictive equations for muscle CSA at different points along the muscle length[23] may more accurately determine hypertrophic responses compared to assessing a single specific region[21]. Figueiredo et al.[23] presented equations to estimate the AST of the rectus femoris (RF) and vastus lateralis (VL) muscles at two locations along the muscle length in a sample of trained men. Based on this previous information, there is still a scarcity of predictive equations capable of estimating the AST of the quadriceps (i.e. the sum of the AST values of the four constituent muscles) and its individual muscles at more than one point along the muscle length, specifically in untrained women. In this way, the present study provides additional findings to those already existing in the literature and can contribute to the practice of health professionals involved in physical assessment and body composition analysis.

Considering the information presented in this introduction, the aim of the study was to develop prediction equations based on anthropometric measurements using ultrasound images to estimate the CSA of the QF and its portions (RF, VL, VI, and VM) at 50% and 70% of femur length (FL) in untrained women. Thus, it is hypothesized that circumference and skinfold data collected at 50% and 70% of FL will enable the development of reliable prediction equations for the CSA of the quadriceps femoris as a whole and for its individual portions.

MATERIALS AND METHODS

Experimental approach to the problem

Each female participant underwent the image acquisition procedure using panoramic ultrasound of the QF and its portions (RF, VL, VI, VM) in the right thigh. Images were obtained from two distinct regions corresponding to 50% and 70% of the distance between the greater trochanter and the lateral epicondyle of the femur. Circumference and skinfolds were measured at the same locations where the US images were acquired. Skinfolds were evaluated according to the protocol of Jackson and Pollock[24]. Body mass and height of the study participants were assessed

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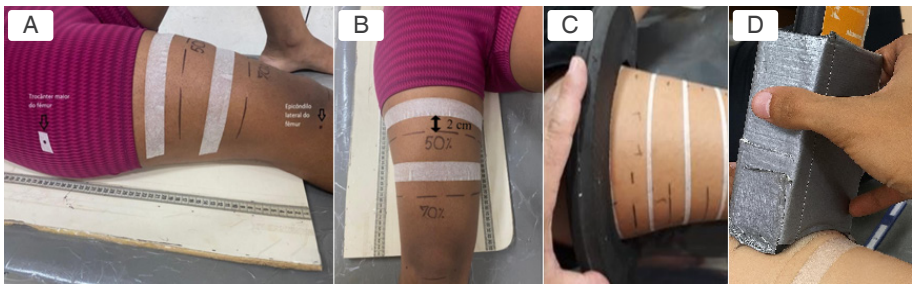


Figure 1. *A, B) Thigh marking procedures; C) Probe guide; D) Probe apparatus.*

in the laboratory using a standardized weight scale with an attached stadiometer.

Subjects

The present study met the following inclusion criteria:

1) Female participants aged between 18 and 35 years;
2) Not having participated in strength training programs for at least six months[25]. Additionally, participants were not allowed to engage in any type of strength training during the research period;
3) No history of musculoskeletal injuries in the lower limbs or pelvic region;
4) Not currently using or having previously used pharmacological or nutritional ergogenic aids. Therefore, this study was conducted with young adult female participants.

Sample size was established following the recommendations of Beck[26], using the software GPower (version 3.1.7; Heinrich Heine Universität Düsseldorf, DE, Germany). Thus, the sample calculation was carried out using the GPower program based on the statistical analysis planned for the present study (multiple linear regression). An alpha level of 0.05, statistical power of 0.80, and two predictors were considered (circumference and analytical skinfold). An effect size (ES) of 0.333 was used, obtained from the correlation coefficient (r = 0.5) reported by Housh et al.[9]. Accordingly, the software calculated a required sample size of 33 individuals. However, the data collection session was conducted with 36 volunteers, accounting for a possible sample loss of 10%.

