

Anthropometric Models to Predict Appendicular Lean Soft Tissue in Adolescent Athletes

ANA L. QUITERIO¹, ELVIS A. CARNERO¹, ANALIZA M. SILVA¹, BRIANNA C. BRIGHT², and LUIS B. SARDINHA¹

¹Exercise and Health Laboratory, Faculty of Human Movement, Technical University of Lisbon, Lisboa, PORTUGAL; and ²Department of Pediatrics, College of Medicine, University of Oklahoma Health Sciences Center, Oklahoma City, OK

ABSTRACT

QUITERIO, A. L., E. A. CARNERO, A. M. SILVA, B. C. BRIGHT, and L. B. SARDINHA. Anthropometric Models to Predict Appendicular Lean Soft Tissue in Adolescent Athletes. *Med. Sci. Sports Exerc.*, Vol. 41, No. 4, pp. 828–836, 2009. **Purpose:** Skeletal muscle (SM), which is found mainly within the appendicular lean soft tissue (ALST) compartment, is a biologically important body compartment. Simple and accurate methods to estimate both SM and ALST remain difficult to obtain. We aimed to develop and to cross-validate anthropometric models for ALST in athletes, using dual-energy x-ray absorptiometry (DXA) as the reference method. **Methods:** ALST equations were developed in 176 athletic boys (15.0 ± 2.8 yr; 64.5 ± 15.8 kg; 1.72 ± 0.15 m) and 92 athletic girls (14.6 ± 2.8 yr; 53.0 ± 13.1 kg; 1.61 ± 0.13 m). Skinfolts were measured at the triceps, the thigh, and medial calf, and circumferences were measured at the midupper arm, the midthigh, and the midcalf. ALST was assessed using DXA (QDR-4500; Hologic, Waltham, MA; fan-beam mode). Two models were developed: a body weight model (WHt model) and a corrected muscle girth model (CMG model), which included the parameters height \times CAG², height \times CTG², and height \times CCG², where CAG is corrected arm girth, CTG is corrected thigh girth, and CCG is the corrected calf. Simple regression analysis was used to identify the best model fit. The equations were internally cross-validated using the predicted residual sum of squares method, and performance of new equations was analyzed by regression analysis and agreement between methods. **Results:** The new WHt model generated the following equation: $ALST = -20.338 + 0.199(W) + 3.294(\text{gender}) + 14.230(\text{height}) + 0.192(\text{age})$, where gender = 1 for male and 0 for female. The CMG model produced the following equation: $ALST = 3.260 + 0.002(\text{height} \times \text{CTG}^2) + 0.007(\text{height} \times \text{CAG}^2) + 0.003(\text{height} \times \text{CCG}^2)$. WHt equation had an $R^2 = 0.91$ and an SEE = 2.00 kg, whereas CMG equation presented an $R^2 = 0.93$ and an SEE = 1.80 kg. In both equations, slopes and intercepts did not differ from the line of identity; no mean differences between predicted and measured values and no trend line were observed ($P > 0.05$). **Conclusions:** Both models accurately predict ALST in young athletes, affording a practical means to quantify this compartment. **Key Words:** SKELETAL MUSCLE, DXA, SKINFOLDS, CROSS-VALIDATION

Skeletal muscle (SM), the largest nonadipose tissue component at the tissue level of human body composition (33), plays an important role in physical activity performance and many nutritional, physiological, metabolic, and biochemical processes (15,21,33). In sports science, it is remarkable that there are no simple and inexpensive satisfactory methods for estimating the mass of the SM in athletes, whereas there is a large body of studies addressing accurate body fat estimations. Information on the physiological profile of an athlete would be improved adding valid regional and total SM measures. Additionally,

simple and accurate methods to evaluate this large and functionally important compartment, easily applied during the training routines, would enable coaches to regularly evaluate athletes and monitor the effects of different training regimes, maintaining the athletes with healthy weights, without a loss of lean tissue, while improving their sports performance.

Despite the potential usefulness of information on the mass of the SM of the human body, accurate and practical methods to quantify SM mass are difficult to assess, costly, and involve imaging techniques, such as computed axial tomography (CT) and magnetic resonance imaging (MRI). In addition, CT method exposes the subject to radiation, which limits its application in children and adolescents (19,27). A practical alternative to assess SM is dual-energy x-ray absorptiometry (DXA) instruments, which are widely available, noninvasive, and can be easily performed in children and adolescents. Whole-body DXA systems enables investigators to identify specific regions for analysis and to separate lower and upper limbs from trunk and its masses into bone, fat, and lean soft tissue compartments (27) using DXA regional specific anatomical landmarks.

Address for correspondence: Luis B. Sardinha, Ph.D., Exercise and Health Laboratory, Faculty of Human Movement, Technical University of Lisbon, Estrada da Costa, Cruz Quebrada, 1495-688, Lisboa, Portugal, E-mail: lsardinha@fmh.mtl.pt

Submitted for publication March 2008.

Accepted for publication October 2008.

0195-9131/09/4104-0828/0

MEDICINE & SCIENCE IN SPORTS & EXERCISE®

Copyright © 2009 by the American College of Sports Medicine

DOI: 10.1249/MSS.0b013e31818ffe4b

Given that lean soft tissue of the extremities is almost entirely SM, except for a small amount of skin and connective tissues, DXA affords an opportunity to estimate appendicular SM mass through the measurements of appendicular lean soft tissue (ALST) (34) and by summing ALST measures of the extremities, that is, in both the right and the left arms and legs. Accordingly, many authors have proposed the use of DXA to estimate total and regional SM (8,12,16,17,32,34). Despite the great interest of studying the extremity muscle *per se*, the appendages account for the larger portion (73–75%) of total body SM (12,29). This concept underlies the rationale for using DXA for SM mass estimates.

