Improved Prediction of Body Fat by Measuring Skinfold Thickness, Circumferences, and Bone Breadths

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Abstract
GARCIA, ADA L., KAREN WAGNER, TORSTEN HOTHORN, CORINNA KOEBNICK, HANS-JOACHIM F. ZUNFT, AND ULRIKE TRIPPO. Improved prediction of body fat by measuring skinfold thickness, circumferences, and bone breadths. *Obes Res.* 2005;13:626–634.
Objective: To develop improved predictive regression equations for body fat content derived from common anthropometric measurements.
Research Methods and Procedures: 117 healthy German subjects, 46 men and 71 women, 26 to 67 years of age, from two different studies were assigned to a validation and a cross-validation group. Common anthropometric measurements and body composition by DXA were obtained. Equations using anthropometric measurements predicting body fat mass (BFM) with DXA as a reference method were developed using regression models.
Results: The final best predictive sex-specific equations combining skinfold thicknesses (SF), circumferences, and bone breadth measurements were as follows: BFM_{New} (kg) for men = −40.750 + {(0.397 × waist circumference) + [6.568 × (log triceps SF + log subscapular SF + log abdominal SF)]} and BFM_{New} (kg) for women = −75.231 + {(0.512 × hip circumference) + [8.889 × (log chin SF + log triceps SF + log subscapular SF)] + (1.905 × knee breadth)}. The estimates of BFM from both validation and cross-validation had an excellent correlation, showed excellent correspondence to the DXA estimates, and showed a negligible tendency to underestimate percent body fat in subjects with higher BFM compared with equations using a two-compartment (Durnin and Womersley) or a four-compartment (Peterson) model as the reference method.
Discussion: Combining skinfold thicknesses with circumference and/or bone breadth measures provide a more precise prediction of percent body fat in comparison with established SF equations. Our equations are recommended for use in clinical or epidemiological settings in populations with similar ethnic background.

Key words: predictive equations, body composition, DXA, anthropometric, overweight

Introduction

Worldwide, overweight and obesity are considered to be a major health problem (1) because of their strong association with a higher risk of diseases of the metabolic syndrome, including diabetes mellitus and cardiovascular disease, as well as with certain forms of cancer (2,3). Obesity is frequently evaluated by using simple indicators such as BMI, waist circumference, or waist-to-hip ratio (3,4). Specificity and adequacy of these indicators is, however, still controversial (5–7) because they do not allow a precise assessment of body composition. Body fat, especially visceral fat, is suggested to be a better predictor of diseases of the metabolic syndrome (8). Therefore, the assessment of body composition is necessary to properly diagnose the nutritional status in individuals, particularly in epidemiological studies. To assess body composition, direct (neutron activation analyses) and indirect (underwater weighing, DXA) in vivo methods have been thoroughly studied (9,10). Highly precise and accurate methods, such as neutron activation analyses and DXA, are considered to be reference methods (11). However, these reference methods find little

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epidemiological applicability because of the high costs and methodological efforts needed. Predictive equations derived from skinfold thickness (SF)[1] measurements provide good associations with body fat mass (BFM) estimation compared with the reference methods (10). Additionally, SF measurements are preferred in clinical or epidemiological settings because of lower costs and less methodological effort. As a result, a broad variety of predictive equations using SF measurements alone or in combination with other anthropometric measurements (circumferences, lengths, breadths) have been developed (12,13). However, many of the equations derived from simple anthropometric measurements show a lack of accuracy in predicting body composition in overweight populations (14). The well-known SF prediction equations from Durnin and Womersley (15), Jackson et al. (16), and the newly developed equation from Peterson et al. (17) have been shown to systematically underestimate body fat in subjects with higher BFM. The inclusion of other anthropometric measurements that provide information of fat distribution (waist and hip circumferences) (18) and body frame (breadths) (19) have each contributed separately to improve the predictive capacity of SF measurements (14,20). The aim of this study was to develop new predictive equations using a few anthropometric measurements (SFs, circumferences, and bone breadths) in adults within a range of body fat content including normal and overweight subjects. These equations are intended to provide improved body fat estimates than the ones derived from existing equations and to avoid underestimation in subjects with a higher BFM.