In this study, CSA was estimated using thigh circumference and skinfold measurements as reference. Upon arrival at the laboratory, participants were informed about the study procedures and signed an informed consent form prior to testing. The study followed the standards established in the Declaration of Helsinki and was approved by the university ethics committee (CAEE - 65740322.0.0000.5115).

Procedures

Initially, the volunteers were informed about the study procedures and signed an informed consent form. The Physical Activity Readiness Questionnaire (PAR-Q) was subsequently administered to assess the participants' physical condition. If a participant answered "YES" to any of the questions, she was excluded from the study, as the sample consisted of healthy young women.

Subsequently, body mass was measured using a digital scale with an accuracy of 0.1 kg, and height was measured using a fixed stadiometer with an accuracy of 0.5 cm (Welmy®, RI/W-200, Santa Bárbara d'Oeste, SP, Brazil). Body composition was then assessed using tetrapolar bioimpedance (Sany, BIA1011-AF, São Bernardo do Campo, SP, Brazil).

Ultrasound images were acquired to analyse the anatomical cross-sectional area (CSA) values of the QF and its portions (RF, VL, VI, VM). The CSA of the QF was determined by summing the CSA values of each of its component muscles. Initially, volunteers remained in the supine position on a stretcher for 15 minutes to allow for fluid redistribution[27]. Femur length (FL) was then obtained by measuring the distance between the greater trochanter and the lateral epicondyle, following the procedure described by Lacerda et al.[28].

A permanent ink pen was used to mark the lateral epicondyle on the skin, and adhesive tape was applied over the participant's legging shorts to indicate the projection of the greater trochanter *(Fig. 1A)*. All markings were performed by a single trained evaluator. Subsequently, the 50% and 70% points of FL (measured from the greater trochanter) were identified and marked on the participant's thigh. A horizontal line was drawn at each site (50% and 70% FL) using a flexible ruler and a permanent ink pen. A strip of micropore tape was then fixed 2 cm from each percentage point on the thigh to delimit the location where the ultrasound probe guide would be positioned during image acquisition *(Fig. 1B)*.

Images were acquired using an extended field-of-view mode ultrasound device (Vinno®, Q5-7L, Suzhou, China), with a 4 cm linear-array probe. The equipment was configured with a frequency range of 6–16 MHz and an acquisition rate of 18 frames/s. Depth and gain settings were individually adjusted for each participant and each muscle to optimize image quality. A procedure bed was placed next to the ultrasound device to accommodate participants during image acquisition, which lasted approximately 45 minutes per individual.

A water-soluble transmission gel (Ultra Gel®, Santa Cruz do Sul, RS, Brazil) was applied to aid acoustic coupling. A custom-made E.V.A. conductor guide was used to help maintain the transducer perpendicular to the skin and to guide its transverse path along the thigh *(Fig. 1C)*. The customized E.V.A. guide was 4 cm wide, which facilitated handling and ensured centralised conduction of the transducer along the curved axial section. Both the E.V.A.

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guide and the supporting receptacle had previously been used in the study by Lacerda et al.[28] *(Fig. 1C)*. Care was taken to avoid applying excessive pressure to the skin, in order to prevent muscle compression during image acquisition. The transducer was slowly moved along the marked longitudinal lines to capture the images. Two images were acquired for each muscle region by a trained operator.

The same markings on the thigh (50% and 70% of FL) were maintained for subsequent anthropometric measurements (circumference and skinfold thickness). Each measurement was performed three times at each region, and the average of the three was used for statistical analysis. Circumference measurements were taken immediately above the tape using a flexible anthropometric tape (Anthropometric Tape Measure®, Sanny, São Bernardo do Campo, SP, Brazil) accurate to the nearest 1 mm. Skinfold thickness was measured using a skinfold caliper (Classic AD1007®, Sanny, São Bernardo do Campo, SP, Brazil), following the protocol described by Jackson and Pollock[24]. Measurements were taken parallel to the longitudinal axis and close to the midpoint of the anterior thigh at each of the marked regions.

