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Development of Predictive Equations to Estimate Regional Muscle Cross Sectional Area Based on Anthropometry

Marina O. C. Figueiredo[1,2], Bárbara T. R. de Souza[1,2], Marcelo D. M. dos Santos[1], Fernanda S. Lessa[1], Bruno F. Rodrigues[1], Maria C. N. Ferreira[1], Lucas T. de Lacerda[3], Fernando V. Lima[1], Mauro H. Chagas[1], Rodrigo C. R. Diniz[1]

[1] *Weight Training Laboratory, School of Physical Education, Physiotherapy and Occupational Therapy, Federal University of Minas Gerais, Belo Horizonte, Brazil*
[2] *Scientific Initiation Research – FAPEMIG, Federal University of Minas Gerais, Belo Horizonte, Brazil*
[3] *Department of Physical Education, State University of Minas Gerais, Divinópolis, Brazil*

CORRESPONDING AUTHOR:
Rodrigo César Ribeiro Diniz
Weight Training Laboratory
School of Physical Education,
Physiotherapy and Occupational Therapy
Federal University of Minas Gerais
Av. Antônio Carlos 6627
Belo Horizonte, Minas Gerais 31270-901,
Brazil
E-mail: rodrigocrd@hotmail.com

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SUMMARY

Background. Muscle hypertrophy is one of the main goals of resistance training and is frequently associated with an increase in muscle cross-sectional area (CSA). Imaging techniques are valid and reliable techniques for measuring CSA but are inaccessible to most professionals. Anthropometric-based multiple regression equations (*i.e.* using circumference and skinfolds outcomes) have been proposed to estimate muscle CSA describing a limited number of muscles.

Purpose. The aim of this study was to develop anthropometric-based multiple regression equations using ultrasound images to estimate CSA of pectoralis major, biceps brachii, triceps brachii, rectus abdominis, rectus femoris, vastus lateralis, biceps femoris, gastrocnemius lateralis and medialis muscles at two distinct regions for each muscle assessed.

Methods. Thirty trained women and men (mean ± SD; body mass = 69.6 ± 11.1 kg; stature = 168.5 ± 8.9 cm; and age = 25.7 ± 4. years) participated in the study. Circumference and skinfold measurements were taken at the same points where ultrasound images were acquired to evaluate the CSA of muscles analyzed. Muscle CSA area was assessed using panoramic-view ultrasound.

Results. Seventeen multiple regression equations were developed using measures of circumference, skinfold, body weight, height and muscle CSA.

Conclusions. Ten equations developed presented the relative errors between 7.2 and 19.9%. These values are comparable or less than those found in equations commonly used by sport and exercise professionals. Thus, these equations are recommended for single-time point estimation of muscle CSA. However, their usefulness for monitoring the CSA changes promoted by resistance training requires further research.

KEY WORDS
Muscle regional hypertrophy; cross-sectional area; predictive equation; ultrasound; resistance training.

INTRODUCTION

Muscle hypertrophy is one of the main goals of resistance training (1, 2). Measurement of hypertrophy is frequently associated with increase in muscle cross-sectional area (CSA) (3). Magnetic resonance imaging (MRI), computed tomography and ultrasonography (US) are valid and reliable techniques for measuring CSA (2-8). These techniques allow distinction between different body tissues, such as bones, muscles and fat (4, 2). However, these methods are expensive and inaccessible to most sport and exercise professionals (2, 4, 5, 6, 8).

Anthropometric-based methods to estimate CSA (*i.e.* using circumference and skinfolds outcomes) are well known and most easily accessible to professionals (2, 3, 5). These methods were primarily used to estimate fat and fat-free mass (3). Earlier attempts to improve accuracy of field methods used equations based on circumference, corrected by skinfolds, estimating bone-muscle CSA (2, 9, 10). However, these methods resulted in overestimation compared to imaging techniques, and they do not assess muscle tissue, but fat-free mass (2, 3). Housh *et al.* (4) went further and used magnetic resonance images to develop an anthropometric-based multiple regression equation that was able to predict thigh muscle CSA. Other equations using similar approach to predict upper limb CSA have also been described (11-14), although these equations do not differentiate between upper limb muscles, such as triceps or biceps brachii.

Additionally, it has been shown by imaging techniques that muscle hypertrophy in response to resistance training may not be homogeneous along different muscle regions (15). This regional hypertrophy response, when a non-uniform increase in CSA along the muscle occurs, has been demonstrated for the triceps brachii (13, 16) biceps brachii (17, 18), and quadriceps femoris (19, 20). Nonetheless, anthropometric-based equations proposed in the literature are not specific for different muscle regions and describe a limited number of muscles. Thus, the purpose of this study was to develop anthropometric-based multiple regression equations using US images to estimate CSA of pectoralis major, biceps brachii, triceps brachii, rectus abdominis, rectus femoris, vastus lateralis, biceps femoris, gastrocnemius lateralis and gastrocnemius medialis muscles at two distinct regions for each muscle assessed. Given the aforementioned reasoning, it was hypothesized that multiple regression equations based on anthropometric measurements would present a small relative standard error to estimate the regional CSA of upper and lower limbs muscles.

METHODS

Experimental approach to the problem

Each participant had the right-side muscle CSA determined through panoramic field-of-view US for two different regions of the pectoralis major, triceps brachii, rectus abdominis, rectus femoris, vastus lateralis, biceps femoris, gastrocnemius lateralis and gastrocnemius medialis muscles, and one region of the biceps brachii muscle. Circumference and skinfolds were measured at the same location as the US images were acquired. Skinfolds were evaluated according to the Jackson and Pollock protocol (21). The mass and height of study participants were assessed in the laboratory.