Research Methods and Procedures

Subjects

Healthy German adult male and female volunteers were recruited by advertisements in the local media. Subjects of the validation group participated in a study designed as a long-term study to compare different methods for estimating body composition (BodyLife, $n = 70$). Body composition was assessed at baseline and at 2 and 4 months during an intervention intended to reduce body weight. For validation, only the data assessed at 4 months were used. A second group participated in a previous body composition study aimed to calibrate the various anthropometric methods available at the department. This group was used as a cross-validation group ($n = 47$) (21). Exclusion criteria in both groups were pregnancy, lactation, and pathologies such as asthma, epilepsy, and cardiovascular, skin, or chronic diseases. Subjects were 20 to 66 years old and had a BMI range of 19.0 to 39.4 kg/m^2. The study protocols were approved by the Ethical Committee of the University of Potsdam. All participants gave written informed consent.

Anthropometric and Body Composition Measurements

All measurements were taken by two experienced anthropometrists. The subjects wore light underwear, and measurements were carried out according to anthropometric standard operating procedures (22). Body weight was recorded after an overnight fast using an electronic calibrated scale (Soehnle, Murrhardt, Germany) to the nearest 0.1 kg. Height was measured with a GPM anthropometer (Siber & Hegner, Zurich, Switzerland) to the nearest 0.1 cm. BMI was calculated as body weight divided by height squared. SFs were measured with a Lange-Caliper (Beta Technology, Cambridge, MA) to the nearest 0.1 mm at the following sites: chin; biceps, triceps; subscapular, chest, abdominal, hip, thigh, knee, and calf (22). Circumferences of waist, hip, and thigh were determined with a soft tape measure to the nearest 0.1 cm. Breadths (chest, elbow, knee, wrist, and ankle) and chest depth were measured using a widespreading caliper (Siber & Hegner, Zurich, Switzerland). The exact site and relevant specifications for the anthropometric measurements are shown in Table 1. Body fat was measured by DXA using a QDR-2000 Bone Densitometer (DXA Hologic, Waltham, MA).

Percentage body fat (BF%) was calculated from DXA and SF measurements according to the equations by Durnin and Womersley (15) and Peterson et al. (17).

Equation Development

A set of SFs, other anthropometric variables, and age were identified that best predicted body fat from DXA. The initial equations included the following variables: age, weight, height, BMI, circumferences (waist, hip, and thigh), breadths (chest, elbow, knee, wrist, and ankle), and SFs (chin, biceps, triceps, subscapular, chest, abdominal, hip, thigh, knee, and calf). Additionally, logarithmic SFs were calculated, and the sums of three or four SFs were also included in the initial analyses. To improve the precision of the estimate, circumference and bone breadths measurements were included. The former can reflect regional adiposity (23), and the latter are related to body size (24).

The preliminary equations derived from the subset of anthropometric measurements that best predicted body fat from DXA were developed separately for both men and women. These equations were developed in the validation group ($n = 70$) and were consecutively tested in the cross-validation group ($n = 47$).

Final equations were obtained from the entire sample ($n = 117$) using the independent variables identified during

[1] Nonstandard abbreviations: SF, skinfold thickness; BFM, body fat mass; BF%, percent body fat; PRESS, predicted residual sum of squares; RMSE, root mean square error.

