Journal of Athletic Training 2022;57(4):393–401
doi: 10.4085/1062-6050-0747.20

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Combining Anthropometry and Bioelectrical Impedance Analysis to Predict Body Fat in Female Athletes

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Context: Accurate methods for predicting the percentage of body fat (%Fat) in female athletes are needed for those who lose weight before competition. Methods mandated by sport governing bodies for minimal weight determination in such athletes lack validation.

Objective: To (1) determine whether combining anthropometry using skinfold (SF) thicknesses and bioelectrical impedance analysis (BIA) in a 3-compartment (3C) model would improve the prediction of %Fat in female athletes and (2) evaluate the Slaughter SF equation.

Design: Cross-sectional study.

Setting: Laboratory-based study during the preseason for collegiate sports.

Participants: A total of 18 National Collegiate Athletic Association Division I female athletes were recruited from swim and gymnastics teams.

Main Outcome Measure(s): We measured %Fat based on a 4-compartment (4C) criterion incorporating body density (air-displacement plethysmography), total body water (D_2O dilution), and bone mineral mass (dual-energy x-ray absorptiometry) compared with predicted %Fat using SF alone (Slaughter equation), BIA (single frequency for total body water estimate), and combined SF and BIA (3C model).

Results: For the %Fat determined using the 4C criterion, the highest adjusted coefficient of determination and lowest prediction error (r^2; ±standard error of estimate) were for the 3C model ($r^2 = 0.87$; ±2.8%), followed by BIA ($r^2 = 0.80$; ±3.5%) and SF ($r^2 = 0.76$; ±3.8%; P values $< .05$ for all). Means differed for the %Fat determined using BIA (26.6% ± 7.5%) and the 3C (25.5% ± 7.2%) versus 4C model (23.5% ± 7.4%; analysis of variance and post hoc analyses: P values $< .05$). The SF estimate (24.0% ± 7.8%) did not differ from the 4C value.

Conclusions: Combining SF and BIA might improve the prediction and lower the prediction error for determining the %Fat in female athletes compared with using SF or BIA separately. Regardless, the Slaughter equation for SF appeared to be accurate for determining the mean %Fat in these female athletes.

Key Words: body density, fat-free mass, minimal weight, gymnasts, swimmers

Key Points

- Combining skinfolds and bioelectrical impedance analysis may be a practical means for improving field methods by increasing the strength of the prediction and reducing the prediction error and therefore warrants further investigation in female athletes.
- A skinfold equation developed in nonathlete females and currently mandated by some sport governing bodies appears valid for use in collegiate female athletes with widely varying fat-free mass compositions, a confounding variable in assessing the percentage of body fat.

Attempting to maximize strength relative to body mass (BM) is among the strategies used by athletes to increase competitiveness. Weight reduction with the elimination of excess body fat is one approach to this. To be eligible to compete in some sports, athletes must "make" a specified weight class established by the sport's governing body (SGB). In this case, when current body fat may be low, other components of BM, namely water, glycogen, and even protein, may be lost to achieve the weight class. As recognized by the National Athletic Trainers' Association, rapid and excessive loss of these components can risk the athlete's safety, health, and performance during the competitive season.[1] As a consequence of the risks, especially those linked to hypohydration, SGBs have implemented programs that include body composition assessment to optimize fat-mass reduction and reduce the risks of exercise-induced heat illness, muscle-mass loss, and nutritional inadequacies.[2,3]

Athletic trainers are often charged with conducting the body composition assessments for guiding safe and reasonable weight reduction. These clinicians must have valid methods for predicting ideal body weight in adolescents and college-aged athletes and must be confident in the methods. The percentages of body fat (%Fat) and fat-free mass (FFM) are used to determine a *minimal weight* (MW), which is defined as the lowest BM that sustains good health and performance. Specifically, MW is set as the mass for which 7% of the body is fat (MW = FFM/0.93) in adolescent or younger males, 5% is fat in collegiate and adult male athletes (MW = FFM/0.95), and 12% is fat for all females (MW = FFM/0.88).[1] The programs for determining a competitive body weight in adolescent and college-aged males measure body composition using field methods that have been evaluated and applied for several decades, particularly to the sport of wrestling.[4–6] The research has produced reasonably accurate and reliable methods for determining a competitive body weight of the male athlete based on a minimal %Fat added to the current FFM. The primary field method being applied for female wrestlers is the skinfold (SF) equation of Slaughter et al[7] (Slaughter equation), which was developed using a nonathlete female sample that represented 4 maturation levels (prepubescent, pubescent, postpubescent, and young adult) and white and black races.[7] The SF sites, triceps and subscapular, are easily accessed in females in an unobtrusive way and have been confirmed as reliable when measured by trained testers.[8] The equation has been adopted and is currently applied by state and collegiate SBGs to assess body composition in female athletes who might intend to lose weight for competition,[2,3] but it has not been validated in samples drawn from any female athlete populations.