Subjects

Thirty individuals, 14 women and 16 men (mean ± SD mass = 69.6 ± 11.1 kg; height = 168.5 ± 8.9 cm; and age = 25.7 ± 4 years), who were engaged on resistance training for at least 6 uninterrupted months (mean ± SD: 32.6 ± 25.4 months) volunteer to participate in this investigation. Sample size was established following the recommendations of Beck (22) using the software G*Power (version 3.1.9.2; Heinrich Heine Universität Düsseldorf, DE, Germany). Thus, the sample calculation was carried out using the G. Power program (version 3.1.7) using the statistical treatment provided for the present study (Multiple Linear Regression). Furthermore, an alpha error of 0.05, a power of 0.95 and four predictors were used (circumference, analytical fold, mass and height). The value of 1.08 was used for the effect size (ES), obtained through the representation coefficient (r = 0.72) presented by Housh *et al.* (4). In this study, hamstring CSA was estimated using thigh circumference and skinfold measurements as reference. Thus, the software calculated a sample size of 23 individuals. However, 30 volunteers were recruited seeking to increase the predictive power of the regression equations. Participants were instructed to avoid any exercises 24 hours before US assessment. Upon their arrival at the laboratory, they received all relevant information regarding the study and completed an informed consent prior to initiating testing. The study followed the standards established in the Declaration of Helsinki and was approved by the university ethics committee (CAAE: 45454321.6.0000.5149 – date of approval: June 25, 2021).

Procedures

Body weight was measured using a digital scale (FILIZOLA, São Paulo, Brazil) to the nearest 0.1 kg. Standing height was measured using a fixed stadiometer to the nearest 0.5 cm (FILIZOLA, São Paulo, Brazil). Anatomical landmarks on the right side of the body were identified through palpation to determine each muscle region. A horizontal line was drawn in each muscle region using a permanent marker brush and a level square. A 0.5 cm wide micropore tape was fixed immediately below the drawn line to delimit the US transducer guide area during image acquisition (**figure 1**), adopting the following references:

- Pectoralis major (men only) – 30% of the distance between the superior border on the sternoclavicular joint and the top of the umbilical scar; and the superior border of the areola mammae.
- Biceps and triceps brachii – 50% and 70% of the distance between the acromion and the humeral lateral epicondyle.
- Rectus abdominis – top of the umbilical scar and 4 cm above the scar.
- Rectus femoris, vastus lateralis, biceps femoris – 50% and 70% of the distance between the greater trochanter and the femur lateral epicondyle.
- Gastrocnemius lateralis and medialis – 25% and 35% of the distance between the superior border of the head of the fibula and the lateral malleolus.

Circumference measurements were made immediately above the tape using a flexible anthropometric tape to the nearest 1 mm. Skinfolds were measured using a body caliper according to Jackson and Pollock (21) protocol. All anthropometric measurements were made by the same examiner, who was experienced in these procedures.

Figure 1. Location of each muscle region for us image acquisition.

Biceps brachii at 50% (A1) and 70% (A2) of the distance between the acromion and the humeral lateral epicondyle; Pectoralis major at 30% of the distance between the superior border on the sternoclavicular joint and the top of the umbilical scar (B1) and the superior border of the areola mammae (B2); Rectus abdominis at top of the umbilical scar (C2) and 4 cm above the scar (C1); Rectus femoris and vastus lateralis at 50% (D1) and 70% (D2) of the distance between the greater trochanter and the femur lateral epicondyle; Triceps brachii at 50% (E1) and 70% (E2) of the distance between the acromion and the humeral lateral epicondyle; Biceps femoris at 50% (F1) and 70% (F2) of the distance between the greater trochanter and the femur lateral epicondyle; Gastrocnemius lateralis at 25% (G1) and 35% (G2) of the distance between the superior border of the head of the fibula and the lateral malleolus; Gastrocnemius medialis at 25% (G3) and 35% (G4) of the distance between the superior border of the head of the fibula and the lateral malleolus.

Before image acquisition, participants were asked to rest in supine on an examination bed to allow fluid shift stabilization for at least 20 minutes (23). Images were acquired using a B-mode ultrasound device (MindRay DC-7, Shenzhen, China) with a 4-cm linear transducer using in extended-field-of-view mode to assess muscle CSA. The equipment was configured with 10 MHz frequency, acquisition rate of 21 frames/s with a depth ranging from 1 to 9 cm and gain between 50 and 64 db. The settings were adjusted for each volunteer to produce the clearest images of the analyzed muscles. In previous studies from our laboratories using the same ultrasound device and similar procedures, we have obtained good inter-evaluator reliability values ($ICC_{3,1} \geq 0.92$) (18, 32, 33). A procedure bed was installed at the side of the US device to accommodate the participant during the image acquisition procedure, which took approximately 45 minutes per individual.

For image acquisition, a water-soluble transmission gel was used to aid acoustic coupling (Ultra Gel®, Brazil). Care was taken to prevent exerting too much pressure on the skin surface, avoiding compression of the muscles whilst the transducer was slowly moved along the marked longitudinal lines to obtain the scanned images. Two images were acquired for each muscle region by a trained operator.

Scans were stored in the US device hard drive then transferred to a flash drive, as a DICOM file. Images were analyzed using (RadiAnt DICOM Viewer software version 1.9.16, 64 bit, Poznan, Poland). The operator manually traced the contour of the muscles, and the software automatically calculated CSA after muscles were traced. Mean CSA of both images for each muscle region was used for statistical analysis.

In addition, five volunteers were randomly selected to perform the procedures again in a new session. The test-retest reliability of circumference, skinfolds and CSA measurements was performed using data from the initial session and the retest session.

Statistical analysis

Analysis was performed using the statistical software SPSS for Windows version 22.0 (SPSS, Inc., Chicago, IL., USA) with a significant level of 0.05. The normal distribution and homogeneity of variances were confirmed using the Shapiro-Wilk and Levene tests, respectively. Multiple regression was used to develop predictive equations of muscle CSA at two distinct regions for each muscle assessed from circumference, skinfolds, weight, and height. The collinearity diagnostic exploration resulted in variance inflation factors (VIF) of < 2.0 and tolerance above of 0.20, which indicates there are no collinearity problems of the independent variables (24). The limits of agreement and the presence of biases were assessed by the Bland-Altman method to compare CSA measured with CSA predicted. Test-retest repeatability was also tested for measurements of circumference, skinfolds and CSA. A two-way mixed effects model was used to calculate the intraclass correlation coefficient ($ICC_{3.1}$), considering data from the initial and retest sessions. The standard error of measurement (SEM) was also calculated using these same data.