Table 1. Site and specifications for anthropometrical measurements

Measurement	Site/specifications
Skinfolds	
Chin	Submental fold concentric to the chin, parallel to the longitudinal axis of the body
Biceps	Front of upper arm, over the belly of the musculus biceps brachii, parallel to the longitudinal axis of the upper arm
Triceps	Midpoint of the back of the upper arm between the tips of olecranon and acromial processes, parallel to the longitudinal axis of the upper arm
Subscapular	Below inferior angle of the scapula, at 45° to the vertical, along the natural cleavage lines of the skin
Chest	At the anterior axillary line, at the level of the seventh rib, taken parallel to the rib
Abdominal	Horizontal fold, 5 cm lateral to and at the level of the midpoint of the umbilicus
Hip	Vertical fold immediately superior to the iliac crest at the mid-axillary line
Thigh	Front of thigh, halfway between inguinal crease and anterior patella, measurement at seated subject, along the long axis of the femur
Knee	Vertical fold on thigh, directly in front of patella, measurement at seated subject, along the long axis of femur
Calf	Vertical fold at posterior surface of the calf, 5 cm below the angle of the leg, measurement at seated subject, leg flexed to an angle of 90°
Circumferences	
Waist	Minimal circumference midway between lower rib margin and superior anterior iliac spine
Hip	Maximal circumference at the level of the trochanters
Thigh	Halfway between inguinal crease and proximal border of patella
Breadths	
Chest	Distance of the lateral aspect of the thorax, at the level of the xyphiale
Elbow	Distance between medial and lateral epicondyles of the humerus, forearm is flexed to a right angle at the elbow
Knee	Distance between medial and lateral epicondyles of the femur, measurement at seated subject, leg forms a right angle
Wrist	Direct distance between processi styloidei of radius and ulna
Ankle	Distance between both supratarsalia of tibia and fibula
Depth	
Chest	Distance between xyphiale and vertebra

the previous procedure. A regression analysis on the total dataset was performed separately for men and women.

Statistical Analyses

Descriptive statistics of the participants are given as mean ± SD and ranges. Student's t tests were used to determine significant differences ($p \leq 0.005$) between the general characteristics of the validation and cross-validation groups. To identify anthropometric measurements that best predicted BFM estimated by DXA, multiple linear regression analyses with backward elimination of independent variables were performed using a tolerance level of 0.3 as exclusion criteria to avoid co-linearity. Removal criteria were a significance level of >0.15 and a tolerance level of <0.3. Development of equations was based on different steps. 1) Preliminary hypotheses were built on existing skinfold equations and our own observations. 2) A dimension reduction was conducted based on preliminary regression models. SFs and other anthropometric variables were used in two separate regression models, and those not contributing significantly to the variance were excluded. SFs were then combined as sums without using the information obtained by linear regression models, and different sums of log-SFs were included in the final regression model with backward elimination. The final regression model for backward elimination of remaining variables was based on six- (men) and eight (women). 3) The cross-validation group was used to test the stability of R^2 and was used iteratively for each alternative model until stable results were achieved. All analyses were performed using SPSS for Windows 11.5

Table 2. Characteristics of the study population

	Validation group		Cross-validation group		p*	
	Men	Women	Men	Women	Men	Women
N	25	45	21	26		
Age (years)	49.1 ± 11.9 (19 to 67)	46.7 ± 14.1 (19 to 67)	59.1 ± 4.5 (43 to 65)	58.4 ± 7.4 (32 to 66)	0.005	0.000
Weight (kg)	85.4 ± 0.6 (66.7 to 106.9)	77.4 ± 16.1 (45 to 110.5)	82.4 ± 12.0 (65.7 to 108.0)	71.0 ± 10.4 (50.1 to 91.6)	0.392	0.079
Height (cm)	176.2 ± 8.6 (160.8 to 189.5)	166.1 ± 6.2 (142.7 to 180.7)	175.8 ± 6.5 (164.2 to 187.0)	164.0 ± 5.7 (150.6 to 174.6)	0.860	0.173
BMI (kg/m^2)	27.5 ± 3.2 (19.7 to 35.7)	28.2 ± 6.1 (19 to 39.4)	26.6 ± 2.7 (22.4 to 31.5)	26.4 ± 3.6 (21.6 to 36.3)	0.300	0.194
BFM (kg) by DXA	19.4 ± 7.8 (5.37 to 36.2)	30.9 ± 12.6 (11.21 to 62.0)	23.2 ± 6.6 (13.9 to 35.7)	30.6 ± 7.9 (18.6 to 47.0)	0.084	0.894
SFs (mm)						
Chin	9.9 ± 3.5 (4 to 18)	13.44 ± 5.8 (4 to 27)	12.1 ± 4.4 (6 to 22)	14.5 ± 4.0 (6 to 23)	0.068	0.418
Triceps	11.1 ± 5.0 (4 to 22)	24.0 ± 7.6 (9 to 25)	10.9 ± 4.0 (4 to 22)	27.8 ± 6.8 (12 to 40)	0.903	0.047
Subscapular	20.4 ± 9.1 (6 to 42)	25.7 ± 11.7 (7 to 48)	21.3 ± 9.1 (11 to 46)	27.5 ± 9.6 (12 to 49)	0.755	0.510
Abdominal	25.4 ± 10.2 (7 to 44)	33.9 ± 12.7 (6 to 58)	32.8 ± 9.6 (16 to 46)	41.1 ± 9.2 (20 to 56)	0.016	0.014
Circumferences (cm)						
Hip	100.8 ± 6.5 (92 to 118.5)	107.2 ± 12.3 (88 to 132)	99.5 ± 5.7 (93 to 118.5)	101.8 ± 7.4 (90 to 116.5)	0.470	0.048
Waist	94.8 ± 12.3 (70.4 to 122.5)	88.0 ± 15.3 (66.5 to 116.8)	94.7 ± 8.9 (79 to 113)	86.3 ± 11.6 (65 to 117)	0.980	0.615
Knee breadth	9.8 ± 0.7 (8.2 to 10.9)	9.5 ± 0.9 (7.2 to 11.8)	9.2 ± 1.8 (4.1 to 11.1)	9.0 ± 0.7 (8.1 to 10.8)	0.215	0.041

