

# Total-body skeletal muscle mass: development and cross-validation of anthropometric prediction models<sup>1-3</sup>

Robert C Lee, ZiMian Wang, Moonseong Heo, Robert Ross, Ian Janssen, and Steven B Heymsfield

## ABSTRACT

**Background:** Skeletal muscle (SM) is a large body compartment of biological importance, but it remains difficult to quantify SM with affordable and practical methods that can be applied in clinical and field settings.

**Objective:** The objective of this study was to develop and cross-validate anthropometric SM mass prediction models in healthy adults.

**Design:** SM mass, measured by using whole-body multislice magnetic resonance imaging, was set as the dependent variable in prediction models. Independent variables were organized into 2 separate formulas. One formula included mainly limb circumferences and skinfold thicknesses [model 1: height (in m) and skinfold-corrected upperarm, thigh, and calf girths (CAG, CTG, and CCG, respectively; in cm)]. The other formula included mainly body weight (in kg) and height (model 2). The models were developed and cross-validated in nonobese adults [body mass index (in kg/m<sup>2</sup>) < 30].

**Results:** Two SM (in kg) models for nonobese subjects ( $n = 244$ ) were developed as follows:  $SM = Ht \times (0.00744 \times CAG^2 + 0.00088 \times CTG^2 + 0.00441 \times CCG^2) + 2.4 \times \text{sex} - 0.048 \times \text{age} + \text{race} + 7.8$ , where  $R^2 = 0.91$ ,  $P < 0.0001$ , and  $SEE = 2.2$  kg; sex = 0 for female and 1 for male, race = -2.0 for Asian, 1.1 for African American, and 0 for white and Hispanic, and  $SM = 0.244 \times BW + 7.80 \times Ht + 6.6 \times \text{sex} - 0.098 \times \text{age} + \text{race} - 3.3$ , where  $R^2 = 0.86$ ,  $P < 0.0001$ , and  $SEE = 2.8$  kg; sex = 0 for female and 1 for male, race = -1.2 for Asian, 1.4 for African American, and 0 for white and Hispanic.

**Conclusion:** These 2 anthropometric prediction models, the first developed in vivo by using state-of-the-art body-composition methods, are likely to prove useful in clinical evaluations and field studies of SM mass in nonobese adults. *Am J Clin Nutr* 2000;72:796–803.

**KEY WORDS** Limb circumference, skinfold thickness, body composition, skeletal muscle, nonobese adults

## INTRODUCTION

Although skeletal muscle (SM) makes up the largest fraction of body mass in nonobese adults (1), measurement methods that are suitable for field studies are lacking. This is unfortunate, because SM is involved in many biological processes and quantification would likely provide new and important insights.

Currently, 2 costly methods are available for estimating SM: computed axial tomography (CT) (2) and magnetic resonance imaging (MRI) (3). The results of recent cadaver studies support the accuracy of CT and MRI as reference methods for estimating SM (4). However, CT remains impractical as a routine method for measuring SM because radiation exposure precludes studies in children and young women.

A practical alternative to CT and MRI for measuring SM is anthropometry (5). Instruments for measuring anthropometric dimensions are portable and inexpensive, procedures are noninvasive, and minimal training is required. Matiegka (6) first suggested an anthropometric approach for quantifying whole-body SM. Martin et al (7) and Doupe et al (8) extended Matiegka's approach and developed anthropometric SM prediction formulas based on the Brussels Cadaver Study (9). Anthropometric dimensions were quantified, the cadavers were dissected, and whole-body SM was measured. Regression equations were then developed by using the cadavers of 12 elderly men (7, 8):

$$SM = Ht \times (0.0553 \times CTG^2 + 0.0987 \times FG^2 + 0.0331 \times CCG^2) - 2445 \quad (1)$$

where  $R^2 = 0.97$ ,  $SEE = 1.53$  kg, SM is whole-body SM (in g), Ht is height (in cm), CTG is corrected thigh girth (in cm), FG is uncorrected forearm girth (in cm), and CCG is corrected calf girth (in cm); and

$$SM = Ht \times (0.031 \times MUTHG^2 + 0.064 \times CCG^2 + 0.089 \times CAG^2) - 3006 \quad (2)$$

where  $R^2 = 0.96$ ,  $SEE = 1.5$  kg, MUTHG is modified upper thigh girth (in cm), and CAG is corrected arm girth (in cm). Corrected girths are limb circumferences that are adjusted for skinfold thickness. The 2 equations differ in selected anthropometric

<sup>1</sup>From the Obesity Research Center, St Luke's-Roosevelt Hospital Center, Columbia University, College of Physicians and Surgeons, New York, and the School of Physical and Health Education, Queen's University, Kingston, Canada.

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<sup>3</sup>Reprints not available. Address correspondence to SB Heymsfield, Weight Control Unit, 1090 Amsterdam Avenue, 14th floor, New York, NY 10025. E-mail sbh2@columbia.edu.

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**TABLE 1**  
Anthropometric measurement sites<sup>1</sup>

Site	Skinfold-thickness measurement	Circumference measurement
Upper arm	Measured in the midline posteriorly over the triceps muscle at a point midway between the lateral projection of the acromion process of the scapula and the inferior margin of the olecranon process of the ulna	Measured midway between the lateral projection of the acromion process of the scapula and the inferior margin of the olecranon process of the ulna
Thigh	Measured at the midline of the anterior aspect of the thigh, midway between the inguinal crease and the proximal border of the patella	Measured midway between the midpoint of the inguinal crease and the proximal border of the patella
Calf	Measured on the medial aspect of the calf at the same level as the calf circumference	Measured at the maximal circumference

<sup>1</sup>Adapted from reference 12. Additional measurement details and technical errors are presented in that reference.

measurement sites. Equation 2 was developed specifically for the analysis of the 1981 Canada Fitness Survey data set (8). However, the earlier anthropometric studies were limited in that SM prediction models were either not validated, as for Matiegka's model (6), or were based on a very small sample of cadavers of elderly men, as for the models of Martin et al (7) and Doupe et al (8).