For both anthropometric assessments, participants stood upright, supported on the left lower limb, with the right lower limb semi-flexed and the arms extended and relaxed alongside the body. All anthropometric measurements were performed by the same experienced examiner.

The ultrasound scans were stored on the device's internal hard drive and subsequently transferred to a flash drive in DICOM format. Images were analysed using RadiAnt DICOM Viewer software (version 1.9.16, 64-bit, Poznań, Poland). The operator manually traced the muscle contours, generating a numerical area value in cm^2. The software automatically calculated the CSA after the contours were drawn *(Fig. 2A–D and 3E–H)*. The mean CSA of the two images obtained at each muscle region was used for statistical analysis.

Statistical analysis

Statistical analysis was performed using SPSS for Windows, version 22.0 (SPSS Inc., Chicago, IL, USA), with a significance level set at 0.05. Prior to conducting the multiple linear regression analysis, the following assumptions were verified: independence of residuals, absence of multicollinearity, absence of outliers, normal distribution of residuals, homoscedasticity, and a linear relationship between the independent variables.

Once these criteria were met, multiple regression analyses were performed to develop predictive equations for the CSA of the QF and its individual muscles (RF, VL, VI, and VM) at each evaluated region of the thigh (50% and 70% of FL), based on circumference and skinfold thickness measurements. Limits of agreement and potential biases were assessed using the Bland–Altman method, which was conducted using SigmaPlot software, version 10.0 (SigmaPlot Inc., San Jose, CA, USA).

RESULTS

Thirty-five female participants were included in the study (body mass: 56.08 ± 17.79 kg; height: 1.60 ± 0.05 m; age: 21.00 ± 2.16 years; body fat mass: 16.08 ± 13.54 kg; body