Values are means ± SD and range.
* Student's t test validation vs. cross-validation group.

(SPSS, Chicago, IL). Tests for accuracy included mean differences and partial R^2. A Bland-Altman analysis (25) was performed to assess the agreement between BFM_{DXA}, BFM_{New}, BFM_{DW}, and $BFM_{Peterson}$.

Pure error for the cross-validation group as a measure of accuracy of the preliminary prediction equation was calculated as the square root of the sum of squared differences between observed and predicted values divided by the number of subjects in the cross-validation group.

The final equations were validated by the predicted residual sum of squares (PRESS) statistic (26), which is equivalent to "leave-one-out" cross-validation. The PRESS statistic is defined as

$$PRESS = \sum e^2_{(i)}$$

where $e^2_{(i)}$ is the residual for observation i computed as the difference between the observed value and the prediction from a regression model, calibrated on the set of $n - 1$ observations from which observation i was excluded. The model fitting included backward elimination of the independent variables following the same procedure as described above, i.e., the PRESS statistic reflects the error of both variable selection procedure and parameter estimation of the final model. The PRESS statistics were calculated using the ipred add-on package (27) within the R system for statistical computing (28), version 1.9.0 (29).

Results

The general characteristics of subjects in the validation and cross-validation groups are shown in Table 2. Between both groups, men and women differed each significantly in height, weight, and BMI, but not in age. Furthermore, significant differences were observed between women in the validation and cross-validation groups for chin and subscapular SFs and for waist circumference and between men for triceps and subscapular SFs and hip and waist circumferences.

Preliminary Equations for the Prediction of BFM and Cross-validation

All possible variable regression analyses were performed separately for men and women. The variables age, weight, height, BMI, thigh circumference, chest, elbow, wrist, and ankle breadths, and logarithmic SFs of biceps, chest, hip, thigh, knee, and calf did not explain the variance of BFM significantly and were, therefore, excluded from the models. In a further step, a combination of three or four SFs, which included at least one SF from the trunk and one of the extremities (30), were included into the regression model. The best predictive preliminary equations obtained in the validation group were:

$$BFM_{PreNew}\text{ (kg) for men} = -38.72 + \{(0.395 \times \text{waist circumference}) + [5.705 \times (\log\text{ triceps SF} + \log\text{ subscapular SF} + \log\text{ abdominal SF})]\}$$

$$BFM_{PreNew}\text{ (kg) for women} = -77.538 + \{(0.424 \times \text{hip circumference}) + [8.777 \times (\log\text{ chin SF} + \log\text{ triceps SF} + \log\text{ subscapular SF})] + (3.128 \times \text{knee breadth})\}$$

where SFs are given in millimeters and circumferences and knee breadth in centimeters.