The validity of the field methods of measuring body fatness relies on several assumptions, including a fixed density of 1.1 g/mL for FFM. This may be erroneous due to variations in the water and bone mineral content (BMC) of the FFM. Even among same-sex, similar-aged young adults, the hydration and mineralization of the FFM may diverge from the assumed and, if not accounted for, may result in an inaccurate measure of body fatness.[9] Variation in body water appears to have a greater effect on body fat estimation than bone-mineral variability, yet deviations in either will bias the estimation of %Fat.[10,11] The conceivable validity of using the Slaughter equation[7] to overcome this in female athletes is based on its original calibration using a 4-compartment (4C) criterion that accounted for FFM variations in the nonathletes studied.

The incorporation of a second field method, such as bioelectrical impedance analysis (BIA), with the SF measurements could potentially further improve the prediction of body fatness and MW. Bioelectrical impedance is typically calibrated to assess total body water (TBW), which is then used to determine %Fat. The BIA could provide information independent of subcutaneous fat as determined by SF thickness, which is unable to account for hydration variation. Attempts at improved prediction of %Fat by combining BIA and anthropometry in nonathletic samples have shown promise. Forslund et al[11] compared the relationships among SF, BIA, and a 4C criterion model, for which variation in the fat-free compartments was quantified. For their assessments, which focused only on men, the r^2 for the multicomponent criterion and either BIA or SF was 0.74 or 0.72, respectively. Combining the field methods substantially increased r^2 to 0.90. Esco et al[12] included females in a similar analysis. For the females only, they reported r^2 values of 0.74 (standard error of estimate [SEE] = 3.1 %Fat) and 0.79 (SEE = 3.3 %Fat) for the respective BIA and SF predictions of the 4C criterion-determined %Fat. Combined, however, the 2 field methods achieved an r^2 of 0.86 (SEE = 2.2 %Fat).[12] In both studies, TBW was not measured directly but estimated using versions of bioelectrical impedance for the 4C criterion and the field method; this could have inflated the correlation because similar bioelectrical impedance methods contributed to both the independent and dependent variable outcomes.[11,12] To our knowledge, the validity of combining the 2 field methods has not been evaluated in female athletes for whom the multicomponent model has been directly measured independent of the predictive tests.

Therefore, we conducted a preliminary investigation of the effect of combining SF thickness with BIA data on predicting body composition. In addition, we examined the use of the Slaughter equation[7] to predict body fatness in a convenience sample of female athletes who were expected to have great variability in lean tissue compartments. We hypothesized that combining the measurement of SF and BIA in a 3-compartment (3C) model would increase the predictability and decrease the prediction error compared with using either field method alone. In addition, we hypothesized that in our sample, prediction of criterion body fatness using the Slaughter equation[7] would produce results comparable with their original work (ie, comparable strength of prediction [r^2] and prediction error [SEE]) and a mean value not different than that of the criterion method. The criterion method used for comparisons was the 4C model that accounts for variations in minerals and TBW, both of which were measured directly and used to correct body density (BD).[13]

METHODS

Participants

A convenience sample of 18 female participants consisting of 7 collegiate swimmers (2 Latina, 5 White athletes) and 11 collegiate gymnasts (1 Latina, 10 White athletes) was recruited. All participants provided written informed consent, and the study was approved by the University of Illinois at Chicago Institutional Review Board.

Design and Procedures

For this cross-sectional study, data were obtained in 1 laboratory session during the first week of October, when both groups were in preseason training. Participants reported to the laboratory at 7 AM after an overnight fast (since 8 PM the previous night) and refrained from drinking or eating for the entirety of the test session, which lasted approximately 4.5 hours.

After arriving at the laboratory, they were provided with an overview of all procedures for the session and then voided to empty their bladders and supply a urine sample for a pregnancy test, assessment of urine specific gravity (USG), and measurement of background deuterium content. Pregnancy testing was mandatory, and a negative test result was required for participation due to the risks imposed by dual energy x-ray absorptiometry (DEXA) radiation exposure. Total body water was measured at the time of all assessments; therefore, we did not exclude any participants based on USG. We measured participants' BM (model ICS439-SW digital scale sensitive to 0.001 kg; Mettler-Toledo) and height (model Seca 240).