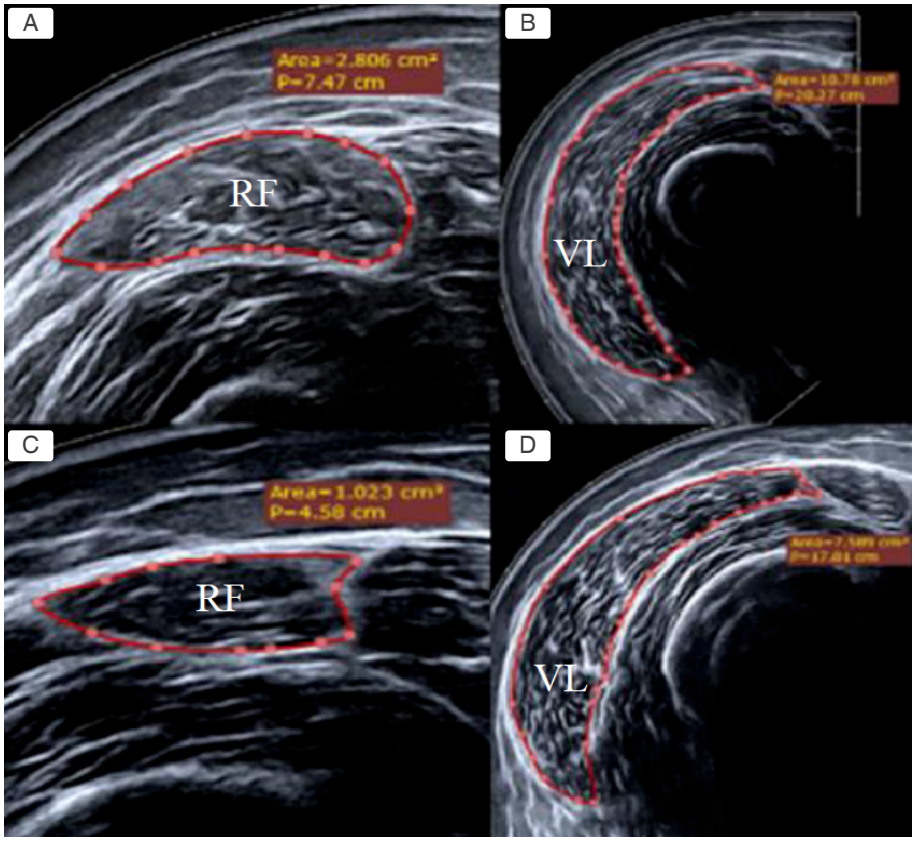


Figure 2. *A, B) Ultrasound imagens and cross-sectional areas (CSA values) at 50% and C, D) 70% of femur length. Abbreviations: RF, rectus femoris; VL, vastus lateralis.*

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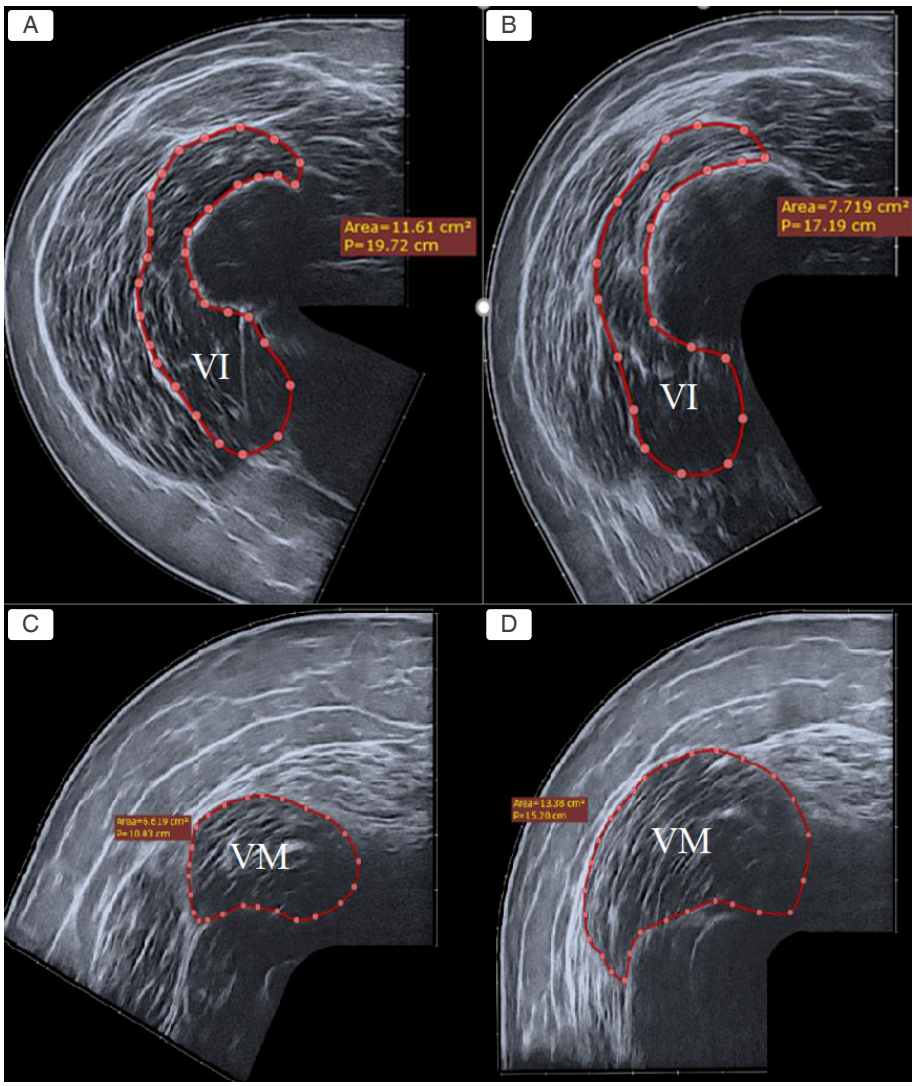