RESULTS

From 30 participants, only men had the pectoralis major muscle assessed. Images from 2 participants were excluded based on technical limitations of US images acquisition, resulting in 14 eligible participants. All other muscles were assessed in both men and women. Biceps brachii was only assessed at 50% of the distance. Due to some imagens being excluded based on technical limitations, the final number of participants included in the final analysis was not equal for all muscles (**figures 2-5**). The test-retest reliability results considering $ICC_{3.1}$ and SEM were 0.999 and 1.17 cm for circumference, 0.966 and 1.8 mm for skinfolds and 0.981 and 1.73 cm² for CSA, respectively. **Table I** presents the descriptive data of the variables and test-retest measurements of muscle cross-sectional area.

Thigh muscles

The regression equations for thigh muscles are presented below. These equations were developed using information on thigh circumference (CC_{THI}) and skinfold thickness of thigh (SK_{THI}) at 50% and 70% of the femur length, body weight (BW), and body height (BH). The Coefficient of Determination (r^2) and the Standard Error of Estimate relative to average (SEEr) are also provided for each equation:

- *Rectus femoris (50%)* $CSA = 0.420 \times CC_{THI} - 0.174 \times SK_{THI} - 0.91 \times BW + 8.313 \times BH - 17.816$ **$r^2 = 0.502$; SEEr = 18.8%**
- *Rectus femoris (70%)* $CSA = 0.386 \times CC_{THI} - 0.042 \times SK_{THI} - 0.119 \times BW + 6.345 \times BH - 17.035$ **$r^2 = 0.364$; SEEr = 41.3%**
- *Vastus lateralis (50%)* $CSA = 0.101 x CC_{THI} - 0.313 x SK_{THI} + 0.564 x BW - 30.421 \times BH + 38.145$ **$r^2 = 0.744$; SEEr = 14.7%**

Table I. Descriptive data (mean ± standard deviation) of variables and test-retest measures of muscle cross-sectional area.

Muscle $_{(region)}$	CSA measured (cm²)	Circumference (cm)	Skinfold thickness (mm)	CSA measured - Test (n = 5) (cm²)	CSA measured – Retest (n = 5) (cm²)
Pectoralis major $_{(30\%)}$	31.21 ± 5.69	103.72 ± 5.39	6.71 ± 2.20	33.92 ± 5.62	34.85 ± 6.95
Pectoralis major $_{(areola\ mammae)}$	28.69 ± 8.05	99.65 ± 5.52	6.71 ± 2.20	38.64 ± 0.03	35.75 ± 0.82
Biceps brachii $_{(50\%)}$	8.98 ± 4.09	31.01 ± 4.03	6.03 ± 3.07	8.90 ± 5.01	8.28 ± 4.15
Triceps brachii $_{(50\%)}$	21.44 ± 10.05	31.26 ± 4.14	10.34 ± 5.04	22.62 ± 8.03	26.48 ± 11.44
Triceps brachii $_{(70\%)}$	17.00 ± 6.80	29.01 ± 3.81	9.58 ± 4.43	16.34 ± 7.77	17.19 ±8.87
Rectus abdominis $_{(umbilical\ scar)}$	8.00 ± 2.63	80.32 ± 6.45	17.20 ± 7.05	10.36 ± 3.21	10.60 ± 2.37
Rectus abdominis $_{(4\ cm)}$	6.00 ± 1.63	76.72 ± 6.83	17.37 ± 7.12	8.00 ± 1.62	7.00 ± 1.72
Rectus femoris $_{(50\%)}$	9.99 ± 2.45	55.45 ± 3.72	18.19 ± 7.74	10.00 ± 2.31	10.00 ± 3.43
Rectus femoris $_{(70\%)}$	3.40 ± 1.59	47.95 ± 3.47	18.03 ± 7.73	3.00 ± 0.69	3.00 ± 0.91
Vastus lateralis $_{(50\%)}$	25.28 ± 6.74	55.09 ± 3.62	17.95 ± 7.64	29.00 ± 5.97	26.68 ± 6.54
Vastus lateralis $_{(70\%)}$	17.92 ± 4.83	47.55 ± 3.44	17.90 ± 7.79	21.00 ± 2.68	21.43 ± 4.03
Biceps femoris $_{(50\%)}$	9.35 ± 2.65	55.22 ± 3.76	17.64 ± 7.26	8.94 ± 2.16	9.10 ± 1.75
Biceps femoris $_{(70\%)}$	10.00 ± 2.76	47.88 ± 3.43	18.25 ± 7.94	10.17 ± 3.17	10.69 ± 2.43
Gastrocnemius lateralis $_{(25\%)}$	8.06 ± 2.58	36.97 ± 2.54	12.48 ± 5.32	8.37 ± 2.58	7.94 ± 2.37
Gastrocnemius lateralis $_{(35\%)}$	6.23 ± 2.20	36.68 ± 2.71	12.60 ± 5.51	8.14 ± 2.50	7.27 ± 1.56
Gastrocnemius medialis $_{(25\%)}$	11.52 ± 3.35	36.97 ± 2.54	11.01 ± 4.92	11.02 ± 3.45	11.41 ± 2.21
Gastrocnemius medialis $_{(35\%)}$	11.51 ± 3.64	36.38 ± 2.71	10.98 ± 5.11	11.35 ± 3.00	10.67 ± 2.12

- *Vastus lateralis (70%)* $CSA = 0.983 \times CC_{THI} - 0.358 \times SK_{THI} - 0.051 \times BW - 3.358 \times BH - 13.340$
  $r^2 = 0.671$; SEEr = 16.9%
- *Biceps femoris (50%)* $CSA = -0.289 \times CC_{THI} - 0.042 \times SK_{THI} + 0.180 \times BW + 8.624 \times BH - 0.775$
  $r^2 = 0.746$; SEEr = 15.8%
- *Biceps femoris (70%)* $CSA = 0.314 \times CC_{THI} - 0.080 \times SK_{THI} + 0.155 \times BW\ 18.844 \times BH + 17.736$
  $r^2 = 0.543$; SEEr = 19.8%

Figure 2 shows the 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 each of the thigh muscles and regions.