Nevertheless, DXA is still costly and is not a portable instrument, which limits its application in epidemiological and field studies. Anthropometry has been referred as a practical and an inexpensive method to estimate SM. In young athletes, anthropometric measurements are easily to perform and can be widely used because minimal training is required to accurately assess anthropometric values. Early studies reported the use of anthropometric prediction models for quantifying SM (5,22). Both these investigations were based on a small sample of cadavers of elderly men. Recently, Lee et al. (19) developed and cross-validated anthropometric prediction formulas for total body SM using MRI as the reference method in a large heterogeneous sample. The general concept is that three quarters of total-body SM exists in the extremities, and ALST is primarily SM. In addition, the model proposed by Lee et al. (19) was based on anthropometric dimensions, assuming that whole-body SM is conceptually in the form of a cylinder, that skinfold (SKF)-corrected limb circumferences provides a measure of corresponding appendicular lean tissue circumferences, that appendicular lean tissue circumferences squared creates an estimate of lean tissue area, and that the product of summed estimated appendicular lean tissue areas and height provides a measure of total-body SM (19). Although the authors found that the designed model was accurate in SM mass prediction in a healthy heterogeneous adult population, its applicability in adolescent athletes is unknown.

Moreover, although sports scientists and investigators from several other disciplines have been interested in the study of SM compartment in athletes to improve health, fitness, and sports performance (1,18,23,26), unfortunately, to our knowledge, there are no simple, inexpensive, and noninvasive methods for SM mass prediction in adolescent athletes, which is a gap in sports science because SM is central in exercise performance.

Hence, the goal of the present investigation was to develop and cross-validate practical anthropometric models for ALST in young athletes, assuming that the larger proportion of SM is in the extremities and the appendicular SM is the main contributor to ALST. Additionally, based on previous studies (5,19,22) where the overall theme is that whole-body SM is in the form of a cylinder, we investigated

whether SKF thickness, circumference measurements and stature (components of the cylinder's dimensions of the SM mass of the human body), and also body weight would be useful tools for accurately quantifying ALST in young athletes.

SUBJECTS AND METHODS

Study Design

Portuguese young athletes were recruited from the following local sports clubs through written and/or oral advertisements: 75 from swimming, 47 from gymnasts, 40 from basketball, 38 from judo, 35 from rugby, 10 from volleyball, 8 from soccer, 8 from triathlon, and 7 from handball. Each participant and one parent were informed about the research design and procedures, with parental consent being obtained by signing a written consent form. All procedures and consent forms were approved by the Ethical Committee of the Faculty of Human Movement, Technical University of Lisbon, Portugal.

Subjects

A total of 176 athletic boys (15.0 ± 2.8 yr; 64.5 ± 15.8 kg; 1.72 ± 0.15 m; 9.4 ± 6.7 h·wk⁻¹ of training) and 92 athletic girls (14.6 ± 2.8 yr; 53.0 ± 13.1 kg; 1.61 ± 0.13 m; 11.8 ± 5.2 h·wk⁻¹ of training) participated in this investigation. The inclusion criterion for the athletes was current participation in competitive sports at national and international levels. The athletes should take part in regular physical training for at least two intense hours per week and for at least 3 yr. Athletes who were taking medication for illness, injuries, or any kind of unnatural supplements did not take part of the study. In addition, we found four amenorrheic gymnasts that were also excluded from the study. We did not evaluate the amenorrheic athletes to ensure that all girls had similar hormonal conditions and because abnormal menstrual patterns are often associated with an extremely low body weight and fat content. Finally, those athletes who were in a process of gaining or losing weight also did not take part in this investigation.

Maturation

Subjects were grouped by Tanner stage, determined by self-assessment, according to Tanner (30). A self-evaluation method was used to identify the degrees of development of the genital organs, breast, and pubic hair.

Sports Training

Hours per week of sports training (h·wk⁻¹) were self-reported by athletes, using a specific questionnaire, developed for the study. The questionnaire included five questions: 1) Which competitive sport do you practice?; 2) How old were you when you started training?; 3) How

many days per week are you engaged on sport training? Please indicate in which days of the week do you practice; 4) Are you engaged on training more than one time per day? If no, please indicate how long takes the training, in each of the week days. If yes, please indicate which week days do you practice twice and how long takes each training; 5) Do you usually miss training? Please indicate: often (a); some times (b); exceptionally (c); almost never (d). Please describe the reason that makes you miss training.

Each coach also reported how many times per week did athletes take part of training and at what time were the habitual training sessions. The coaches confirmed the answers of each athlete at the time of the measurements or later on the training. Training participation was also assessed using standard club assiduity reports, fulfilled by the coaches, during the previous 12 months of the training season. Hours per week were determined by multiplying the number of training sessions performed during a week by hours per training session. Modifications of usual training intensity and volume caused by injuries, illness, and competition were noted and accounted for in the final calculation.

Assessment of Body Composition

Body composition measurements were performed on the same day, during a visit to the study laboratory, over a 4-h period. The measurements were performed by the same technician in standardized conditions. Subjects were asked to fast from the previous evening and also to avoid moderate-to-vigorous exercise training intensity from the previous 24 h.

Anthropometric measures. Anthropometric measurements were performed using standardized procedures. The measurements were performed by a highly trained technician in standardized conditions.

Body weight was measured twice using an electronic scale (SECA model 770, Hamburg, Germany) to the nearest 0.1 kg, with the average used as their weight. Stature was also measured twice, without shoes, to the nearest 0.1 cm with the average used as their height.