Despite these limitations, the cadaver studies showed the potential of predicting total-body SM from appendicular circumferences and skinfold thicknesses. The general concept is that about three-quarters of total-body SM exists in the extremities and that appendicular lean tissue is primarily SM (1), that skinfold-corrected limb circumferences provide a measure of corresponding appendicular lean tissue circumferences, that squaring the appendicular lean tissue circumferences creates a lean tissue area estimate, and that taking the product of summed estimated appendicular lean tissue areas and height provides a measure of total-body SM in appropriate volume units. The purpose of the present prospective study was to develop and cross-validate, in a large subject group, anthropometric prediction models for total-body SM by using MRI as the reference method.

## SUBJECTS AND METHODS

### Experimental design

Healthy adults were recruited for study and completed anthropometric and MRI evaluations. The subjects were then divided into 2 groups, nonobese [body mass index (BMI; in kg/m<sup>2</sup>) < 30] and obese (BMI ≥ 30). The obese subjects were evaluated separately because there is some concern about the accuracy of anthropometric measurements in obese populations (10). The nonobese subjects were randomly assigned to 1 of 2 groups: a model-development group (group A) and a cross-validation group (group B). Two prediction equations were developed by using data from the model development group, one based mainly on appendicular skinfold thicknesses and circumferences and the other based mainly on body weight and height. The equations developed were then cross-validated on the second nonobese group with the aim of pooling the data for all the nonobese subjects, if the models were successfully cross-validated, to develop final SM prediction equations. The last stage of analysis was to cross-validate the equations in obese subjects.

### Subjects

Subjects were evaluated at 2 collaborating centers, the Human Body Composition Laboratory, St Luke's-Roosevelt Hospital,

New York, and Queen's University, Kingston, Canada. Subjects were excluded from the study if they were aged <20 y, were involved in a structured physical activity program (11), had medical conditions or used medications known to affect body composition, or reported recent weight change (>10% of body weight within the previous year). The subjects evaluated at the New York site (189 nonobese and 24 obese subjects) were recruited from among Hospital employees and students at local universities. The subjects evaluated at the Kingston site (55 nonobese and 56 obese subjects) were recruited from Queen's University and Hospital and from the general public through local media. Race was defined according to US federal guidelines (Statistical Directive 15, US Federal Government Office of Management and Budget). All participants at both sites completed informed consent statements approved by the respective institutional review boards.

### Anthropometric measurements

Anthropometric measurements were all made by a highly trained observer at each study site using standardized procedures as reported by Lohman et al (12). Body weight was measured to the nearest 0.1 kg in fasting subjects wearing minimal clothing. Height was measured with a stadiometer to the nearest 0.1 cm.

Skinfold thickness was measured on the right side of the body at appropriately marked sites and recorded to the nearest 0.1 mm with a Lange caliper (Country Technology Inc, Gay Mills, WI) in New York and a Harpenden caliper (British Indicators Ltd, St Albans, United Kingdom) in Kingston. Skinfold thickness was measured at the triceps, thigh, and medial calf according to the standardized anatomic locations and methods reported by Lohman et al (12) and as summarized in **Table 1**.

Circumference measurements were made in the plane orthogonal to the long axis of the body segment being measured. Circumferences of the midupper arm, midthigh, and mid-calf were evaluated with a flexible standard measuring tape as reported in the Anthropometric Standardization Reference Manual (12) (Table 1). All circumference measurements were recorded to the nearest 1 mm.

A series of 3 skinfold-thickness and 3 circumference measurements were made and the mean of all measurements was used for the analysis. Intrameasurer technical errors for skinfold-thickness and circumference measurements were consistent with those reported earlier (12).

The limb circumferences ( $C_{limb}$ ) were corrected for subcutaneous adipose tissue thickness (7, 8). The skinfold caliper measurement ( $S$ ) was assumed to be twice the subcutaneous adipose tissue thickness. The corrected muscle (including

bone) circumferences ( $C_m$ ) were calculated as  $C_m = C_{limb} - \pi S$ . For dimensional consistency, corrected muscle circumferences were squared and multiplied by height to obtain a 3-dimensional SM measure (7, 8).

## Magnetic resonance imaging

### *Skeletal muscle measurement*

Whole-body MRI scans were prepared by using 1.5 Tesla scanners (6X Horizon; General Electric, Milwaukee) at both laboratory sites. A T1-weighted spin-echo sequence with 210-ms repetition time and a 17-ms echo time was used to obtain the MRI data. The MRI protocol was described in detail previously (13, 14). Briefly, the subjects lay in the magnet in a prone position with their arms placed straight overhead. By using the intervertebral space between the fourth and fifth lumbar vertebrae (L4-L5) as the point of origin, transverse images (10-mm slice thickness) were obtained every 40 mm from hand to foot, resulting in a total of  $\approx 41$  images for each subject (6 data sets of 7 images). The total time required to acquire all of the MRI data for each subject was  $\approx 25$  min. All MRI data were transferred to a computer workstation (Silicon Graphics Inc, Mountain View, CA) for analysis using specially designed image analysis software (Tomovision Inc, Montreal).