Leg muscles

The regression equations for leg muscles were developed using information on leg circumference (CC_{LEG}) and skinfold thickness of leg (SK_{LEG}) at 25% and 35% of the fibula

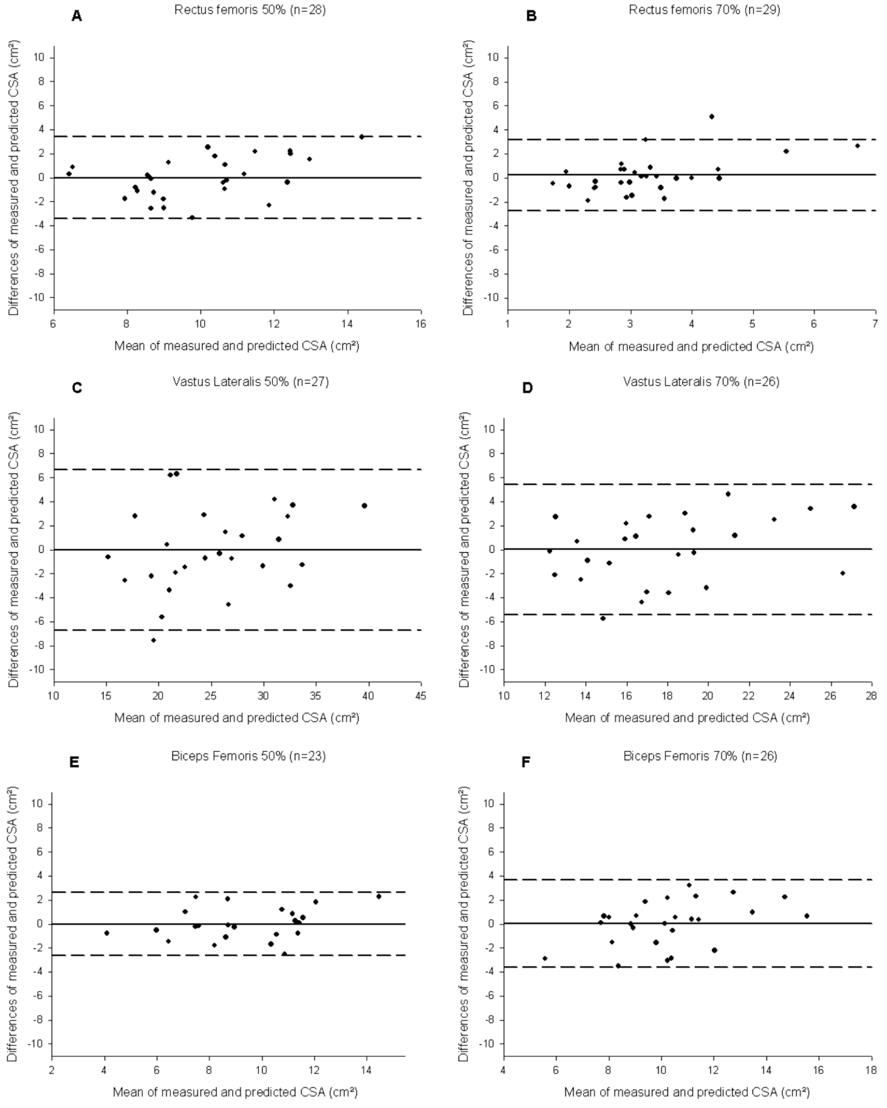

Figure 2. Bland-Altman method plots comparing the error obtained between the values of CSA measured by ultrasound and the values of CSA predicted by the equations for each of the thigh muscles and regions.

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)** and 70% **(B)**, vastus lateralis at 50% **(C)** and 70% **(D)**, and biceps femoris at 50% **(E)** and 70% **(F)**. The solid line represents the mean differences between the measured CSA and the predicted CSA. The dashed lines represent the confidence interval of the differences between the measured CSA and the predicted CSA.

length, BW, and BH. The r^2 and the SEEr are also provided for each equation:

- *Gastrocnemius lateralis (25%) CSA* = $0.673 \times CC_{LEG} - 0.225 \times SK_{LEG} + 0.089 \times BW - 9.975 \times BH - 3.343$ **$r^2 = 0.819$; SEEr = 14.8%**
- *Gastrocnemius lateralis (35%) CSA* = $0.312 \times CC_{LEG} - 0.137 \times SK_{LEG} + 0.133 \times BW - 14.658 \times BH + 12.148$ **$r^2 = 0.595$; SEEr = 24.5%**
- *Gastrocnemius medialis (25%) CSA* = $0.364 \times CC_{LEG} - 0.294 \times SK_{LEG} + 0.112 \times BW - 8.022 \times BH + 7.073$ **$r^2 = 0.498$; SEEr = 22.3%**
- *Gastrocnemius medialis (35%) CSA* = $0.547 \times CC_{L} - 0.193 \times SK_{L} + 0.215 \times BW - 25.818 \times BH + 22.368$ **$r^2 = 0.619$; SEEr = 21.3%**

Figure 3 shows the 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 each of the leg muscles and regions.