Figure 3. *A, C) Ultrasound imagens and cross-sectional areas (CSA values) at 50% and B, D) 70% of femur length. Abbreviations: VI, vastus intermedius; VM, vastus medialis.*

fat percentage: 28.76 ± 10.49%; fat-free mass: 39.12 ± 4.01 kg; and fat-free tissue percentage: 71.24 ± 10.49%). One participant's image was excluded due to technical limitations during ultrasound image acquisition, resulting in a final sample of 35 eligible participants *(Fig. 4)*.

Intra-rater reliability for circumference and skinfold measurements was assessed using the intraclass correlation coefficient (ICC). Circumference measurements at 50% and 70% of femur length (FL) showed ICC values above 0.982, while skinfold measurements showed

Muscles (region)	Equations	r^2	SEEr
Rectus femoris (50%)	CSA = 0.402 + 0.045 × CCTHI + SKTHI × 0.017	0.304	21.90%
Vastus lateralis (50%)	CSA = 5.696 + 0.135 × CCTHI + 0.035 × SKTHI	0.351	12.40%
Vastus intermedius (50%)	CSA= 7.497 + 0.040 × CCTHI + 0.073 × SKTHI	0.505	13.50%
Vastus medialis (50%)	CSA = 4.499 + 0.088 × CCTHI + (-0.007) × SKTHI	0.190	12.90%
Quadriceps femoris (50%)	CSA = 19.518 + 0.253 × CCTHI + 0.136 × SKTHI	0.446	7.80%
Vastus lateralis (70%)	CSA = 1.387 + 0.71 × CCTHI + 0.68 × SKTHI	0.169	33.80%
Vastus intermedius (70%)	CSA = 3.005 + 0.0117 × CCTHI + (-0.004) × SKTHI	0.200	17.80%
Quadriceps femoris (70%)	CSA = 9.372 + 0.444 × CCTHI + 0.011 × SKTHI	0.356	12.40%

Table 1. *Equations multiple linear regression elaborated for each of the muscles and their respective regions. Abbreviations: CSA, cross-sectional area; CCTHI, thigh circumference; SKTHI, skinfold thickness; r^2, coefficient of determination; SEEr, relative standard error of estimate.*

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ICC values above 0.984. Intra-rater reliability for CSA measurements was also evaluated, with two images acquired for each muscle and region. The ICC values for all muscles and both regions were above 0.912.

The regression equations for the thigh muscles are presented below *(Table 1)*. These equations were developed using thigh circumference (CCTHI) and skinfold thickness (SKTHI) measurements taken at 50% and 70% of FL. The results obtained for the RF muscle at 70% of FL and the VM muscle at 70% of FL did not meet all statistical assumptions and did not show significant values ($p = 0.46$ and 0.18, respectively). Therefore, predictive equations were not developed for these two muscles at their respective regions.

The coefficient of determination (r^2) and the relative standard error of estimate (SEEr) are presented for each equation below. *Figure 4* shows the Bland-Altman plots comparing the error obtained between the CSA values measured by ultrasonography and the CSA values predicted by the equations for each of the thigh muscles and regions.

DISCUSSION

The present study aimed to develop predictive equations to estimate the cross-sectional area (CSA) of the quadriceps femoris (QF) and its individual muscles (RF, VL, VI, and VM) in a population of untrained women, using two regions of the thigh (50% and 70% of femur length [FL]). Thigh circumference and skinfold thickness were used as reference measurements. The study hypothesis was partially confirmed, as only the equations developed at 50% of FL were able to reliably predict the CSA of all QF