Skinfolds (SKF) were measured three times to the nearest 0.1 mm and averaged for analysis. All SKF measurements were made on the right site of the body, at appropriately marked sites, using a Lange caliper (Cambridge Scientific, Cambridge, MD). SKF were measured at the triceps, the thigh, and the medial calf according to the standardized anatomic locations and methods (20). On the basis of test-retest using 10 subjects, the technical error of measurements (TEM) for triceps, thigh, and medial calf SKF measurements were 0.39, 0.47, and 0.39 mm, respectively, according to the following equation: $(\sum d^2 / 2n)^{1/2}$, where d stands for the difference between repeated measurements, and n is the number of paired repeated measurements. The intraclass coefficient of correlation (ICC) for triceps, thigh, and medial calf SKF were 0.997, 0.994, and 0.996, respectively.

Circumference measurements were made in the plane orthogonal, according to the standardized procedures (20). Circumferences were measured at the midupper arm, the midthigh, and the midcalf three times and averaged for analysis. On the basis of test-retest using 10 subjects, the TEM for the midupper arm, the midthigh, and the midcalf circumference measurements were 0.04, 0.35, and 0.27 cm, respectively. The ICC were 1.000, 0.998, and 0.995, respectively.

Each limb circumference (C_{limb}) was corrected for subcutaneous adipose tissue thickness, according to Lee et al. (19). The corrected muscle circumferences (C_m) were calculated as $C_m = C_{limb} - \pi S$, where S stands for the SKF caliper measurement, which is assumed to be twice the subcutaneous adipose tissue thickness.

DXA. Whole-body and regional body composition were estimated by using DXA (QDR-4500; Hologic, Waltham, MA; fan-beam mode). After completion the scans, the system provided the total and the regional body composition results of fat-free soft tissue, body fat, and bone mineral content (BMC). The DXA system software first divides pixels into bone mineral and soft tissue compartments. Soft tissue is then further separated into lean soft tissue and fat (25). Appendicular lean soft tissue (ALST) mass was considered as the sum of lean soft tissue in both left and right arms and legs. The same laboratory technician positioned the subjects, performed the scans, and executed the analyses using the standard protocol. On the basis of test-retest using 10 subjects, the TEM and the coefficient of variation for BMC in our laboratory were 0.02 kg and 1.6%, respectively.

Statistical Analysis

Descriptive results are expressed in terms of group means \pm SD, and between-gender differences were explored by using Student's t -test.

Two anthropometric prediction models were prepared: a body weight model (WHt model) and a corrected muscle girth model (CMG model). First, we select age, gender, maturation, body weight, and height as the independent variables (WHt equation). We develop a model based on body weight and height, without corrected muscle girths parameters, because it enables these measures, which are widely used and easily to perform without specific technician training, to predict ALST. In the second model (CMG equation), each limb circumference corrected for subcutaneous adipose tissue thickness was added, along with age, gender, and maturation. For dimensional consistency, corrected muscle circumferences were squared and multiplied by height so that each term of the equation took the form of a length cubed, providing a measure of total muscle area and regional variation in SM mass and distribution area (19,22): height \times CAG²; height \times CTG²; height \times CCG², where CAG is corrected arm girth, CTG is corrected thigh girth, and CCG is corrected calf girth.

TABLE 1. Characteristics and body composition measurements of the athletes.*

	All (N = 268)	Girls (n = 92)	Boys (n = 176)
Age (yr)	14.9 ± 2.7	14.6 ± 2.8	15.0 ± 2.8
Sport training (h·wk ⁻¹)	10.2 ± 6.4	11.8 ± 5.2	9.4 ± 6.7 ^b
Maturation (Tanner stages)	1.70 ± 0.7	1.85 ± 0.74	1.62 ± 0.68 ^b
Weight (kg)	60.5 ± 15.9	53.0 ± 13.1	64.5 ± 15.8 ^a
Height (m)	1.68 ± 0.15	1.61 ± 0.13	1.72 ± 0.15
BMI (kg·m ⁻²)	21.0 ± 2.8	20.2 ± 2.48	21.5 ± 2.84 ^a
SKF thickness (mm)			
Triceps	11.7 ± 5.8	15.0 ± 5.9	9.9 ± 4.9 ^a
Biceps	5.5 ± 3.2	6.9 ± 3.3	4.8 ± 2.9 ^a
Mid thigh	16.3 ± 7.9	22.4 ± 7.8	13.1 ± 5.7 ^a
Mid calf	11.3 ± 6.1	14.7 ± 6.6	9.6 ± 4.9 ^a
Circumferences (cm)			
Mid upper arm	26.8 ± 3.7	25.1 ± 3.3	27.8 ± 3.6 ^a
Mid thigh	49.1 ± 5.7	47.7 ± 5.4	49.8 ± 5.7 ^b
Mid calf	35.2 ± 3.8	33.7 ± 3.6	35.9 ± 3.7 ^a
Corrected muscle girths CMG (cm)			
Triceps (CAG)	26.7 ± 3.7	24.8 ± 3.2	27.6 ± 3.5 ^a
Mid thigh (CTG)	36.3 ± 7.7	30.1 ± 4.7	30.1 ± 4.7 ^a
Mid calf (CCG)	26.3 ± 5.6	22.2 ± 4.2	28.4 ± 5.1 ^a
DXA			
BMD (g·cm ⁻²)	1.14 ± 0.20	1.10 ± 0.17	1.17 ± 0.21 ^b
BMC (kg)	2.34 ± 0.80	2.04 ± 0.63	2.50 ± 0.84 ^a
BF (kg)	11.3 ± 6.6	12.8 ± 5.5	10.5 ± 7.0 ^b
BF (%)	18.8 ± 7.5	23.7 ± 5.7	16.2 ± 7.0 ^a
LST (kg)	46.4 ± 13.4	37.6 ± 8.2	51.0 ± 13.3 ^a
ALST (kg)	20.6 ± 6.6	15.9 ± 3.6	23.1 ± 6.4 ^a

* All values are expressed as mean ± SD.