Arm muscles

The regression equations for arm muscles were developed using information on arm circumference (CC_{ARM}) and skinfold thickness of biceps brachii (SK_{BIC}) or triceps brachii (SK_{TRI}) at 50% and 70% of the humeral length, BW, and BH. The r^2 and the SEEr are also provided for each equation:

- *Biceps brachii (50%) CSA* = $0.912 \times CC_{ARM} - 0.285 \times SK_{BIC} - 0.035 \times BW + 2.045 \times BH - 18.640$ **$r^2 = 0.881$; SEEr = 17.2%**
- *Triceps brachii (50%) CSA* = $1.955 \times CC_{ARM} - 0.338 \times SK_{TRI} - 0.139 \times BW + 9.727 \times BH - 42.990$ **$r^2 = 0.692$; SEEr = 28.4%**

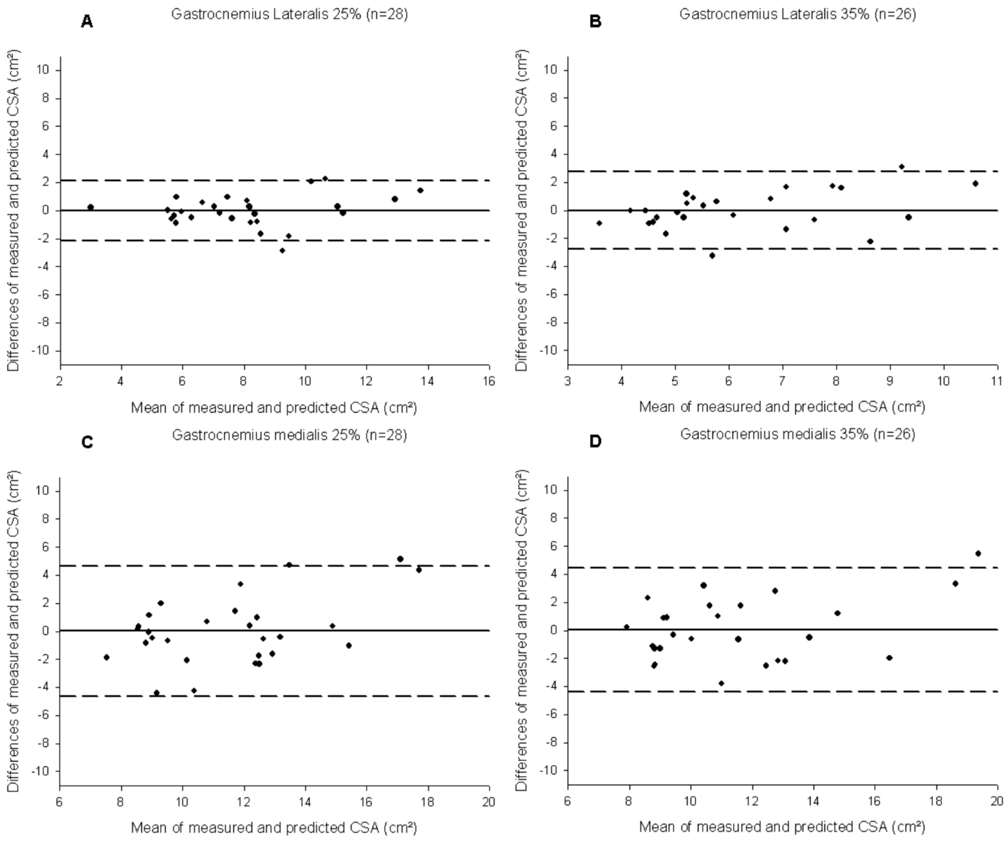

Figure 3. Bland-Altman method plots comparing the error obtained between the values of CSA measured by ultrasound and the values of CSA predicted by the equations for each of the leg muscles and regions.

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 gastrocnemius lateralis at 25% (**A**) and 35% (**B**), and gastrocnemius medialis at 25% (**C**) and 35% (**D**). The solid line represents the mean differences between the measured CSA and the predicted CSA. The dashed lines represent the confidence interval of the differences between the measured CSA and the predicted CSA.

- *Triceps brachii (70%)* $CSA = 1.169 \times CC_{ARM} - 0.462 \times SK_{TRI} + 0.029 \times BW + 4.305 \times BH - 21.734$ **$r^2 = 0.873$; SEEr = 15.7%**

Figure 4 shows the 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 each of the arm muscles and regions.

Trunk muscles

The following multiple regression equations were developed using information on trunk circumference (CC_{TRU}) and skinfold thickness of Pectoralis major (SK_{PTM}) or Rectus abdominis (SK_{RAB}) at different regions on the trunk, BW, and BH. The r^2 and the SEEr are also provided for each equation:

- *Pectoralis major (30%)* $CSA = 0.153 \times CC_{TRU} + 0.184 \times SK + 0.712 \times BW - 29.406 \times BH + 10.279$ **$r^2 = 0.893$; SEEr = 7.2%**
- *Pectoralis major (areola mammae)* $CSA = -0.202 \times CC_{TRU} + 0.092 \times SK + 0.953 \times BW - 69.846 \times BH + 95.923$ **$r^2 = 0.557$; SEEr = 22.3%**
- *Rectus abdominis (umbilical scar)* $CSA = -0.069 \times CC_{TRU} + 0.007 \times SK + 0.304 \times BW - 13.213 \times BH + 14.380$ **$r^2 = 0.706$; SEEr = 19.9%**
- *Rectus abdominis (4 cm)* $CSA = -0.038 \times CC_{TRU} - 0.014 \times SK + 0.172 \times BW - 9.369 \times BH + 13.553$ **$r^2 = 0.423$; SEEr = 20.9%**

Figure 5 shows the 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 each of the trunk muscles and regions.