Participants consumed a premeasured dose (1.0007 ± 0.0041 g) of deuterium oxide (D_2O, 99.9% deuterium; Sigma-Aldrich) and remained under observation for 4 hours to allow the deuterium to equilibrate in the body fluids.

Two hours postingestion, participants voided, and the urine was discarded to avoid inflating the mass of deuterium in the bladder before isotopic equilibrium had occurred in the whole body (4-hour urine collection). Additionally, tracer lost at 2 hours could have affected the dose; however, a pilot study of 8 participants in our laboratory showed that not correcting for the loss of the tracer at the 2-hour mark resulted in a small error of only 0.3% (160 mL) in the TBW value. Urine samples were collected again 4 hours postingestion of the tracer and were stored at –80°C in cryogenic vials until analysis.

During the tracer equilibration time, participants underwent measurements that consisted of anthropometry, densitometry, DEXA, and BIA. For anthropometry, SF thicknesses were measured in triplicate at the triceps and subscapular sites, as previously described,[7] using Lange SF calipers (Beta Technology).

For densitometry, we measured body volume (BV) using air-displacement plethysmography (GS model BOD POD; COSMED). Thoracic gas volume was measured; however, in 2 participants, the thoracic lung volume was used because of repeated high-merit values. A pilot study in our laboratory and the work of others[14] confirmed that using the predicted thoracic lung volume varied the %Fat outcome by $<1\%$ compared with the estimate when lung volume was measured. Body density was determined using the BV corrected for lung volume and BM.

We conducted DEXA scans to measure BMC (in grams) and density (in g/cm^2; Lunar iDXA with enCORE software version 13.6; GE Healthcare). Standard full-body scans lasting 7 minutes were performed on participants, all of whom fit within the height and width restrictions of the iDXA scanner table.

We conducted BIA using single-frequency technology (Quantum IV; RJL Systems). Participants lay supine for a minimum of 4 minutes before the measurement. Two electrodes were placed on the hand and 2 on the foot as specified by the manufacturer. Resistance was measured 3 times, and the average was used for the analyses.

Analytical Methods

Urine Specific Gravity. Baseline urine was measured for specific gravity using a digital refractometer (ATAGO). The refractometer had a coefficient of variation of $\sim$0.1% for triplicate measurement of a urine sample.

Deuterium. We quantified deuterium in urine samples using cavity ring-down spectroscopy (CRDS).[15] To eliminate compounds that can interfere with the spectroscopy,[16] we purified the urine samples by adding activated charcoal to a 2-mL aliquot and vortexing for 30 seconds. After 72 hours of refrigeration in sealed test tubes, each urine sample was centrifuged and filtered (Amicon Ultra 2 mL 10K centrifugal unit; Millipore). Samples were then measured using CRDS for the ratio of deuterium to hydrogen isotope abundances.[17] Samples were analyzed 10 to 15 times to correct for memory effects of the previous sample. The samples were corrected to the international Vienna Standard Mean Ocean Water isotope scale by measuring 3 internal laboratory standards before, during, and after each run. The coefficient of variation for triplicate analyses of 3 g of D_2O in 40 L of tap water ranged from 0.06% to 1.2%. Recovery was tested using 0.04 g of D_2O mixed in 1.5 L of urine and resulted in a value that was 5.7% of the expected value.

The following general equation was used to calculate TBW (in liters) based on dilution of the initial dose[18]:

$$\mathrm{TBW} = \left[\left(\frac{d}{\mathrm{MW\ D_2O}}\right)\left(\frac{\mathrm{AP}}{100}\right) \times 18.02\left(\frac{1}{\mathrm{D_2O\ ppm\ post} - \mathrm{D_2O\ ppm\ pre}}\right) \times 1000\ \mathrm{g/L}\right] \times 0.958,$$

where $d = D_2O$ dose in grams, MW $D_2O = D_2O$ molecular weight, AP = tracer enrichment (0.999), 18.02 = H_2O molar weight, D_2O ppm post = amount of deuterium in urine sample in parts per million, D_2O ppm pre = amount of deuterium in urine sample before the deuterium dose was ingested, and 0.958 = correction for deuterium overestimation of body water due to 4.2% exchange with nonaqueous compartment.[18]

Body Composition Calculations. ***Percentage of Fat Using SF.*** Using the average of triplicate measures (in millimeters) at the 2 SF sites, %Fat was calculated with the following equation[7]:

$$\mathrm{SF\ \%Fat} = 1.35(\mathrm{Sum\ SF}) - 0.012(\mathrm{Sum\ SF})^2 - 3.4,$$

where Sum SF = triceps mean (in millimeters) + subscapular mean (in millimeters).