### *Segmentation and calculation of tissue area, volume, and mass*

The model used to segment the various tissues was described and illustrated previously (4, 13, 14). Briefly, a multiple-step procedure was used to identify tissue area (in  $\text{cm}^2$ ) for a given MRI image. In the first step, 1 of 2 equivalent techniques was used. Either a threshold was selected for adipose and lean tissues on the basis of the gray-level image pixel histograms or a filter-based watershed algorithm was used to identify tissue boundaries. Next, the observer labeled different tissues by assigning each one a specific code. Images were then reviewed by an interactive slice editor program (SLICE-O-MATIC; Tomovision Inc) that allowed for verification and potentially correction of the segmented results. The original gray level was superimposed on the binary-segmented image by using a transparency mode to facilitate the corrections. The areas (in  $\text{cm}^2$ ) of the respective tissues in each image were computed automatically by summing the given tissue pixels and multiplying by the individual pixel surface area. The volume (in  $\text{cm}^3$ ) of each tissue in each slice was calculated by multiplying tissue area ( $\text{cm}^2$ ) by slice thickness (1.0 cm). The volume of each tissue was calculated by using a mathematical algorithm (13, 14). Volume units (L) were converted to mass units (kg) by multiplying the volumes by the assumed constant density for SM (1.04 kg/L) (1).

We determined recently the reproducibility of MRI-SM measurements by comparing the intra- and interobserver estimates of MRI measurements (one series of 7 images taken in the legs) obtained in 3 male and 3 female subjects (4). The intraobserver difference was calculated by comparing the analysis of 2 separate MRI acquisitions in a single observer, and the interobserver difference was determined by comparing 2 observers' analyses of the same images. The interobserver difference was  $1.8 \pm 0.6\%$  and the intraobserver difference was  $0.34 \pm 1.1\%$  (4). In addition, we determined the reproducibility of whole-body MRI-SM measurements across the laboratories by comparing the 2 laboratories' analyses of the same images for 5 subjects. The interlabora-

tory difference was  $2.0 \pm 1.2\%$ . One experienced technician read all of the MRI scans at each site.

## Statistical analysis

Continuous baseline variables are described as the group mean  $\pm$  SD, and between-sex differences were explored by using Student's *t* test. The chi-square test was used for testing between-sex racial distribution differences.

The data sets from the 2 laboratories were combined because initial analyses did not detect between-center differences in developed models. Combining subjects creates a laboratory-independent prediction model and increases statistical power. Prediction models were prepared for the development sample with and without added skinfold-circumference measurements by using multiple regression analysis. When preparing formulas with added skinfold thicknesses, we forced models to include the 3 variables— $\text{Ht} \times \text{CAG}^2$ ,  $\text{Ht} \times \text{CTG}^2$ , and  $\text{Ht} \times \text{CCG}^2$ —as a means of incorporating regional variation in SM mass and distribution. We then explored the addition of other baseline variables and selected the highest adjusted  $R^2$  model. We also explored a body weight and height model without added skinfold-thickness measurements that had the highest adjusted  $R^2$ . The rationale for building this model was that it enables body weight and height to be measured easily and the model provides a rapid and simple means by which to estimate a subject's SM mass. All statistical analyses were carried out by using STATVIEW for WINDOWS (version 4.5; SAS Institute, Cary, NC). Graphics were produced by S-PLUS (Mathsoft, Inc, Seattle).

## RESULTS

### Subject characteristics

The baseline characteristics of the 135 male and 109 female nonobese subjects are shown in **Table 2**. Four racial groups (African American, Asian, white, and Hispanic) were represented in the sample and the racial distribution was similar between men and women. The age range of the 244 subjects was 20–81 y ( $\bar{x}$ :  $39.6 \pm 13.8$  y). Age did not differ significantly between men and women. BMI was significantly greater in the men than in the women ( $P = 0.0005$ ). Total-body SM was  $32.6 \pm 5.2$  kg, or 41.3% of body weight, in men and  $20.9 \pm 3.6$  kg, or 33.1% of body weight, in women. There was no significant difference in demographic characteristics between the model-development group (group A) and the cross-validation group (group B).

Among the 80 obese subjects recruited for cross-validation (Table 2), the mean age of the men was  $42 \pm 13$  y and of the women was  $43 \pm 10$  y. Men ( $n = 39$ ; BMI =  $33.8 \pm 2.7$   $\text{kg}/\text{m}^2$ ) and women ( $n = 41$ ; BMI =  $34.8 \pm 3.5$   $\text{kg}/\text{m}^2$ ) were on average moderately obese; there was no significant differences in BMI between men and women. In addition, racial distribution did not differ significantly by sex in the obese subjects.

Circumference measurements were greater in the men than in the women and in obese than in the normal-weight subjects (Table 2). The one exception was that midthigh circumference in the obese women exceeded that in the obese men. Skinfold-thickness measurements were all smaller in the men and in the nonobese subjects than in the women and the obese subjects. The corrected limb girths were all larger in the men and in the obese subjects than in the women and the nonobese subjects, respectively.