^a Significant differences between male and female athletes (Student's *t*-test), *P* < 0.001.

^b Significant differences between male and female athletes (Student's *t*-test), *P* < 0.05. BMD, bone mineral density; BMC, bone mineral content; BF, body fat; LST, lean soft tissue; ALST, appendicular lean soft tissue.

Stepwise regression analysis was performed to identify which combination of variables would best predict ALST measured by DXA. The coefficient of determination (R^2) and the SEE were estimated. The criterion for inclusion (addition and retention) of predictors was the highest R^2 model and the lowest SEE. The two models were then internally validated by using the predicted residual sum of squares (PRESS) statistics method as described elsewhere (14).

In the current study, the model adequacy was measured using the alternative suggested by Holiday et al. (14) and Myers (24):

$$R^2 = 1 - [\text{PRESS}/\text{SS}(\text{total})]. \quad [1]$$

Similarly, SEE was calculated as follows:

$$\text{SEE} = \sqrt{\text{PRESS}/n}. \quad [2]$$

where *n* is the number of observations. Simple regression analysis was performed to determine the relationships between ALST predicted by the new equations and ALST assessed by DXA. Slopes and intercepts were examined as well as the R^2 and the SEE. In addition, the pure error (PE) was assessed as another measure of validation using the following equation: $[\sum(Y - \hat{Y})^2 / n]^{1/2}$, where \hat{Y} is the predicted ALST, *Y* is the observed value of ALST, and *n* is the number of subjects (28). Agreement between the reference method and the two prediction equations was also assessed, by analyzing the mean differences between methods, limits of agreement, and trend, according to Bland

and Altman (3). Instead of the standard Bland–Altman plot, in the current study, a plot of residuals (prediction errors) against predicted values was performed. This plot is similar to the plot suggested by Bland and Altman (3), except that predicted values of ALST (using the new developed anthropometric equations) are plotted on the *x*-axis rather than the average of predicted and measures ALST values (7). Data were analyzed by using SPSS for WINDOWS version 15.0 (SPSS Inc., Chicago, IL), and statistical significance was set at *P* < 0.05.

RESULTS

Subjects Characteristics

The characteristics of all the studied athletes are shown in Table 1. There were no significant differences in age between boys and girls. Girls were significantly more mature. Boys presented significantly less hours per week of sports training compared with girls and were significantly heavier, presenting also a higher BMI in relation to girls. SKF values were significantly higher in girls, whereas the circumferences measures were greater in boys. All lean measures obtained using DXA were significantly higher in male athletes comparing with female athletes, whereas body fat was greater in girls.

Anthropometric Prediction Models

Body weight and height model (WHt equation). New anthropometric models generated in current Portuguese athletes (entire sample) are given in Table 2. Maturation level was not significant in the prediction of ALST after including age, gender, weight, and height into the WHt model (*P* = 0.246). Weight was the strongest predictor of DXA-measured ALST, explaining 83% of the variation in ALST, with an SEE of 2.72 kg. Gender and height explained an additional 5% and 3%, respectively, of the variance in measured ALST, and the SEE decreased for 2.3 and 2.0 kg, respectively. Finally, age added 0.4% of the

TABLE 2. Regression models and internal cross-validation for the prediction of DXA-measured ALST.

	R^2	SEE	Coefficient	<i>P</i> Value	Cross-validation	
					R_{PRESS}^2	SEE _{PRESS}
WHt model						
Intercept			−20.338	<0.001		
Weight			0.199	<0.001		
Gender			3.294	<0.001		
Height			14.230	<0.001		
Age			0.192	0.001		
Total model	0.91	2.01			0.91	2.01
CMG model						
Intercept			3.260	<0.001		
Height × CTG ²			0.002	<0.001		
Height × CAG ²			0.007	<0.001		
Height × CCG ²			0.003	<0.001		
Total model	0.93	1.80			0.92	1.82

Maturation was not a significant predictor in the final developed WHt model (*P* = 0.246). Age, gender, and maturation were not significant predictors in the final developed CMG model (*P* = 0.142, 0.614, and 0.274, respectively).

variation in ALST, with the final equation accounting for 91% of the variability of ALST ($R^2 = 0.91$; SEE = 2.0 kg; $P < 0.05$). The slope of gender had a clinically meaningful ($b = 3.294$) because it indicates that for a given weight, male athletes had approximately more 3.3 kg of ALST comparing with female athletes.

The selected prediction equation based on weight and height was (Table 2):

$$\text{ALST} = -20.388 + 0.199 (W) + 3.294 (\text{gender}) + 14.230 (\text{Ht}) + 0.192 (\text{age}), \quad [3]$$

where gender = 1 for male athletes and 0 for female athletes, W is weight (kg), Ht is height (m), and age is in years.

Corrected muscle girth model (CMG equation). Age, gender, or maturation level were not significant in predicting DXA-measured ALST after including CMG parameters into the model ($P = 0.142$, 0.614 , and 0.274 , respectively). The results obtained in stepwise regression analysis indicate that all the three corrected limb circumferences (CTG, CAG, and CCG) explained 86% of the variance in ALST, with an SEE of 2.43 kg (data not shown). However, the stronger predictors of ALST were the square of each corrected limb circumferences multiplied by height. The parameter height \times CTG² explained 84% of the variation in ALST, with an SEE of 2.63 kg. Height \times CAG² and height \times CCG² explained an additional 6% and 2% of the variability in ALST, with SEE of 2.04 and 1.80 kg, respectively ($P < 0.001$; Table 2). Considering the stronger predictors, that is, the square of all the corrected muscles girths multiplied by height, the selected equation was then developed (Table 2):

$$\text{ALST} = 3.260 + 0.002 (\text{Ht} \times \text{CTG}^2) + 0.007 (\text{Ht} \times \text{CAG}^2) + (\text{Ht} \times \text{CCG}^2), \quad [4]$$

where CTG is corrected thigh girth, CAG is corrected arm girth, and CCG is corrected calf girth.