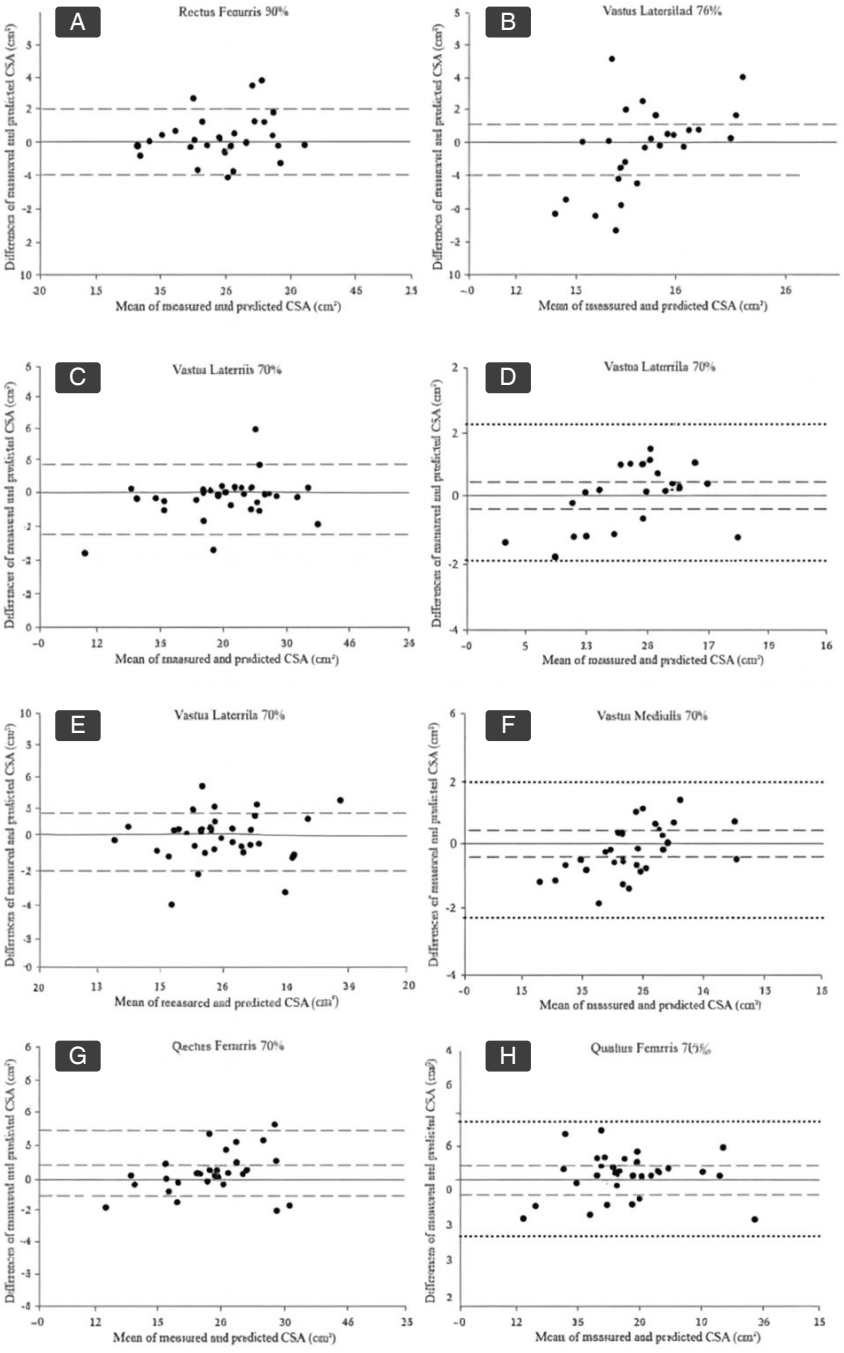


Figure 4. *Bland-altman method plots comparing the error obtained between the values of CSA measured by ultrasound and the values of CSA predicted by the equations for rectus femoris at 50% (A), vastus lateralis at 50% (B) and 70% (C), medialis at 50% (D) vastus intermedius at 50% (E) and 70% (F) and quadriceps femoris at 50% (G) and 70% (H). The solid line denotes the mean difference between measured and predicted CSA values. Dashed lines represent the 95% confidence interval of the differences between measured CSA and predicted CSA, while the dotted lines represent the limits of agreement, defined as ± 1.96 times the standard deviation of the differences between measured and predicted CSA.*

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muscles. In contrast, at 70% of FL, the equations were able to predict the CSA values of the QF, VL, and VI only.