DISCUSSION

The purpose of this study was to develop multiple linear regression equations to predict CSA for two different regions of upper limb, lower limb, and trunk muscles based on anthropometry and US images. 17 equations were derived: two equations for pectoralis major, triceps brachii, rectus abdominis, rectus femoris, vastus lateralis, biceps femoris, gastrocnemius lateralis and gastroc-

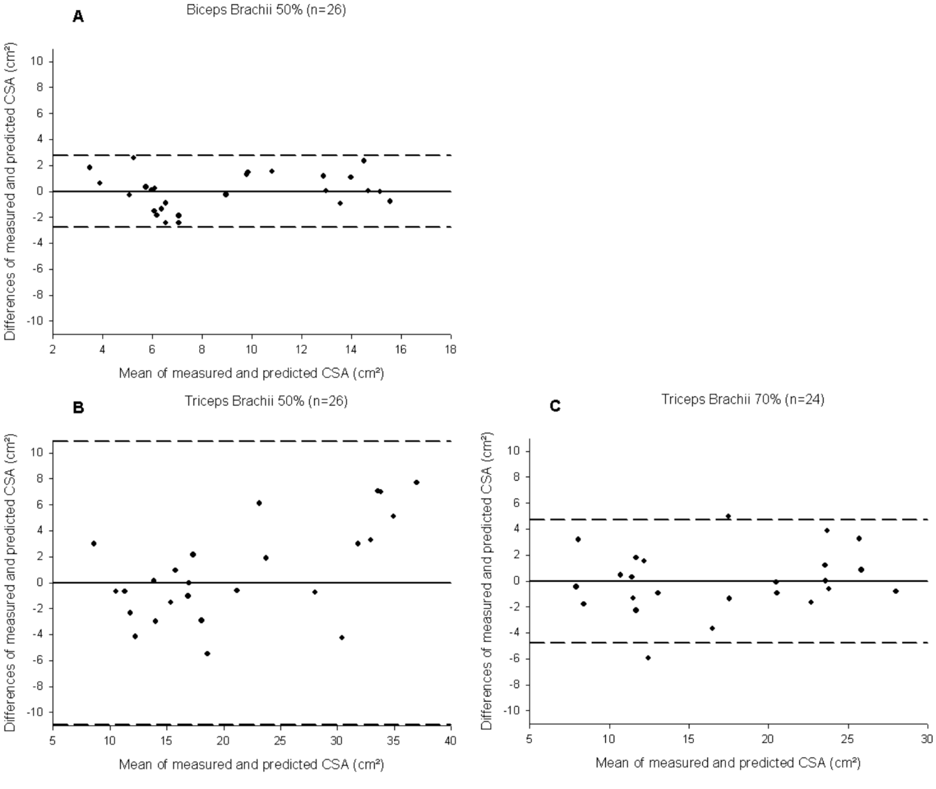

Figure 4. Bland-Altman method plots comparing the error obtained between the values of CSA measured by ultrasound and the values of CSA predicted by the equations for each of the arm muscles and regions.

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 biceps brachii at 50% (**A**), and triceps brachii at 50% (**B**) and 70% (**C**). The solid line represents the mean differences between the measured CSA and the predicted CSA. The dashed lines represent the confidence interval of the differences between the measured CSA and the predicted CSA.

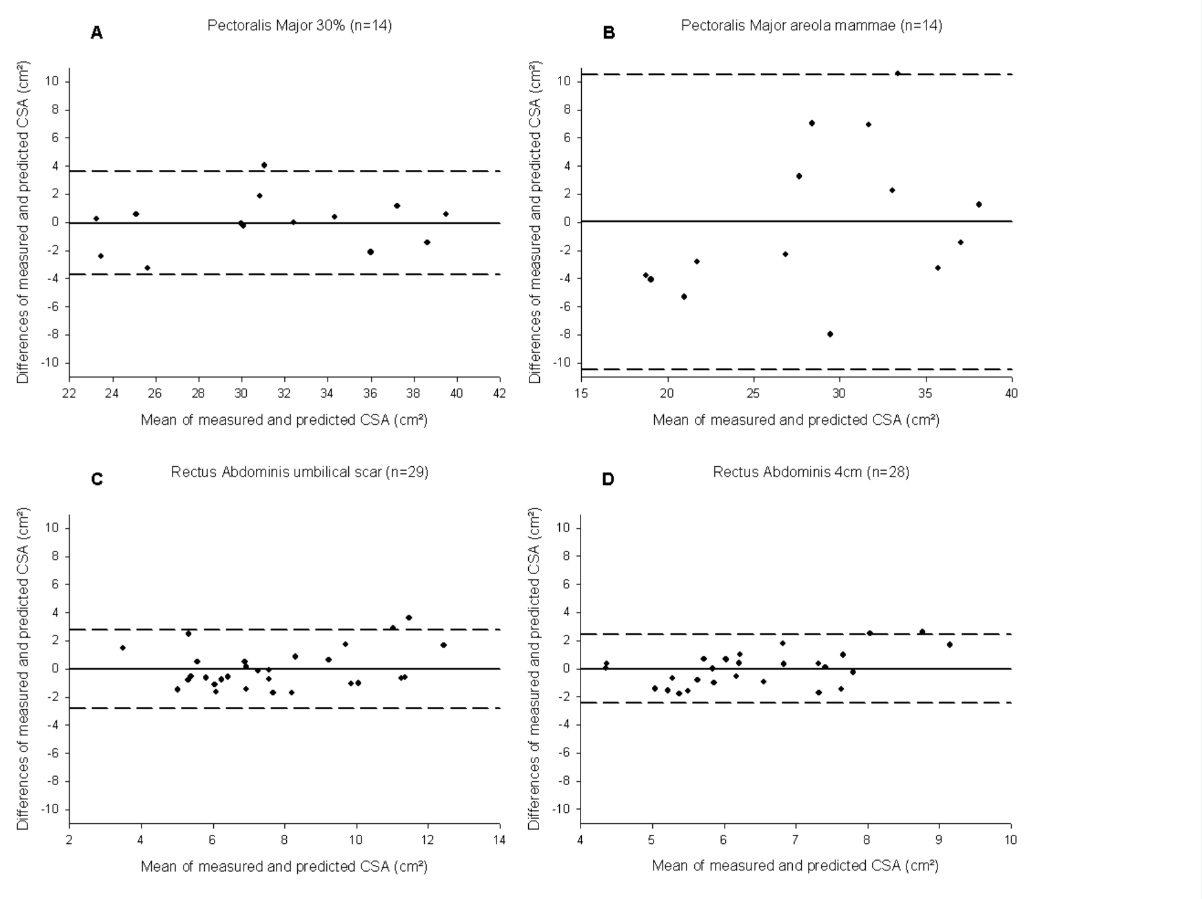

Figure 5. Shows the Bland-Altman method plots comparing the error obtained between the values of CSA measured by ultrasound and the values of CSA predicted by the equations for each of the trunk muscles and regions.