**TABLE 2**Subjects' physical characteristics and body-composition measurements at baseline<sup>1</sup>

	Nonobese subjects		Obese subjects	
	Men ( <i>n</i> = 135)	Women ( <i>n</i> = 109)	Men ( <i>n</i> = 39)	Women ( <i>n</i> = 41)
Age (y)	38 ± 12 <sup>2</sup>	41 ± 15	42 ± 13	43 ± 10
Body weight (kg)	79.0 ± 11.7	63.2 ± 11.6	106.9 ± 10.9	92.0 ± 10.7
Height (cm)	176.8 ± 6.9	162.8 ± 7.5	177.8 ± 5.7	162.6 ± 5.0
BMI (kg/m <sup>2</sup> )	25.2 ± 3.1	23.8 ± 3.4 <sup>3</sup>	33.8 ± 2.7	34.8 ± 3.5
Race				
African American	24	20	3	10
Asian	20	17	—	—
White	76	60	32	29
Hispanic	15	12	4	2
Circumference (cm)				
Midupper arm	32.4 ± 3.3	28.9 ± 3.5	37.3 ± 2.5	36.6 ± 3.7
Midthigh	55.3 ± 5.2	53.8 ± 5.4	62.4 ± 4.6	65.0 ± 5.5
Midcalf	37.8 ± 2.9	35.7 ± 2.8	42.3 ± 3.1	41.6 ± 2.9
Skinfold thickness (mm)				
Triceps	12.5 ± 6.5	23.3 ± 8.2	20.1 ± 7.7	37.0 ± 9.2
Midthigh	15.6 ± 6.9	32.2 ± 11.6	24.7 ± 9.9	47.4 ± 10.4
Midcalf	9.7 ± 5.0	17.9 ± 7.4	16.0 ± 5.9	28.4 ± 8.4
Corrected circumference (cm)				
CAG	28.5 ± 3.0	21.6 ± 2.2	31.0 ± 2.7	25.0 ± 2.5
CTG	50.4 ± 4.9	43.7 ± 4.3	54.6 ± 4.9	50.1 ± 6.0
CCG	34.8 ± 2.8	30.1 ± 2.5	37.2 ± 2.9	32.7 ± 2.8
Skeletal muscle mass (kg)	32.6 ± 5.2	20.9 ± 3.6	37.3 ± 4.2	25.3 ± 3.7

<sup>1</sup>CAG, corrected arm girth; CTG, corrected thigh girth; CCG, corrected calf girth.<sup>2</sup> $\bar{x} \pm \text{SD}$ .<sup>3</sup>Significantly different from nonobese men, *P* = 0.0005.

### Skinfold-circumference model

The results of single-predictor regression analysis performed on all anthropometric measurements are shown in **Table 3**. Partial correlations for the single SM predictors, after adjustment for age, are also presented. All anthropometric predictors were significantly correlated with total-body SM mass. The best one-predictor variables were the square of each corrected limb circumference multiplied by height (*R* range: 0.83–0.90). A multiple regression analysis including all possible subsets was used to evaluate every possible combination of predictor variable. The selected prediction equation on the basis of group A (*n* = 122) was

$$\begin{aligned} \text{SM (kg)} = & \text{Ht} \times (0.00587 \times \text{CAG}^2 + 0.00138 \\ & \times \text{CTG}^2 + 0.00574 \times \text{CCG}^2) + 2.4 \\ & \times \text{sex} - 0.026 \times \text{age} + \text{race} + 4.4 \end{aligned} \quad (3)$$

where *R*<sup>2</sup> = 0.92, *P* < 0.0001, and SEE = 2.3 kg; sex = 1 for male and 0 for female, race = −1.6 for Asian, 1.2 for African American, and 0 for white or Hispanic. Height is expressed in m.

There was no significant difference (−0.3 ± 2.5 kg; *P* = 0.23) between MRI-measured SM and predicted SM when the prediction equation was cross-validated in group B. Predicted SM was correlated with MRI-measured SM and the resulting regression equation had an *R*<sup>2</sup> of 0.89 (*P* < 0.0001) and an SEE of 2.5 kg (**Figure 1A**). A Bland-Altman graph (15) was also plotted as the measured and predicted SM difference versus MRI-measured SM (**Figure 1B**). The correlation between measured and predicted SM difference and measured SM was not significant.

The variables were then regressed on a combined data set from groups A and B to generate a prediction equation with the

maximum number of subjects (*n* = 244). The selected prediction equation generated for both groups (**Table 4**) was

$$\begin{aligned} \text{SM (kg)} = & \text{Ht} \times (0.00744 \times \text{CAG}^2 + 0.00088 \\ & \times \text{CTG}^2 + 0.00441 \times \text{CCG}^2) + 2.4 \\ & \times \text{sex} - 0.048 \times \text{age} + \text{race} + 7.8 \end{aligned} \quad (4)$$

where *R*<sup>2</sup> = 0.91, *P* < 0.0001, and SEE = 2.2 kg; sex = 1 for male and 0 for female, race = −2.0 for Asian, 1.1 for African American, and 0 for white or Hispanic.

This final equation was cross-validated in the obese group. There was no significant difference (0.4 ± 3.0, *P* = 0.28) between MRI-measured SM and predicted SM. There was a high correlation between predicted SM and MRI-measured SM (*R*<sup>2</sup> = 0.83, *P* < 0.0001, SEE = 2.9 kg) (**Figure 1C**). The correlation between measured and predicted SM difference and measured SM was significant (*R*<sup>2</sup> = 0.90, *P* = 0.009) (**Figure 1D**).