Cross-Validation of New Generated Anthropometric Models

The developed models were validated by using the PRESS statistics method. The accuracy of the two developed anthropometric prediction equations is illustrated in Table 2. Considering the new developed anthropometric models, the high R^2 and the low SEE observed after using the PRESS statistic method indicate an excellent accuracy for both methods, although CMG model presented a higher R^2 and a lower SEE than the model based on weight and height ($R^2 = 0.92$ vs 0.91 ; SEE = 1.82 vs 2.01 kg, respectively).

Regression analysis between predicted and measured ALST showed that WHt equation had an R^2 of 0.91 and an SEE of 2.00 kg (Fig. 1A), whereas CMG equation was strongly correlated with DXA-measured ALST and the

resulting regression equation had an R^2 of 0.93 and a lower SEE of 1.80 kg (Fig. 1C). In both equations, slopes and intercepts did not differ from the line of identity because slopes were not significantly different from 1 and intercepts were not significantly different from 0 ($P > 0.05$). In addition, the PE for ALST predicted using CMG equation was lower than using WHt model (0.34 vs 1.42 kg, respectively). The relation between residuals and predicted ALST values is illustrated in Figure 1B and D. No significant mean differences between predicted and measured values and small limits of agreement were found (bias \pm 1.96 SD = -0.03 ± 3.90 kg, $P = 0.057$; and bias \pm 1.96 SD = 0.21 ± 3.55 kg, $P = 0.822$, using the WHt and the CMG equations, respectively). As shown in Figure 1B and D, the spread of prediction error was consistent across the range of predicted ALST using both the new developed equations, and no significant trend line was observed ($r = -0.003$, $P = 0.958$; and $r = 0.093$, $P = 0.130$, using WHt and CMG equations, respectively).

DISCUSSION

The primary aim of the present investigation was to develop two anthropometric models to predict ALST in athletes based on DXA–ALST as the reference method. The first model is a simple and a rapid weight and height model, using also gender and age as predictive factors. The second model is based on anthropometric dimensions of limb girths. Both new anthropometric models showed to be valid, nonbiased, and to accurately predict ALST because high coefficients of determination were obtained, the slopes and intercepts of the regressions did not differ from the line of identity, no significant mean differences between predicted and measured ALST were observed, small limits of agreement were found, and the relation between residuals and predicted ALST from derived equations showed no significant trend line. In addition, both equations were found to have high values of R_{PRESS}^2 and low SEE_{PRESS}, in particular the CMG equation (0.92 and 1.82 kg, respectively). The PRESS method avoids data splitting, and thus a large number of subjects were used to develop and cross-validate the new anthropometric equations. It is established that, in generally, PRESS statistics generates less confident estimates of an equation's potential (14), which underscores the accuracy of our prediction equations.

To our knowledge, this is the first study aimed to develop and cross-validate anthropometric equations for ALST based on DXA instrument in young athletes.

The current investigation was based on earlier reports (5,22) and extends the study developed by Lee et al. (19), which was designed with the underlying concept that whole-body SM is in the form of a cylinder and the combination of SKF thickness, circumference values, and stature can be used to obtain the cylinder's dimensions of body. The previous anthropometric models purposed by

Lee et al. (19) were based on total body SM measures obtained using the standard magnetic resonance imaging (MRI) method. Our investigation used DXA as the reference method to estimate ALST. In the absence of the expensive MRI, this procedure is a practical approach for SM prediction in subjects, through ALST measures (8,12,16,27,31,32,34).

The sample used in the study developed by Lee et al. (19) was a heterogeneous group of healthy adults (>20 yr). The cross-validation of the developed models was performed firstly on a similar nonobese group and secondly on an obese group. The combination height \times CAG² was found to be the best predictor of whole-body SM in the investigation of Lee et al. (19) ($r = 0.90$), followed by height \times CCG² ($r = 0.87$) and height \times CTG² ($r = 0.83$). Both our study and Lee et al.'s study (19) suggest that the square of each corrected muscle girth multiplied by height is the anthro-

pometric parameter that most contributed for the ALST and the SM variance. These results confirm that the corrected muscle circumference measurements and stature (components of the cylinder's dimensions of the SM mass of the human body) are useful tools for accurately quantifying ALST and SM in young athletes and nonobese adults, respectively. It is interesting to note that the strongest correlation coefficient observed in our athletes, between each single corrected limb girth variables and DXA-measured ALST without adjustments, was observed for CTG ($r = 0.76$) followed by CCG ($r = 0.65$) and CAG ($r = 0.58$) (data not shown). Although our results are slightly opposite to the frequent theory that arm girth is a measure of total body SM and subject protein status (9,11), Martin et al. (22) in their sample of male cadavers showed that the single midarm girth was the weakest predictor of total body SM ($r = 0.82$), whereas midthigh girth was found to be the best SM predictor