The BFM calculated from the preliminary equation correlated highly with BFM_{DXA} in both men ($r = 0.969$, $p < 0.001$) and women ($r = 0.965$, $p < 0.001$). In men, the sum of three SFs (triceps, subscapular, and abdominal) explained 78.0% ($R^2 = 0.780$, $p < 0.001$) of the variance. R^2 increased by 15.8% ($R^2_{change} = 0.158$, $p < 0.001$) after inclusion of waist circumference into the regression model. In women, the sum of three SFs (triceps, subscapular, and chin) explained 80.0% ($R^2 = 0.800$, $p < 0.001$) of the variance. R^2 increased by 11.1% ($R^2_{change} = 0.111$, $p < 0.001$) after inclusion of hip circumference and by an additional 2.0% ($R^2_{change} = 0.020$, $p = 0.001$) after inclusion of knee breadth to the regression model.

The preliminary equations were used to calculate BFM in the cross-validation group. BFM_{PreNew} in the cross-validation group also correlated well with BFM_{DXA} in both men ($r = 0.936$, $p < 0.001$) and women ($r = 0.882$, $p < 0.001$). The root mean square error (RMSE) for the validation group was 2.03 kg in men and 3.40 kg in women, and the pure error for the cross-validation group was 2.98 kg in men and 3.38 kg in women.

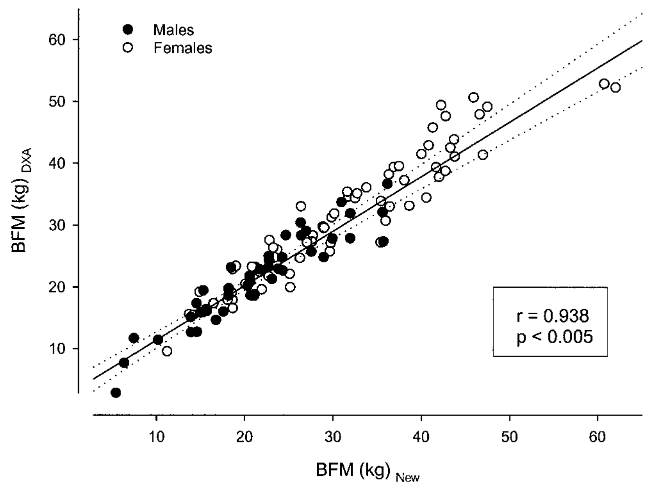

Figure 1: Linear regression (and 95% confidence interval) of BFM (kg) predicted by the new equation (BFM_{New}) against BFM measured by DXA (BFM_{DXA}) in healthy adults ($n = 117$).

Final Equations for the Prediction of BFM

Final equations for BFM were calculated based on the total sample ($n = 117$):

$$BFM_{New}\text{ (kg) for men} = -40.750 + \{(0.397 \times \text{waist circumference}) + [6.568 \times (\log\text{ triceps SF} + \log\text{ subscapular SF} + \log\text{ abdominal SF})]\}$$

$$BFM_{New}\text{ (kg) for women} = -75.231 + \{(0.512 \times \text{hip circumference}) + [8.889 \times (\log\text{ chin SF} + \log\text{ triceps SF} + \log\text{ subscapular SF})] + (1.905 \times \text{knee breadth})\}$$

The BFM calculated from the new equation correlated highly with BFM_{DXA} in both men ($r = 0.938$, $p < 0.001$) and women ($r = 0.949$, $p < 0.001$), as shown in Figure 1. In men, the sum of three SFs (triceps, subscapular, and abdominal) explained 73.6% ($R^2 = 0.736$, $p < 0.001$) of the variance. R^2 increased by 14.5% ($R^2_{change} = 0.145$, $p < 0.001$) after inclusion of waist circumference to the regression model. In women, the sum of three SFs (triceps, subscapular, and chin) explained 70.0% ($R^2 = 0.700$, $p < 0.001$) of the variance. R^2 increased by 19.1% ($R^2_{change} = 0.191$, $p < 0.001$) after inclusion of hip circumference and