### Body weight and height model

The second anthropometric prediction equation was developed with body weight (BW); in kg and height (in m) as the major predictors. The other independent variables included were age, sex, and race. The resulting prediction equation on the basis of group A was

$$\begin{aligned} \text{SM (kg)} = & 0.226 \times \text{BW} + 13.0 \times \text{Ht} - 0.089 \\ & \times \text{age} + 6.3 \times \text{sex} + \text{race} - 11.0 \end{aligned} \quad (5)$$

where *R*<sup>2</sup> = 0.85, *P* < 0.0001, and SEE = 3.0 kg; sex = 1 for male and 0 for female; race = −1.6 for Asian, 1.9 for African American, and 0 for white or Hispanic. This equation was cross-validated in group B, with the following correlation between

**TABLE 3**  
Correlation coefficients of predictors with total-body skeletal muscle mass obtained from the 244 nonobese subjects by using magnetic resonance imaging (MRI)<sup>1</sup>

Variable	<i>r</i>	<i>P</i>	SEE (kg) <sup>2</sup>	Partial correlation <sup>3</sup>
Age	−0.21	0.0012	7.30	—
Body weight	0.80	<0.0001	4.49	0.83
Height	0.79	<0.0001	4.54	0.79
BMI	0.48	<0.0001	6.54	0.54
CAG	0.88	<0.0001	3.57	0.88
CTG	0.78	<0.0001	4.69	0.77
CCG	0.82	<0.0001	4.31	0.81
Ht × CAG <sup>2</sup>	0.90	<0.0001	3.19	0.91
Ht × CTG <sup>2</sup>	0.83	<0.0001	4.18	0.82
Ht × CCG <sup>2</sup>	0.87	<0.0001	3.74	0.86

<sup>1</sup>CAG, corrected arm girth; CTG, corrected thigh girth; CCG, corrected calf girth.

<sup>2</sup>Obtained from simple linear regressions on the MRI-measured total-body skeletal muscle.

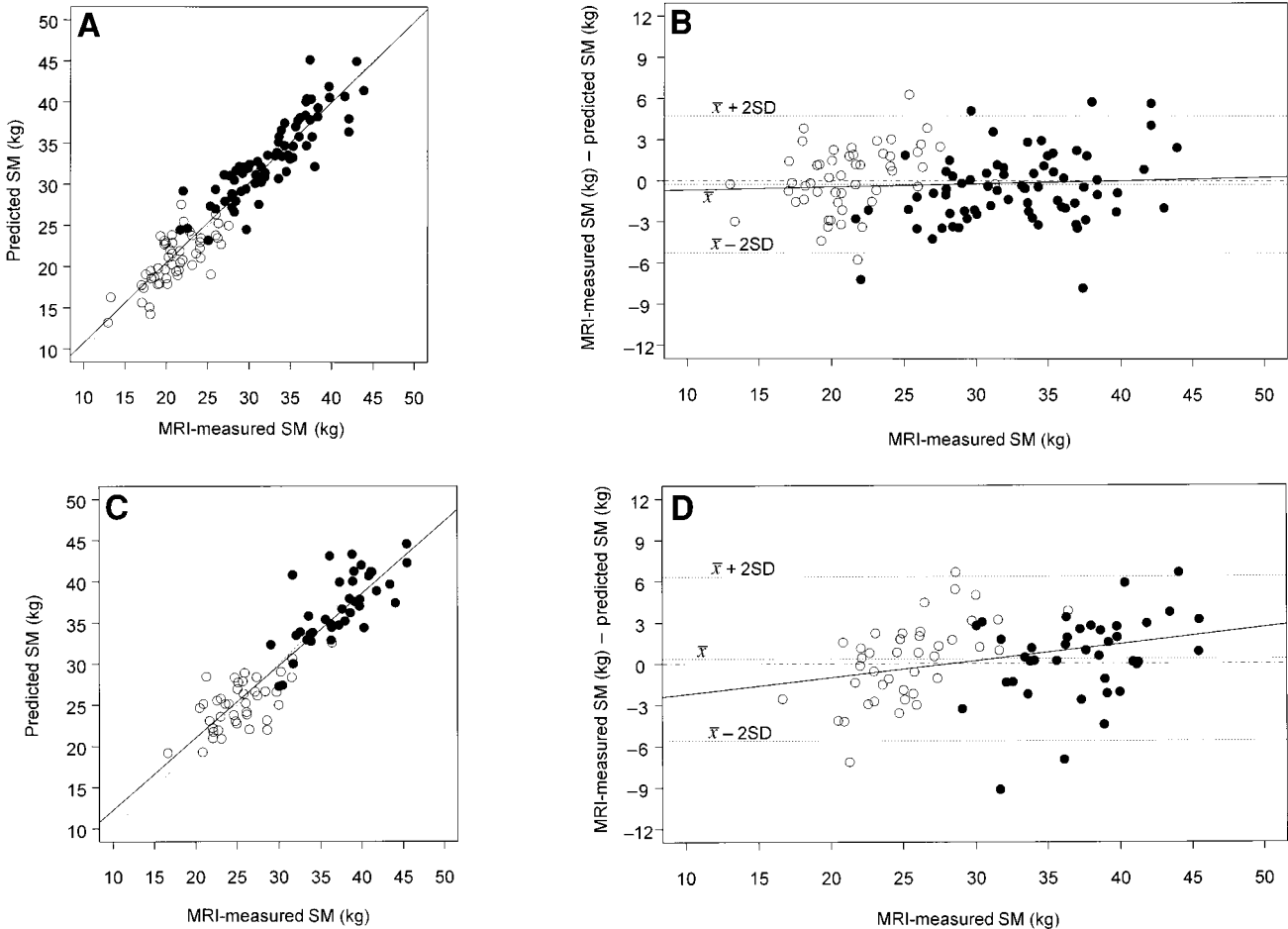
<sup>3</sup>Age was controlled for.

predicted SM and MRI-measured SM:  $R^2 = 0.86$  ( $P < 0.0001$ ) and SEE = 2.6 kg (**Figure 2A**). There was no significant difference between MRI-measured SM and predicted SM ( $-0.3 \pm 2.7$  kg;  $P = 0.17$ ). The correlation between measured and predicted SM difference and MRI-measured SM was significant ( $R^2 = 0.07$ ,  $P = 0.003$ ) (Figure 2B).