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 pectoralis major at 30% **(A)**, and areola mammae **(B)**, and Rectus abdominis at umbilical scar **(C)** and 4 cm of umbilical scar **(D)**. The solid line represents the mean differences between the measured CSA and the predicted CSA. The dashed lines represent the confidence interval of the differences between the measured CSA and the predicted CSA.

nemius medialis muscles, and one equation for biceps brachii muscle. From the equations developed, 10 of them presented a magnitude of relative error between 7.2 and 19.9%, values which are comparable or less than those found in commonly used equations to estimate body density (SEEr = 17%) (21) and cardiorespiratory capacity (VO_2 maximum; relative errors of 20 and 16% for men and women, respectively (25). Additionally, Bland-Altman analysis shows that all equations demonstrated an error close to zero, revealing a high level of agreement between CSA measured by ultrasound and the values of CSA estimated by the equations. Thus, the results of present study demonstrate the ability of the multiple linear regression equations derived to predict CSA of pectoralis major at 30%, biceps brachii at 50%, triceps brachii at 70%, rectus abdominis at umbilical scar level, rectus femoris at 50%, vastus lateralis 50 and 70%, biceps femoris at 50 and 70%, and gastrocnemius lateralis at 25%.

It is important to emphasize that all regression equations have an inherent error and the decision to use the equation is usually based on a compromise between practicality and accuracy (4). The decision whether to use an equation must consider the magnitude of error that can be expected (4).

Equations using anthropometric measures to estimate muscle + bone area, or lean body mass, are based on three or four assumptions: 1) the upper and lower limbs would have cylindrical shapes; 2) skinfold measurement would be equivalent to twice the average diameter of adipose tissue and this tissue in the subcutaneous region would have a uniform thickness; 3) muscle and bone compartments of the limbs would have a cylindrical shapes (4, 11, 14); and 4) there would be no adipose tissue between and within muscles (14). However, given that the information presented above is not necessarily true, researchers have attributed to those assumptions the errors found when such equations are used (2, 4, 10, 13, 14) which can vary between 15 and 25% (2, 10). The use of multiple regression equations based on both anthropometric measures and imaging exams for predicting muscle area, such as the one developed by Housh *et al.* (4), does not require assumptions about muscle shape, limb shape, or subcutaneous adipose tissue. It is important to emphasize that any regression equation that does not exhibit a perfect relationship between variables (r = 1.00 or -1.00) contains an inherent error, and the decision to use the equation should be based on a trade-off between practicality and accuracy, considering expected error for the measurement (4).

Regression equations are also used for other purposes in sports science. Jackson and Pollock (21, 26) developed generalized equations capable of estimating body density for male and female individuals. The proposed equations for males can predict body density considering different ages and body compositions, with an average error of 17% (4, 21). However, the equations proposed for females, while showing a valid degree of accuracy for estimating body composition, may not be as accurate for individuals over 40 years old and with a body mass index below 20% (26, 27). The American College of Sports Medicine (ACSM) regression equation commonly used to predict maximum oxygen uptake has an error of 20% for men and 16% for female people, overestimating cardiorespiratory capacity when used (25).

The use of imaging exams to validate anthropometric equations is another factor that would contribute to reducing prediction errors of equations (4, 13). Housh *et al.* (4) developed the equation using images obtained with MRI, whichare considered gold standards in the evaluation of body tissues, as well as images by CT scans (2-4, 5-8). However, MRI and CT scans are the most expensive and least accessible methods for professionals (2, 4, 5, 6, 8). Ultrasound was initially used to evaluate muscle and adipose tissue thickness, but the development of panoramic ultrasound allowed this technique to assess muscle area with good accuracy compared to gold standard methods (2, 8, 28, 34). The technological advancements have made this technique accessible with better cost-effectiveness (2, 28). Considering all these information, the present study used anthropometric measures (circumference and skinfolds), employed multiple linear regression analysis, and added muscle area data obtained through panoramic ultrasound images to develop equations that could predict muscle area with low relative error values. Therefore, sports and exercise professionals could accurately assess the muscular area of the lower limbs, upper limbs and trunk in their practice. In the present study, relative prediction errors were considered acceptable when the values obtained from the developed equations were less than or equal to 20%. These criterion was based on prediction errors values of other equations commonly used in sports science (4, 22, 25).

Thigh muscle

To quantify muscle CSA, Housh *et al.* (4) proposed a multiple regression equation based on anthropometry and MRI images of the quadriceps, the hamstrings, and hip adductors at 50% of the distance between the superior border of the head of the femur to the inferior border of the medial condyle. The researchers derived equations presenting potential errors ranging from approximately 7.3%-19.5% of the estimated quadriceps CSA, 12.6-22.3% of the estimated hamstrings CSA, and 7.1-17.7% of the total thigh muscles CSA. In the present study, the rectus femoris, vastus lateralis, and biceps femoris were analyzed individually. At 50% distance, the proposed equations presented a SEEr of 18.8%, 14.7%, and 15.8%, respectively. The equations derived for the vastus lateralis, and biceps femoris at 70% of the distance also presented good predictive ability, with a SEEr of 16.9%, and 19.8%, respectively. The vastus lateralis muscle represents a large area and volume of the thigh segment, which explains the lower error associated with the predictions of the CSA. However, different from the results found by Housh *et al.* (4), the SEEr found for the hamstrings CSA are below 22.3%, in both 50% (15.8%), and 70% distance (19.8%). At 70% distance, rectus femoris CSA represents a small area of the thigh segment (average of 3.4 cm^2), thus, the greater error associated with the prediction of the CSA (41.3%) was an expected finding.