Percentage of Fat Using BIA. Resistance (R) obtained from BIA was used to predict TBW using the female-specific equation[19]:

$$\mathrm{BIA} - \mathrm{TBW} = 3.747 + 0.113 \times \mathrm{BM} + \left[0.45\left(\frac{\mathrm{Stature}^2}{R}\right)\right].$$

For the calculation of %Fat using BIA, the FFM was assumed to be 73.8% water[20] and thereafter used with BM to calculate BIA %Fat. In our study, the correlation coefficient for BIA-predicted TBW and TBW measured using deuterium was 0.94 ($P < .001$), and the mean values were nearly identical at 34.5 ± 3.7 L and 34.4 ± 3.4 L, respectively ($P = .89$).

Percentage of Fat Using SF and BIA. Data using the 2 field-method values were incorporated into the 3C model to predict %Fat (3C %Fat)[21]:

$$3\mathrm{C\ \%Fat} = 2.118\left(\frac{\mathrm{BV}}{\mathrm{BM}}\right) - 0.78\left(\mathrm{BIA}\frac{\mathrm{TBW}}{\mathrm{BM}}\right) - 1.351,$$

in which TBW was estimated using the BIA method and BV was determined by rearranging the equation of Siri[21] following the calculation of BD using the SF-estimated %Fat:

$$\mathrm{BD} = \frac{4.95}{(\mathrm{\%Fat}/100) + 4.5}$$

$$\mathrm{BV} = \frac{\mathrm{BM}}{\mathrm{BD}}.$$

Percentage of Fat Using 4C Criterion. The criterion method for %Fat to which field estimates were compared was the 4C model that incorporated directly measured

Table 1. Participants' Characteristics by Sport

Characteristic	Group (Mean ± SD) Gymnasts	Swimmers	t_{16} Value	*P* Value
Age, y	19.6 ± 1.1	19.0 ± 1.4	0.91	.38
Mass, kg[a]	58.9 ± 7.6	73.6 ± 12.4	3.15	.006
Height, cm[a]	161.3 ± 4.3	171.2 ± 9.8	2.97	.009
Body mass index[a]	22.7 ± 3.0	25.0 ± 1.7	3.05	.09
Time in sport, y	13.5 ± 3.3	12.1 ± 1.8	0.96	.35
Starting age, y	8.7 ± 2.2	7.0 ± 1.9	1.73	.10

[a] $P < .05$ for differences between groups.

TBW and BMC using the following Lohman 1992 equation presented by Wang et al[13]:

$$4\text{C }\%\text{Fat} = \left[\left(\frac{2.747}{BD_c}\right) - \left(\frac{0.714 \times TBW_c}{\text{BM}}\right) + \left(\frac{1.146 \times Mo_c}{\text{BM}}\right) - 2.053\right] \times 100,$$

where BD_c was BD determined using BOD POD (COSMED), TBW_c was TBW in kilograms from deuterium dilution, and Mo_c was the total body mineral in kilograms expressed as a fraction of BM (DEXA BMC × 1.2741 to correct for nonosseous mineral mass and loss of BMC during ashing process[20]). All components of the criterion were determined independently of the methods used for the field test estimates. Fat-free mass was calculated using BM and the appropriate %Fat value.

Calculation of MW. For each determination of %Fat, the respective MW (in kilograms) was calculated using the following equations:

$$\text{FFM} = \text{BM} - (\text{BM} \times \text{Decimal of Body Fat})$$

$$\text{MW} = \text{FFM}/0.88,$$

where 0.88 is the theoretical portion of the BM that is fat free when 12% of the mass is fat (1.00–0.12).

Statistical Analyses

Data were summarized as mean ± SD. We used independent *t* tests to compare the participants by sport for physical characteristics; sport history; and the components of body composition including BD, TBW, BMC, bone mineral density, ratio of TBW to FFM from DEXA, and total body mineral content (Mo) to FFM from DEXA. To test the hypotheses relevant to accuracy, 1-way repeated-measures analysis of variance (ANOVA) was computed to compare mean values for the 4 methods. Bivariate correlation and regression were calculated to test hypotheses about the strength of relationships and prediction between the 4C criterion and each prediction method using the correlation coefficient (*r*), the adjusted coefficient of determination (r^2), and the SEE. Bland-Altman analysis was conducted to determine the limits of agreement and consistency of the prediction methods versus the criterion.[22] The hypothesis testing was performed for both %Fat and MW. We selected an α level of .05 to establish statistical significance. All statistical analyses were conducted using SPSS (version 24; IBM Corp).