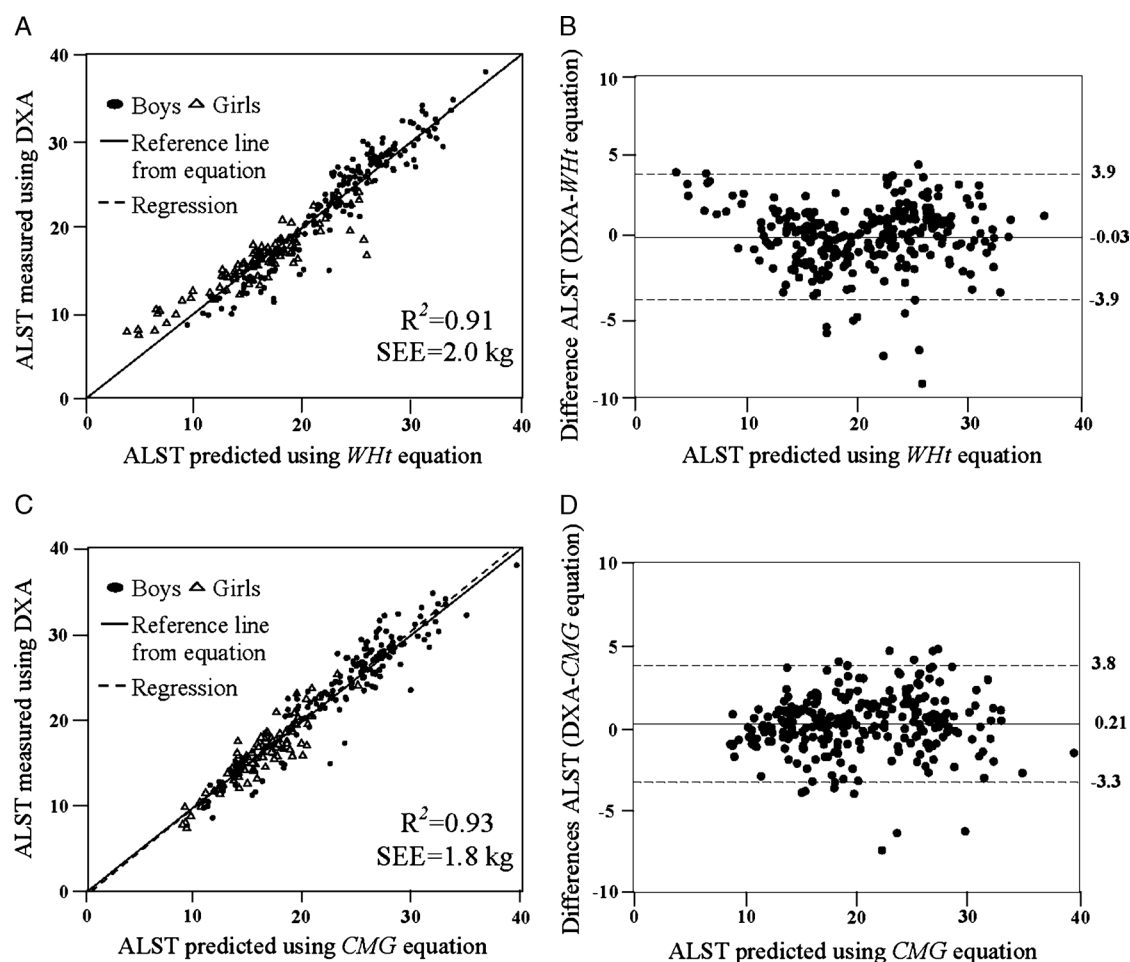


FIGURE 1—Performance of the two generated anthropometric equations to predict appendicular lean soft tissue (ALST) in the adolescent athletes. DXA is the reference method. The left panels are linear regressions between ALST measured using the reference method (DXA) and ALST estimated using both derived equations (upper panel (A): weight and height model (Wht); lower panel (C): corrected muscle girth model (CMG)) for male and female athlete. The coefficients of determination (R^2), the SEE, and the reference line from the equation are presented. The right panels illustrate the relation between the residuals (mean differences between ALST measured by DXA and predicted by derived equations) and ALST predicted by each of the two new equations (upper panel (B): Wht model; lower panel (D): CMG model)). The solid lines represent the mean differences between the reference technique and the anthropometric equations. The dashed lines represent 95% limits of agreement (± 1.96 SD). All values are expressed in kilograms.

($r = 0.94$), followed by the calf-girth ($r = 0.84$), which is in accordance with our results (22). In the present study, we did not include the forearm measure, as Martin et al. (22) did, because it was suggested that, nowadays, forearm value is an atypical measurement and the single midarm girth should be used (10,19).

Even considering the simplistic and empirical assumption that the human body is in the form of a cylinder and consequently, including the respective parameters to construct the corrected muscle girths model, after the cross-validation stage, our results suggest that using these dimensional measures provides an excellent and nonbiased method to accurately predict ALST in athletes ($R = 0.93$, $SEE = 1.80$ kg). This approach was also demonstrated to accurately predict SM in nonobese adults ($R^2 = 0.89$, $SEE = 2.5$ kg) and to a less extent in obese subjects ($R^2 = 0.83$, $SEE = 2.9$ kg) (19).

Regarding our first developed model, based on the simple measures of body weight and height, after performing a stepwise regression analysis, we found body mass to be the strongest ALST predictor, explaining 83% of the variance in ALST. Overall, the final model included weight, gender, height, and age and presented an $R^2 = 0.91$ with a low SEE of 2.01 kg. Lee et al. (19) also developed a model based on body weight and height values, including age and gender as predictor variables, demonstrating, however, lower accuracy in their two cross-validation stages in nonobese and obese adults comparing with our athlete's model (19). Our findings indicate that with easy anthropometric measures, such as body mass and stature, ALST is able to be accurately predicted in adolescents, with low individual variability. Additionally, our results showed a weak significant association between ALST and maturation level before adjustments ($R^2 = 0.17$, $P < 0.0001$; data not shown). Nevertheless, we observed that the Tanner stages failed to contribute significantly to the final developed anthropometric models, after the addition of body weight, height, and CMG interaction terms ($P = 0.246$ and 0.274 for WHt and CMG models, respectively). The strong contribution of body mass and CMG interaction terms for the prediction of ALST may have left little variance of ALST to be explained by maturation level. Moreover, the young athletes used in the current investigation presented a similar maturation level (mean Tanner stage = 1.7 ± 0.7), which also may have contributed to the weak effect of maturity on ALST variance. Kim et al. (16) also demonstrated that the Tanner stages did not enter into the final SM-developed model after including ALST, body weight, and interaction of height with ALST.