A final equation was developed with subjects from both groups (**Table 5**):

$$\text{SM (kg)} = 0.244 \times \text{BW} + 7.80 \times \text{Ht} - 0.098 \times \text{age} + 6.6 \times \text{sex} + \text{race} - 3.3 \quad (6)$$

where  $R^2 = 0.86$ ,  $P < 0.0001$ , and SEE = 2.8 kg; sex = 1 for male and 0 for female, race = −1.2 for Asian, 1.4 for African American, and 0 for white or Hispanic. This equation was cross-validated with the independent sample of obese subjects ( $R^2 = 0.79$ ,  $P < 0.0001$ , SEE = 3.0 kg) (Figure 2C). There was a significant difference ( $-2.3 \pm 3.3$  kg;  $P < 0.0001$ ) between measured SM and predicted SM. There was also a significant correlation between measured and predicted SM difference and measured SM ( $R^2 = 0.18$ ,  $P < 0.001$ ) (Figure 2D). The cross-validation



**FIGURE 1.** Skeletal muscle (SM) mass predicted by Equation 3 versus magnetic resonance imaging (MRI)-measured SM mass in healthy nonobese men (●) and women (○) ( $y = 0.976x + 0.94$ ;  $R^2 = 0.89$ ,  $P < 0.0001$ , SEE = 2.5 kg; the dotted line is the line of identity) (A), Bland-Altman plot for the corresponding linear relation plotted in panel A as the difference between MRI-measured and predicted SM versus MRI-measured SM ( $y = 0.002x - 0.94$ ;  $R^2 = 0.005$ ,  $P = 0.45$ ; the dotted horizontal lines are mean differences and 95% CIs) (B), SM mass predicted by Equation 4 versus MRI-measured SM mass in obese subjects ( $y = 0.878x + 3.43$ ;  $R^2 = 0.83$ ,  $P < 0.0001$ , SEE = 2.9 kg; the dotted line is the line of identity), and Bland-Altman plot for the corresponding linear relation plotted in panel C as the difference between MRI-measured and predicted SM versus MRI-measured SM ( $y = 0.122x - 3.43$ ;  $R^2 = 0.09$ ,  $P = 0.009$ ; the dotted horizontal lines are mean differences and 95% CIs) (D).

**TABLE 4**

Regression model with squared corrected girths  $\times$  height and sex, age, and race as independent variables<sup>1</sup>

Variable	$\beta \pm \text{SE}$	<i>t</i>
Intercept	7.84 $\pm$ 1.01	7.80 <sup>2</sup>
Ht $\times$ CAG <sup>2</sup>	0.00744 $\pm$ 0.001	10.25 <sup>2</sup>
Ht $\times$ CTG <sup>2</sup>	0.00088 $\pm$ 0.0003	3.47 <sup>2</sup>
Ht $\times$ CCG <sup>2</sup>	0.00441 $\pm$ 0.001	7.12 <sup>2</sup>
Sex (F = 0, M = 1)	2.41 $\pm$ 0.51	4.78 <sup>2</sup>
Age (y)	-0.048 $\pm$ 0.012	-4.09 <sup>2</sup>
Asian subjects	-1.96 $\pm$ 0.45	-4.34 <sup>2</sup>
African American subjects	1.05 $\pm$ 0.40	2.64 <sup>3</sup>

<sup>1</sup>*n* = 244. Model  $R^2 = 0.91$ ,  $P < 0.0001$ , and SEE = 2.2 kg. CAG, corrected arm girth; CTG, corrected thigh girth; CCG, corrected calf girth.

<sup>2</sup> $P < 0.001$ , df = 236.