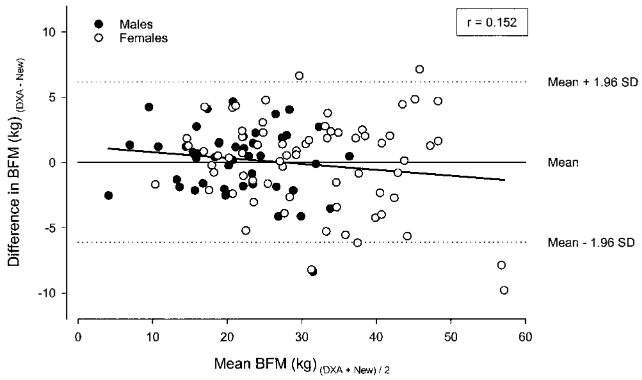

Figure 2: Agreement plot showing the difference between BFM measured by DXA (BFM_{DXA}) and predicted from the final equation (BFM_{New}) plotted against the arithmetic mean of both measurements according to Bland-Altman (25) in healthy adults (n = 117).

by an additional 1.0% (R^2_{change} = 0.010, p = 0.010) after inclusion of knee breadth to the regression model.

Bland-Altman analysis showed good agreement between BFM_{New} and BFM_{DXA} (Figure 2). The mean difference between BFM_{New} and BFM_{DXA} was 0.046 ± 2.575 kg in men and 0.007 ± 3.467 kg in women. This difference does not vary significantly from zero. The absolute difference between BFM_{New} and BFM_{DXA} was <5% in 34 (29%) subjects, between 5% and 10% in 40 (34%) subjects, between 10% and 20% in 31 subjects (27%), and >20% in 13 (10%) subjects.

The predictive capability of the new equation was judged using the PRESS statistic. A good agreement was observed between RMSE (2.56 kg for men and 3.44 kg for women) and PRESS RMSE (2.98 kg for men and 3.97 for women).

Comparison to Other SF Equations

The results of %BF calculated from DXA, the new equations, the Durnin and Womersley equation, and the Peterson et al. equation are shown in Table 3. The $\%BF_{New}$ is closest to the $\%BF_{DXA}$, followed by Peterson et al. ($\%BF_{Peterson}$) and Durnin and Womersley ($\%BF_{DW}$). The mean difference between $\%BF_{New}$ and $\%BF_{DXA}$ was 0.1 ± 3.1% in men and 0.1 ± 4.4% in women compared with 6.7 ± 4.5% in men and −9.8 ± 4.4% in women for the difference between $\%BF_{DW}$ and $\%BF_{DXA}$ and compared with 2.3 ± 4.1% in men and –2.4 ± 3.8% in women for the difference between $\%BF_{Peterson}$ and $\%BF_{DXA}$ (Figure 3, A and B). The absolute difference between %BF according to the different equations and $\%BF_{DXA}$ was as follows: <5% in 108 (92%) subjects by the new equation, in 103 (88%) subjects by Peterson et al., and in 86 (73%) subjects by Durnin and Womersley; between 5% and 10% in 9 (8%) subjects by the new equation, in 13 (11%) subjects by Peterson et al., and in 22 (19%) by Durnin and Womersley; and between 10% and 20% in 1 (1%) subject by Peterson et al. and in 9 (8%) subjects by Durnin and Womersley. The difference between $\%BF_{DW}$ and $\%BF_{DXA}$ (r = −0.859, p < 0.001) and the difference between $\%BF_{PET}$ and $\%BF_{DXA}$ (r = −0.703, p < 0.001) are highly dependent on $\%BF_{DXA}$. However, the difference between $\%BF_{NEW}$ and $\%BF_{DXA}$ showed only a slight systematic error (r = −0.247, p = 0.007).

Discussion

We developed predictive sex-specific equations combining SFs, circumferences, and bone breadths for normal and overweight subjects that are precise and accurate, but most importantly, their underestimation in BF% in subjects with higher BFM is negligible compared with other carefully developed and well-established equations. We compared our equations first with the classical ones of Durnin and Womersley because they were derived from a two-compartment model as a reference method. Second, we compared our equations with the new and improved equation of Peterson et al. because it was based on a four-compartment model as a reference, improving the predictive capacity of the SF equations. Because of the limitations in the use of a two-compartment model as a reference method (31), four-

Table 3. BF% estimated by DXA, the final new equations, the Durnin and Womersley equation, and the Peterson et al. equation

BF%	Men	Women
N	46	71
DXA	24.9 ± 6.9 (7.6 to 35.9)	39.9 ± 0.1 (19.9 to 56.3)
Final new equation	24.9 ± 6.7 (4.1 to 36.8)	40.1 ± 7.6 (16.7 to 51.6)
Durnin and Womersley	31.6 ± 5.1 (16.2 to 41.0)	30.2 ± 5.6 (12.1 to 40.1)
Peterson et al.	27.2 ± 4.9 (9.6 to 35.9)	37.6 ± 7.1 (18.4 to 50.2)

Values are means ± SD and range.