Anthropometry has been widely used in field and epidemiological studies because it is simple to perform, inexpensive and noninvasive, and also despite the importance of the SM mass in the human body metabolism, few studies have been conducted to develop and to cross-validate anthropometric models to predict SM or ALST. We are aware of two anthropo-

metric approaches to estimate muscle mass in adults (10,19). Unfortunately, data reporting SM estimates in children, adolescents, and young athletes are lacking. Kim et al. (16) developed and cross-validated a whole-body DXA SM equation for children based on the reference MRI technique. First, this author tested the validity of a previous adult DXA SM model (17) in a sample of pediatric subjects, concluding that the previous adult model was valid in children and adolescents who were at the final Tanner stage 5, but below this stage, there was an overestimation of SM in the pediatric sample. The recent pediatric DXA-prediction models developed by Kim et al. (16) showed to accurately predict SM ($R^2 = 0.98$ – 0.99 , $SEE = 0.6$ – 0.5 kg). Two important issues from the previous investigations, based on DXA and MRI measurements, shall be considered in our study of young athletes: first, children and adolescents below Tanner stage 5 are likely to present a smaller portion of total-body SM relative to ALST (ratio SM/ALST = 1.01) compared with the adult group (ratio SM/ALST = 1.11); and second, ALST measured by using DXA explained *per se* 98.2% of the variance in MRI-measured SM (16). These observations are relevant because we used DXA to estimate ALST, assuming that the greatest portion of ALST is mainly SM and that the largest portion of the total SM is within the limbs segments (appendicular SM), as it was previously reported (13,28). The high correlation found between ALST assessed by DXA and SM determined by using the standard MRI in a pediatric sample confirms these assumptions in children and adolescents (16), although it seems that the intrinsic portions of the three SM measures are likely to change from the assumed stable relations, with growth and maturation processes.

Anthropometric approaches in athletes have been widely used (2,4,6,7,35), but lack of information regarding accurate anthropometric methods to predict ALST in these population is available. This is an important handicap in the sports science and human body composition fields because SM is fundamental for movement and consequently for exercise performance (21).

Our new anthropometric models provide simple and accurate methods for ALST prediction in young athletes, with the underlying concept that the greatest portion of ALST is SM. The parameters used in the current investigation and their inherent assumptions need, however, to be critically tested in similar athletic populations.

Study Limitations

Although we achieved sufficient diverse athletic population, mainly because we avoid splitting data for the cross-validation procedure, the race effect was not tested in the current investigation.

The square of each corrected muscle girths multiplied by height is the anthropometric parameter based on the conceptual assumption that the human body is in the form

of a cylinder. These measures showed to accurately predict ALST, although the human anatomic assumption used to build this empirical model tends to oversimplify the human anatomy.

Finally, we used DXA system (and measured ALST) as the reference method instead of MRI or CT (and measured SM) to developed anthropometric models.

CONCLUSIONS

In summary, two new anthropometric models were developed for children and adolescent athletes and were cross-validated to ensure its applicability in similar samples. The first model is based on simple body weight and height measures, and the second model uses dimensional parameters based on SKF and limb circumferences (corrected muscle girths). Both anthropometric models showed to

accurately predict DXA-measured ALST at a group basis and also at an individual basis because high correlation coefficients were found between predicted and measured means and low limits of agreement were also observed, with no mean differences between predicted and measured values. These new generated equations afford a practical means to quantify ALST in young athletes. Additional validation studies are needed to critically validate these models in similar samples within an exercise and sports training context.

The authors gratefully acknowledge the effort of the participants, their parents, and coaches, without whom this study would not have been possible. This research was supported by the Portuguese Science and Technology Foundation.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