Multiple linear regression was used to develop the predictive models. By inputting thigh circumference and skinfold thickness as independent variables, the model predicted the CSA of the QF and its portions (RF, VL, VI, VM) at 50% of FL with the following coefficients of determination (r^2): 44.6% for QF, 30.4% for RF, 35.1% for VL, 50.46% for VI, and 19% for VM. At 70% of FL, the model predicted the CSA of the QF, VL, and VI with r^2 values of 16.9%, 20%, and 35.6%, respectively. The standard error of estimate relative to the mean (SEEr) for the 50% FL equations was 7.8% for QF, 21.9% for RF, 12.4% for VL, 13.5% for VI, and 12.9% for VM. For the 70% FL equations, the SEEr values were 12.4% for QF, 33.8% for VL, and 17.8% for VI. Therefore, the results of this study demonstrate that multiple linear regression equations can reliably predict muscle CSA at 50% of FL for the QF, RF, VL, VI, and VM, and at 70% of FL for the QF, VL, and VI.

It is noteworthy that the use of predictive equations to estimate the cross-sectional area (CSA) of the quadriceps femoris (QF) and its individual portions is well supported in the literature, particularly in contexts where access to gold-standard imaging techniques (e.g. computed tomography and magnetic resonance imaging) is limited[9]. Housh et al.[9] emphasized that predictive equations offer both practicality and satisfactory accuracy for estimating the CSA of the QF and its components, although their model was limited to a single anatomical site (50% of femur length). In contrast, the present study adopted a dual-point assessment approach along the femur, which may have contributed to the greater reliability and robustness of the estimates obtained. The rationale for this methodological strategy is supported by existing evidence of non-uniform hypertrophic responses along the length of skeletal muscles. Such regional variability has been reported in upper limb muscles (i.e. triceps brachii and biceps brachii)[22,29-31], as well as in lower limb muscles, including the rectus femoris (RF) and vastus lateralis (VL)[19,32-36].

In this regard, Noorkoiv et al.[37] estimated the CSA of QF muscles, specifically the RF and VL, using panoramic ultrasonographic images acquired at various sites along the femoral length (10% to 50%). Their study demonstrated excellent validity compared to computed tomography (ICC ranging from 0.951 to 0.998) and high intra- and inter-rater reliability (between 0.6% and 2.7%), highlighting the importance of rigorous methodological standardization in selecting anatomical measurement sites. These findings are consistent with the methodology employed in the present study, which evaluated CSA at two distinct femoral locations (50% and 70% of femur length).

The current literature reinforces the notion that muscle hypertrophy does not occur uniformly along the muscle belly, and that the selection of the measurement site can significantly affect the validity of predictive models, whether based on ultrasound imaging or anthropometric data. In this context, the predictive equations developed in this study proved effective in estimating the CSA of the QF and its respective portions in a sample of untrained adult women. Therefore, caution is advised when attempting to generalize these findings to populations with different characteristics.