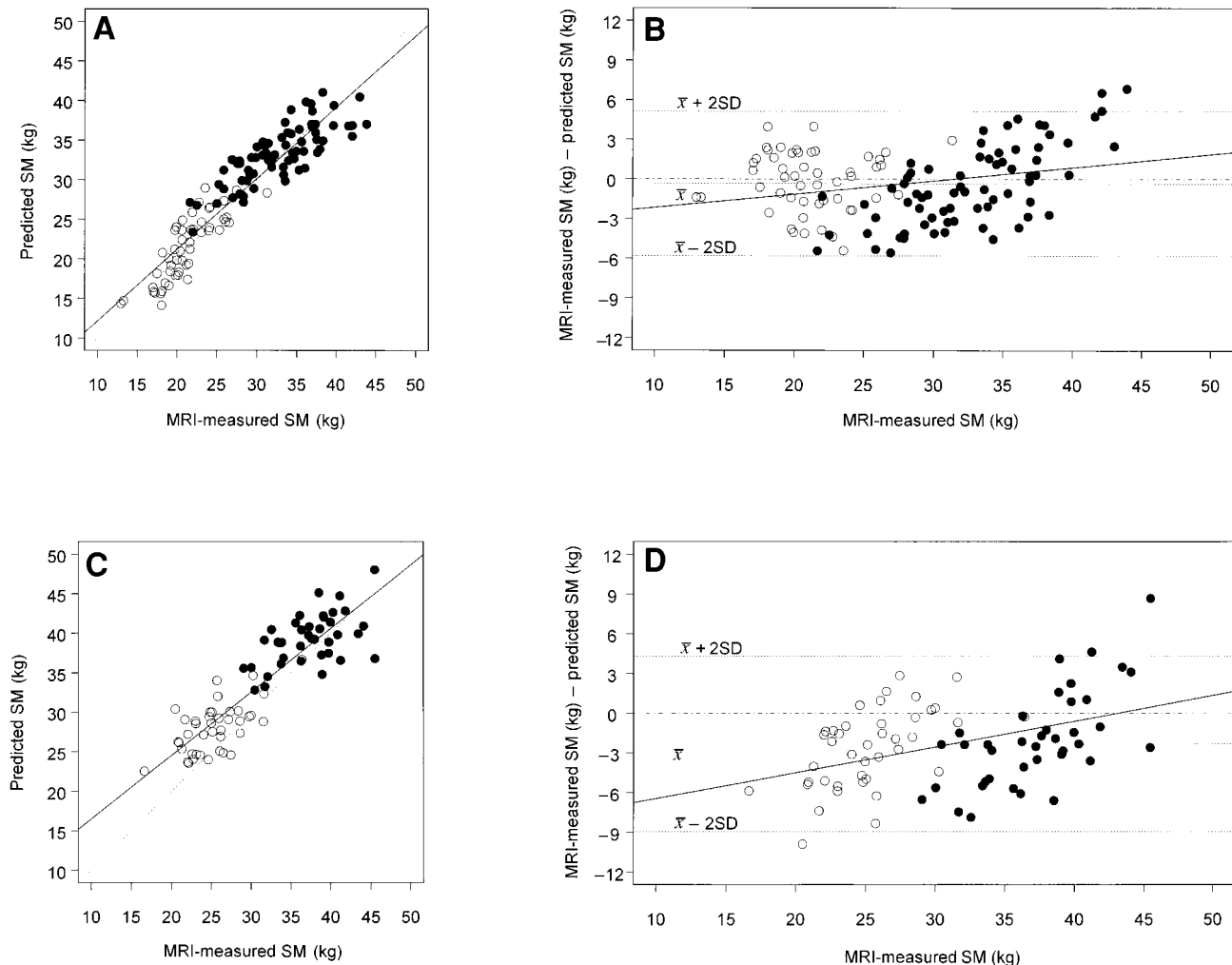
<sup>3</sup> $P < 0.009$ , df = 236.

results for the 2 SM prediction equations for nonobese and obese subjects are summarized in **Table 6**.

## DISCUSSION

The present study was designed to develop whole-body SM prediction formulas based on anthropometric dimensions. With use of multislice MRI as the reference, 2 prediction models were developed and then cross-validated in a large and heterogeneous subject population.

The overall theme of the first model is that whole-body SM is conceptually in the form of a cylinder. Skinfold thicknesses, circumference measurements, and stature, along with various geometric constructs, are used to obtain the cylinder's dimensions. Obviously, the model oversimplifies human anatomy and, by necessity, many assumptions are made in developing the various empirical model terms. There is a possibility that individual



**FIGURE 2.** Skeletal muscle (SM) mass predicted by Equation 5 versus magnetic resonance imaging (MRI)-measured SM mass in healthy nonobese men (●) and women (○) ( $y = 0.899x + 3.2$ ;  $R^2 = 0.86$ ,  $P < 0.0001$ , SEE = 2.6 kg; the dotted line is the line of identity) (A), Bland-Altman plot for the corresponding linear relation plotted in panel A as the difference between MRI-measured and predicted SM versus MRI-measured SM ( $y = 0.101x - 3.2$ ;  $R^2 = 0.07$ ,  $P = 0.003$ ; the dotted horizontal lines are mean differences and 95% CIs) (B), SM mass predicted by equation 6 versus MRI-measured SM mass in obese subjects ( $y = 0.805x + 8.4$ ;  $R^2 = 0.79$ ,  $P < 0.0001$ , SEE = 3.0 kg; the dotted line is the line of identity) (C), and Bland-Altman plot for corresponding linear relation plotted in panel C as the difference between MRI-measured and predicted SM versus MRI-measured SM ( $y = 0.195x - 8.4$ ;  $R^2 = 0.18$ ,  $P < 0.001$ , SEE = 3.0 kg; the dotted horizontal lines are mean differences and 95% CIs) (D).

**TABLE 5**Regression model with body weight, height, sex, and race as dependent variables<sup>1</sup>

Variable	$\beta \pm SE$	<i>t</i>
Intercept	$-3.29 \pm 4.81$	$-0.686$
Body weight (kg)	$0.244 \pm 0.021$	$11.42^2$
Height (m)	$7.804 \pm 3.268$	$2.39^3$
Sex (F = 0, M = 1)	$6.583 \pm 0.521$	$12.63^2$
Age (y)	$-0.098 \pm 0.014$	$-6.94^2$
Asian subjects	$-1.22 \pm 0.58$	$-2.093^4$
African American subjects	$1.43 \pm 0.49$	$2.907^5$

<sup>1</sup>*n* = 244. Model  $R^2 = 0.86$ ,  $P < 0.0001$ , and SEE = 2.8 kg.<sup>2</sup> $P < 0.001$ , df = 237.<sup>3</sup> $P = 0.018$ , df = 237.<sup>4</sup> $P = 0.037$ , df = 237.<sup>5</sup> $P = 0.004$ , df = 237.

assumptions of the model can be critically tested and that even better equations can be developed in the future.

The final formula we developed (Equation 4) includes skinfold thicknesses and circumferences measured at 3 widely used extremity sites (12). The inclusion of commonly measured anatomic sites ensures the equation's versatility in accounting for individual SM distribution differences. The use of forearm circumference in models, as suggested by Matiegka (6) and included in the equation of Martin et al (7), was not considered in the present study because the forearm is now an atypical anthropometric measurement site.