Leg muscles

Other studies proposed equations to predict CSA of lower limb muscles based on anthropometry and images techniques (13, 29). Similar to Housh *et al.* (4), the equations derived in those studies were proposed to predict CSA of muscle groups or the limb, not for muscles individually. Rice *et al.* (13) assessed CSA of the plantar flexor muscles in young and aged males using anthropometry and computed tomography. The authors noted that the predictive ability of muscle size using anthropometry depends on the limb and the age of the subject. They also observed that the prediction error of total leg area using anthropometry overestimated the CSA when compared to CT scans in both groups. For the young male group, the relative error varied between 1.4%-15.1%, and for the elderly male group, the SEEr varied between 5.4%-9.6%. Rice *et al.* (13) concluded that the equations derived from their study were valid and could be used to estimate muscle CSA of calf muscles in young males. Thus, it can be inferred that the equation proposed in the present study to predict CSA of lateral gastrocnemius muscle at 25% distance, which demonstrated a SEEr of 14.8%, also presents a good predictive ability and can be used to assess muscle CSA of young individuals.

Arm muscles

Similar to lower limb muscles, prediction equations proposed for upper limb muscles using anthropometry and imaging techniques do not assess muscles individually. Heymsfield *et al.* (11) proposed a revised equation to predict arm muscle area minus bone and, after correcting the equation proposed earlier for Jelliffe and Jelliffe (10), the final equation presented with a SEEr of 8% when compared to area measured using computed tomography. The authors suggested that despite the error and overestimation of the arm muscle area, the equation using circumference and triceps skinfold can provide valuable information that is inexpensive, simple, and practical to collect. Rice *et al.* (13) also proposed equations to predict area of arm muscles in young and aged males using anthropometry and computed tomography. However, the predictive equations demonstrated an error twice as large as for the leg for young males and 30% larger for aged males. The authors believe that the main difficulty can be attributed to the fact that none of the muscle groups represents more than 40% of the total limb size, and neither predominates (13). The present study proposed equations for two distinct regions of the triceps brachii and one region of the biceps brachii. The equation derived for the triceps muscle at 70% distance presented with a SEEr of 15.7% and the equation for the biceps muscle at 50% demonstrated a SEEr of 17.2%. The muscles were analyzed individually, different from other proposed equations, which reduces even further their proportion related to the segment. Thus, although the proposed equations for triceps brachii at 70% and biceps brachii at 50% present greater SEEr compared to previous studies, they show good ability to predict muscle CSA. The biceps brachii at 70% distance was not assessed due to limitations of US image acquisition.

Trunk muscles

There are no previous studies that developed multiple regression equations to predict CSA of pectoralis major or rectus abdominis muscles. Pectoralis major muscle was only analyzed in male participants; the scans were acquired at 30% of the distance between the superior border on the sternoclavicular joint and the top of the umbilical scar; and the superior border of the areola mammae, which required that, participants were bare-breasted, and this procedure could be uncomfortable for some women. The equation developed for the pectoralis major muscle at 30% of the distance demonstrated the lowest SEEr, 7.2%. The sample of the present study was characterized by male, trained individuals and low adipose tissue thickness. in the evaluated region, thereby reducing the contribution of this tissue to circumference measurement. Furthermore, a small amount of intramuscular fat may have improved the quality of the ultrasound image, which would contribute to reducing the equation's error in predicting muscle CSA (28). The rectus abdominis muscle demonstrated acceptable predictive capability at the distance immediately above the umbilical scar, where the SEEr found was 19.9%. Despite the muscle representing a small portion of the abdomen, a reduced thickness of adipose tissue in the region of the evaluated participants, as well as in the chest, may have contributed to an acceptable error, albeit at the upper limit of the determined error.

Final considerations

As has been previously reported in the literature, imaging techniques, especially MRI, are the gold standard tools to measure muscle CSA (2-8). Although MRI can accurately determine muscle size, Barnouin *et al.* (30) reported a mean interrater difference of 4.4% when measuring quadriceps femoris muscle CSA. Some degree of error is expected when using regression equations; however, the estimation of muscle CSA using equations can be useful when more sophisticated procedures are not available. Perhaps applying equations to monitor training-induced changes in muscle CSA is more important than a single-time point assessment, which allows researchers to test the efficacy of exercise interventions (8). DeFreitas *et al.* (5) applied Housh's equation to detect changes in quadriceps CSA following 8 weeks of resistance training. Although Housh's equation underestimated changes in muscle CSA when compared to computed tomography, the anthropometric-based equation was able to show a significant increase in muscle CSA after only 2 weeks of training.

Nevertheless, it must be emphasized that care must be taken when using the equations in a population different from the one to which they were developed for, as regression equations are population specific (21, 26, 27, 31). Applying these equations in a different population will undoubtedly magnify the prediction error.

CONCLUSIONS

Thus, the present study developed 10 multiple regression equations to predict CSA of thigh, leg, arm and trunk muscles that demonstrated error of estimate similar to other equations commonly used by sport and exercise professionals. The anthropometric equations developed in the present study are recommended for single-time point assessment of muscle CSA, however, their usefulness for monitoring training-induced changes requires further research.

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DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

RCRD: funding, conceptualization, data analysis, writing – original draft. MOCF, BTRS, MDMS: data analysis, writing – original draft. MOCF, BTRS, FSL, BFR, MCNF, LTL: study execution. MOCF, FVL, MHC, LTL, RCRD: writing – review & editing.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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