Figueiredo et al.[23] developed predictive equations based on measurements taken at 50% and 70% of femur length, focusing on two portions of the quadriceps femoris (QF) muscle (rectus femoris - RF and vastus lateralis - VL). In addition to circumference and skinfold thickness, the authors incorporated two additional anthropometric variables (height and body mass) into the development of their linear regression models. The standard error of estimate (SEE) values reported for the RF were 18.8% at 50% of femur length and 41.3% at 70%. The estimated values obtained for the RF and VL at 50% of femur length were consistent with those found in the present study, showing similar SEE values. However, the predictive equation for the RF at 70% of femur length in the present study did not yield statistically significant results, in contrast to the findings reported by Figueiredo et al.[23], who observed significance at that same anatomical site. This discrepancy may be attributed to differences in sample characteristics, as Figueiredo et al.[23] evaluated trained women, which may have resulted in higher CSA values in the distal thigh region. Consequently, a stronger correlation may have emerged between ultrasound-derived measurements and those based on circumference and skinfold data, thereby improving the precision of their predictive model. Moreover, the inclusion of height and body mass variables in their model likely enhanced its robustness and contributed to the development of more consistent equations. Notably, the present study also evaluated two additional portions of the QF muscle (vastus intermedius - VI and vastus medialis - VM), which were not assessed by Figueiredo et al.[23]. This methodological distinction represents a key contribution of the current research, as no previous studies have investigated predictive equations for estimating the CSA of the VI and VM portions. Similarly, the findings of De Freitas et al.[10], who reported variability in predictive accuracy depending on the muscle analyzed, support the interpretation that equations must be muscle-specific and validated for the intended population. This is reflected in the present study through the higher r^2 values for the VI and QF at 50% FL, contrasted with the low predictive power for the VL at 70% FL. Importantly, the high intra-rater reliability (ICC >0.91) observed here indicates that these discrepancies arise from the statistical models rather than measurement error.

The present results align with Matsui et al.[38], who demonstrated high validity and reproducibility of ultrasound for assessing QF CSA. However, despite the accuracy of imaging methods, their cost and limited accessibility continue to restrict routine use. In this context, the predictive equations developed here provide a practical

alternative for professionals who need rapid and low-cost estimations of muscle size, supporting training load monitoring, injury prevention, and rehabilitation planning. Nevertheless, as reported by several authors[9,10,38,39], predictive equations must be applied carefully, respecting population characteristics and anatomical site definitions. Differences in how femur length is defined such as those between this study and the definition used by Housh et al.[9] can influence comparability and should be considered in future research designs. However, caution is warranted when applying these equations to populations that differ from those for which they were originally developed, as this may lead to increased standard error of estimate (SEE)[40]. Additional factors such as sex, physical condition, and training status can also influence the accuracy of CSA estimations obtained via predictive models. Moreover, it is important to acknowledge that the criterion used to define femur length (FL) can hinder comparisons between studies. Specifically, while the present study defined FL as the distance between the greater trochanter and the lateral epicondyle of the femur, Housh et al.[9] defined it as the distance between the femoral head and the inferior border of the femoral condyle. This methodological difference may have contributed to discrepancies in the findings between the two studies. Given these considerations, future research is encouraged to explore the applicability of predictive equations across different populations, muscles, and muscle regions, as well as to assess their sensitivity in detecting both acute and chronic CSA adaptations to various strength training protocols.

CONCLUSIONS

The present study aimed to develop predictive equations based on anthropometric measurements, using ultrasound imaging, to estimate the cross-sectional area (CSA) of the quadriceps femoris (QF) and its respective portions (rectus femoris - RF, vastus lateralis - VL, vastus intermedius - VI, and vastus medialis - VM) at 50% and 70% of femur length in untrained women. The findings demonstrated that the equations developed at 50% of femur length were valid and reliable for estimating the CSA of the QF and all its individual components. In contrast, the equations developed at 70% of femur length were effective only for predicting the CSA of the QF, VL, and VI.

These equations should be applied with caution outside of the specific population and muscle groups examined, as variables such as training level, the muscle evaluated, and the anatomical criteria used to define femur length can influence their accuracy and increase the standard error of the estimate. Consequently, external validation is essential. Therefore, future research should evaluate these models in diverse populations and muscle groups and examine their ability to detect acute and chronic adaptations to strength training.

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