Of all the limb circumferences, CAG had the highest correlation with total-body SM ( $R = 0.88$ ,  $P < 0.0001$ ) (Table 3). This supports the frequent use of arm girth or arm muscle area as a measure of total-body SM and subject protein status (16–18). In contrast, CAG in the Martin et al equation was the weakest predictor of total-body SM of the corrected limb girths. This between-study inconsistency may have several origins, including differential effects of aging on SM distribution, sex, and race-related SM distribution differences and the use of healthy subjects rather than subjects with diseases in model development (19).

The final model we developed (Equation 4) had a high  $R^2$  (0.91) and a low SEE (2.2 kg). When this model was applied in the obese cross-validation group, there was a significant difference between measured and predicted SM, although there was a high correlation ( $R^2 = 0.83$ ,  $P < 0.0001$ , SEE = 2.9 kg) between the 2 SM measures (Table 6). There are several possible explanations for this observation, including application of the prediction model outside the BMI boundaries within which it was developed, difficulties and techni-

cal errors encountered in measuring skinfold thicknesses in subjects who are obese (20), different validities of underlying geometric models (21), and inclusion of different components in MRI and anthropometric measurements. As a method of measuring SM, MRI is capable of quantifying large adipose tissue deposits within the SM compartment (eg, that surrounding neuromuscular bundles). The MRI-measured SM component includes a small amount of intramuscular adipose tissue and intracellular lipid beyond the resolution of conventional MRI. On the other hand, anthropometric measurements cannot discern any level of intramuscular adiposity and this method thus provides an estimate of anatomic SM tissue. Anthropometry as applied in the present study also fails to account for extremity bone that passes through the central portion of the evaluated SM compartment and accounts for 5–10% of the evaluated cross-sectional area (21). The anthropometric model we developed may, according to our observations, therefore provide a slightly biased estimate of SM in individual obese subjects.

The skinfold-circumference model developed in this study has the potential of being widely applied. Anthropometry has the advantage of being simple, inexpensive, and noninvasive, thus making it practical for application in epidemiologic studies (eg, the 1981 Canada Fitness Survey). The group was large ( $n = 244$ ), given the complexity and cost of the applied MRI reference method. The demographic characteristics of the subjects were similar to those of a large proportion of the United States and Canadian population (ie, aged 20–81 y, racially mixed, and with BMIs between 20 and 30). As with all descriptive anthropometric prediction methods, the developed formula is population specific. For example, the model may not be appropriate for use in bodybuilders, highly trained athletes, or patients with anorexia nervosa or HIV-related illnesses. Moreover, the error of prediction from skinfold thicknesses and circumferences may be considerable in some persons, even when group mean values are accurate. Finally, additional studies are needed to establish whether the model accurately predicts longitudinal changes in SM with various interventions.

The second prediction model (Equation 6) includes easily obtained measurements—body weight, height, sex, age, and race. This model also had good prediction qualities, with an  $R^2$  of 0.86 and an SEE of 2.8 kg. The additional explained variance of the skinfold-circumference model (ie,  $\approx 5\%$ ) was likely due to the improved sampling of individual differences afforded by extremity skinfold thickness and circumference measurements that is not offset by greater measurement error. Additionally, a small bias was observed when the model developed in group A was cross-validated in the nonobese group B subjects and in the obese

**TABLE 6**


Comparison of the 2 prediction models

Cross-validation group	Difference <sup>1</sup>	Bland Altman $P^2$	$R^2$ <sup>3</sup>	SEE <sup>3</sup>
Nonobese subjects ( <i>n</i> = 122)				
Skinfold-circumference model (3)	$-0.27 \pm 2.50^4$	0.45	0.89	2.5
Body weight and height model (5)	$-0.34 \pm 2.73$	0.003	0.86	2.6
Obese subjects ( <i>n</i> = 80)				
Skinfold-circumference model (4)	$-0.36 \pm 2.99$	0.009	0.83	2.9
Body weight and height model (6)	$-2.33 \pm 3.31^5$	<0.001	0.79	3.0

<sup>1</sup>Skeletal muscle (SM) measured by magnetic resonance imaging (MRI) minus predicted SM.<sup>2</sup>For simple linear regressions of the MRI-measured SM on the difference between MRI-measured SM and predicted SM.<sup>3</sup>Obtained from simple linear regressions of the MRI-measured SM on the predicted SM.<sup>4</sup> $\bar{x} \pm SD$ .<sup>5</sup> $P < 0.001$ .

subjects. Moreover, the predicted group mean SM was significantly larger ( $\approx 10\%$ ) than that measured for the obese group. Hence, the second model should not be applied in obese subjects.

The results of previous studies strongly support the view that total-body SM is a function of independent variables in addition to body mass and other anthropometric dimensions, namely sex, age, and race (22–24). As might be anticipated, our models indicated that men have a greater SM than do women and that younger subjects have more SM than do older subjects, after other predictor variables are controlled for. Our models also support a racial SM difference, with lower SM in Asians, greater SM in African Americans, and intermediate SM in whites and Hispanics. These observations strengthen the results of earlier studies that showed racial regional (22) and whole-body SM differences (24).

In summary, 2 anthropometric prediction equations for total-body SM were developed and then cross-validated in independent samples of nonobese and obese subjects. The skinfold-circumference model had a higher accuracy than did the body weight and height model in predicting total body SM in healthy adult populations, and both models were sex, age, and race specific. When applied to obese subjects, the skinfold-circumference model was more robust than was the body weight and height model. Additional validation studies are needed to test the usefulness of these equations in predicting longitudinal SM changes with various nutritional, exercise, and pharmacologic interventions. 

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