- Andreoli A, Monteleone M, Van Loan M, Promenzio L, Tarantino U, De Lorenzo A. Effects of different sports on bone density and muscle mass in highly trained athletes. *Med Sci Sports Exerc.* 2001;33(4):507–11.
- Bertini I, Pujia A, Giampietro M. A follow-up study of the variations in the body composition of karate athletes. *Acta Diabetol.* 2003;40(Suppl 1):S142–4.
- Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet.* 1986;1:307–10.
- Damsgaard R, Bencke J, Matthiesen G, Petersen JH, Muller J. Body proportions, body composition and pubertal development of children in competitive sports. *Scand J Med Sci Sports.* 2001; 11:54–60.
- Doupe MB, Martin AD, Searle MS, Kriellaars DJ, Giesbrecht GG. A new formula for population-based estimation of whole body muscle mass in males. *Can J Appl Physiol.* 1997;22: 598–608.
- Duthie GM, Pyne DB, Hopkins WG, Livingstone S, Hooper SL. Anthropometry profiles of elite rugby players: quantifying changes in lean mass. *Br J Sports Med.* 2006;40:202–7.
- Evans EM, Rowe DA, Misic MM, Prior BM, Arngimsson SA. Skinfold prediction equation for athletes developed using a four-component model. *Med Sci Sports Exerc.* 2005;37(11):2006–11.
- Fuller NJ, Laskey MA, Elia M. Assessment of the composition of major body regions by dual-energy x-ray absorptiometry (DEXA), with special reference to limb muscle mass. *Clin Physiol.* 1992; 12:253–66.
- Gurney JM, Jelliffe DB. Arm anthropometry in nutritional assessment: nomogram for rapid calculation of muscle circumference and cross-sectional muscle and fat areas. *Am J Clin Nutr.* 1973;26:912–5.
- Heymsfield SB, McManus C, Smith J, Stevens V, Nixon DW. Anthropometric measurement of muscle mass: revised equations for calculating bone-free arm muscle area. *Am J Clin Nutr.* 1982; 36:680–90.
- Heymsfield SB, McManus C, Stevens V, Smith J. Muscle mass: reliable indicator of protein-energy malnutrition severity and outcome. *Am J Clin Nutr.* 1982;35:1192–9.
- Heymsfield SB, Smith R, Aulet M, et al. Appendicular skeletal muscle mass: measurement by dual-photon absorptiometry. *Am J Clin Nutr.* 1990;52:214–8.
- Heymsfield SB, Wang Z, Baumgartner RN, Ross R. Human body composition: advances in models and methods. *Annu Rev Nutr.* 1997;17:527–58.
- Holiday DB, Ballard JE, McKeown BC. PRESS-related statistics: regression tools for cross-validation and case diagnostics. *Med Sci Sports Exerc.* 1995;27(4):612–20.
- Janssen I, Heymsfield SB, Wang ZM, Ross R. Skeletal muscle mass and distribution in 468 men and women aged 18–88 yr. *J Appl Physiol.* 2000;89:81–8.
- Kim J, Shen W, Gallagher D, et al. Total-body skeletal muscle mass: estimation by dual-energy x-ray absorptiometry in children and adolescents. *Am J Clin Nutr.* 2006;84:1014–20.
- Kim J, Wang Z, Heymsfield SB, Baumgartner RN, Gallagher D. Total-body skeletal muscle mass: estimation by a new dual-energy x-ray absorptiometry method. *Am J Clin Nutr.* 2002;76:378–83.
- Kubo J, Chishaki T, Nakamura N, et al. Differences in fat-free mass and muscle thicknesses at various sites according to performance level among judo athletes. *J Strength Cond Res.* 2006;20:654–7.
- Lee RC, Wang Z, Heo M, Ross R, Janssen I, Heymsfield SB. Total-body skeletal muscle mass: development and cross-validation of anthropometric prediction models. *Am J Clin Nutr.* 2000; 72:796–803.
- Lohman TG, Roche AF, Martorell R. *Anthropometric Standardization Reference Manual.* Champaign: Human Kinetics; 1988. p. 125–9.
- Lukaski HC. Measurement of muscle mass. In: Roche AF, Heymsfield SB, Lohman TG, editors. *Human Body Composition: Methods and Findings.* Champaign: Human Kinetics; 1996. p. 217–56.
- Martin AD, Spenst LF, Drinkwater DT, Clarys JP. Anthropometric estimation of muscle mass in men. *Med Sci Sports Exerc.* 1990;22(5):729–33.
- Midorikawa T, Sekiguchi O, Beekley MD, Bemben MG, Abe T. A comparison of organ-tissue level body composition between college-age male athletes and nonathletes. *Int J Sports Med.* 2007;28:100–5.
- Myers RH. *Classical and Modern Regression with Applications.* Boston: Duxbury Press; 1986. p. 100–66.
- Pietrobelli A, Formica C, Wang Z, Heymsfield SB. Dual-energy x-ray absorptiometry body composition model: review of physical concepts. *Am J Physiol.* 1996;271:E941–51.

26. Prior BM, Modlesky CM, Evans EM, et al. Muscularity and the density of the fat-free mass in athletes. *J Appl Physiol.* 2001;90:1523–31.
27. Shih R, Wang Z, Heo M, Wang W, Heymsfield SB. Lower limb skeletal muscle mass: development of dual-energy x-ray absorptiometry prediction model. *J Appl Physiol.* 2000;89:1380–6.
28. Sun SS, Chumlea C. Statistical methods. In: Heymsfield SB, Lohman TG, Wang Z, Going S, editors. *Human Body Composition*. Champaign: Human Kinetics; 2005. p. 151–60.
29. Snyder WS, Cook MJ, Nasset ES, Karhansen LR, Howells GP, Tipton IH. *Report of the Task Group on Reference Men*. Oxford (UK): Pergamon Press; 1975. p. 108–12.
30. Tanner JM. *Growth and Adolescence*. Oxford (UK): Blackwell Scientific. 1962. p. 28–39.
31. Visser M, Fuerst T, Lang T, Salamone L, Harris TB. Validity of fan-beam dual-energy x-ray absorptiometry for measuring fat-free mass and leg muscle mass. Health, Aging, and Body Composition Study—Dual-Energy X-ray Absorptiometry and Body Composition Working Group. *J Appl Physiol.* 1999;87:1513–20.
32. Wang W, Wang Z, Faith MS, Kotler D, Shih R, Heymsfield SB. Regional skeletal muscle measurement: evaluation of new dual-energy x-ray absorptiometry model. *J Appl Physiol.* 1999;87:1163–71.
33. Wang ZM, Pierson Jr RN, Heymsfield SB. The five-level model: a new approach to organizing body-composition research. *Am J Clin Nutr.* 1992;56:19–28.
34. Wang ZM, Visser M, Ma R, et al. Skeletal muscle mass: evaluation of neutron activation and dual-energy x-ray absorptiometry methods. *J Appl Physiol.* 1996;80:824–31.
35. Warner ER, Fornetti WC, Jallo JJ, Pivarnik JM. A skinfold model to predict fat-free mass in female athletes. *J Athl Train.* 2004;39:259–62.