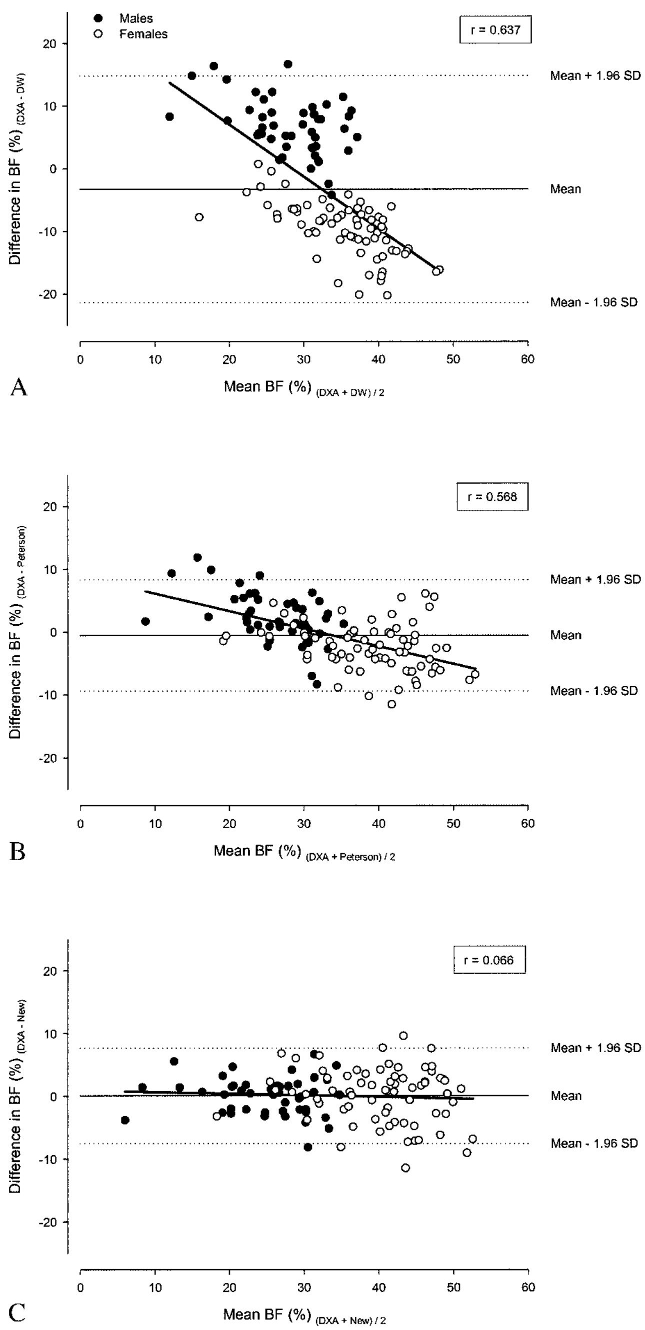

Figure 3: Agreement plots showing the difference between %BF measured by DXA ($BF\%_{(DXA)}$) and (A) predicted from Durnin and Womersley equation, (B) predicted from the equation of Peterson et al., and (C) predicted from the new final equation plotted against the arithmetic mean of both measurements according to Bland-Altman (25) in healthy adults (n = 117).

compartment models have been recommended, and their use in research settings has increased (17,20,32). Furthermore, it should be considered that the BFM estimation derived from the four-compartment model is not completely independent from DXA, and therefore, the increased accuracy of the four-compartment model against DXA is still marginal (32) and is observed mostly in lean subjects (33,34). Additionally, concern still exists because of the propagation of measurement error associated with the determinations of body density, total body water, and bone mineral mass in the four-compartment model (35). Therefore, we considered the use of DXA as a reference method to be as accurate as the four-compartment model. In addition, some SF-derived equations predictive for specified samples [e.g., for older Chinese subjects (36), for children (37), or for sex-specific groups (14,38,39)] have been developed using DXA as reference method. Specific equations for healthy male and female adult whites within a broad range of BMI using DXA as reference method are lacking. Apart from a higher BMI among our study population, our cohorts are comparable to the ones of Durnin and Wormersley (16) and Peterson et al. (17). Nevertheless, it should be considered that the study population of Durnin and Womersley was measured decades ago.

The preliminary equations were highly precise, with excellent correlation values and a negligible mean difference between BFM_{PreNew} and BFM_{DXA}. The accuracy of the preliminary prediction equation was confirmed by the close agreement between the RMSE of the validation group and the pure error in the cross-validation group.

Our newly developed final equations had no significant mean differences with $BF(\%)_{DXA}$ in both men and women. Furthermore, the precision in our new equation was improved in comparison with the equation of Peterson et al., because our mean differences (0.1% for men and 0.1% for women) are lower than the ones reported by Peterson et al. in their final equation (0.18% for men and 0.25% for women). On the other hand, the high similarity between the RMSE and PRESS RMSE suggests that the final equation calculated in the whole group provides valid estimates of BFM. Thus, our new BFM equation had a high predictive capability.

The improvement in the predictive capacity of our equations can be explained by various facts. First, we transformed the absolute SF measures to logarithmic ones (20). Second, we included SFs from the trunk and extremities, as reported in other equations. The SF combination for men included frequently used sites that have extensively been shown to be good predictors of BFM (12). In the equation for women, a rarely included site (chin) had better performance on our regression model in comparison with other common sites; chin SF has been shown to correlate well with body fat (40). Third, we included circumferences that provide an estimate of regional fat distribution (23,41). These circumference measures were good predictors of overweight and obesity (42,43). Waist circumference in men (18) has been associated with central overweight and obesity. Subsequently, the addition of these parameters increased the R^2 of the respective sex-specific equation in our model. Finally, the inclusion of knee breadth to the model further improved the R^2 in the female equation. Associations between knee breadth and body fat have been previously reported (44).

When estimating BF% in our cohort using Durnin and Womersley and Peterson et al. equations, a trend toward BF% underestimation was observed. Using Bland-Altman plots, the underestimation of BF% was clearly stronger for the Durnin and Womersley equation, a fact that has already been reported (17,45). Additionally, the highest percentage of subjects according to our equation had absolute mean differences <5%, followed by Peterson et al. and Durnin and Womersley, and no subject in our equation showed absolute differences between 10% and 20%, contrary to the other two other tested equations.

In our cohort, the lower and upper limits of agreement according to Durnin and Womersley were –21.4% and 18.0%. The Peterson et al. equation showed much lower underestimation compared with the Durnin and Womerseley equation, with –9.3% as a lower limit and 8.3% as an upper limit. The level of underestimation further decreased by using our equation with –7.6% as lower and 7.6% as upper limits. The low accuracy in the Durnin and Womersley estimation can be explained by a systematic overestimation of body density derived from the errors in the assumptions of the two-compartment model (46). Furthermore, from our own experience, hydrodensitometry, which was used as the reference method by Durnin and Womerseley, presents methodical limitations because of the difficulties in the procedures when overweight subjects are being measured. Moreover, Durnin and Womersley did not cross-validate their equations, and the number of overweight subjects included in their population samples was not specified. A clear improvement in the BF% estimates was observed using the equation of Peterson et al., explainable by their improved approach in developing the equation (cross-validation and use of the four-compartment model). However, our equations showed better performance because of the improvement derived from the combination of different anthropometric measurements.

In summary, we developed predictive equations for healthy adult whites with a higher range of BMI (normal and overweight adults) that provided excellent estimates of BFM using DXA as a reference method without a tendency to underestimate body fat. A suitable sum of logarithmic SFs, complemented by the addition of waist circumference for the male equation and hip circumference and knee breadth for the female equation, provided a good combination of anthropometric measurements that is easy to measure and can be applied in clinical and anthropometric studies.

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