RESULTS

Physical characteristics and sport history of the swimmers and gymnasts are presented in Table 1. Each athlete group averaged ≥12 years of training in their sport based on surveys they completed on sport participation history ($P = .35$ for group difference). The swimmers were taller ($t_{16} = 2.97$, $P = .009$), had a greater BM ($t_{16} = 3.15$, $P = .006$), and tended to have a greater body mass index ($t_{16} = 3.05$, $P = .09$) compared with the gymnasts. All participants had USG of <1.0250 except for 1 swimmer (USG = 1.0267). Body density and components of FFM (Table 2) differed between groups as expected. Likely due to size (BM) differences, TBW was greater in swimmers than in gymnasts ($t_{16} = 2.78$, $P = .01$). We observed that BMC and bone mineral density were not different between groups, although gymnasts tended to have 6.6% greater bone mineral density compared with swimmers ($t_{16} = 2.09$, $P = .053$). For swimmers, water made up a greater proportion of their FFM ($t_{16} = 3.47$, $P = .003$), while in gymnasts, Mo made up a greater percentage of the FFM ($t_{16} = 4.45$, $P < .001$; Table 2).

The mean %Fat predicted using each method is summarized in Table 3. The ANOVA demonstrated a difference in the mean values of %Fat ($F_{1.76,29.92} = 5.90$, $P = .009$). Post hoc tests showed that the means for BIA (26.6% ± 7.5%) and the 3C model (25.5% ± 7.2%) differed from the 4C criterion mean (23.5% ± 7.4%, $P < .05$). Percentage of body fat using SF (24.0% ± 7.8%) alone did not differ from values determined using any other method. The regression analysis for prediction of %Fat revealed that the 3C model accounted for the highest adjusted variance in the 4C model (adjusted $r^2 = 0.87$), followed by BIA (adjusted $r^2 = 0.80$) and SF (adjusted $r^2 =$

Table 2. Descriptive Statistics for Density and Fat-Free Mass Components by Sport

Variable	Group (Mean ± SD) Gymnasts	Swimmers	t_{16} Value	*P* Value
Density, kg/L	1.059 ± 0.013	1.032 ± 0.015	3.92	.001[b]
Total body water, L	32.96 ± 2.75	36.79 ± 2.98	2.78	.01[b]
Bone mineral content, g	2.369 ± 0.323	2.229 ± 0.231	0.99	.34
Bone mineral density, g/cm²	1.283 ± 0.083	1.203 ± 0.071	2.09	.053
Total body water : fat-free mass	72.72 ± 2.85	76.85 ± 2.17	3.47	.003[b]
Total body mineral[a] : fat-free mass	6.63 ± 0.35	5.93 ± 0.29	4.45	<.001[b]
Protein : fat-free mass	20.65 ± 2.66	17.22 ± 2.34	2.90	.01[b]

[a] Bone mineral content multiplied by 1.2741 to account for the 4% of bone mineral lost during the ashing process and the 23% of ash considered bone mineral contributed by nonosseous material.

[b] Between-groups difference ($P < .05$).

Table 3. Comparison of Current Study and Relevant Literature Using Field Methods to Predict Multicomponent Outcome for Percentage of Body Fat

Study	Participants	Method	Body Fat, %	*r* versus Criterion	Standard Error of Estimate, %	Limits of Agreement, %[a]	*r* for Bland-Altman
Esco et al[12]	59 Healthy nonathlete adult females	3C model[b,c]	27.2 ± 5.9	NR	NR	NR	NR
		3C model[d]	26.9 ± 5.6	0.93	2.2	−0.3 ± 4.3	0.01
		SF	22.2 ± 4.9[e]	0.89	3.3	−4.9 ± 5.9	0.17
		BIA	30.6 ± 5.9[e]	0.86	3.1	3.4 ± 6.2	0.03
Forslund et al[11]	22 Healthy adult males, including 6 athletes	4C criterion[f]	17.6 ± 5.7	NR	NR	NR	NR
		3C model	17.1 ± 5.0	0.95	NA	NA	NA
		SF	17.1 ± 5.7	0.85	NA	NA	NA
		BIA	17.1 ± 5.7	0.86	NA	NA	NA
Present study	18 Collegiate female athletes	4C criterion[g]	23.5 ± 7.4	NR	NR	NR	NR
		3C model	25.5 ± 7.2[e]	0.93	2.8	1.96 ± 5.39	0.05
		SF	24.0 ± 7.8	0.87	3.8	0.53 ± 7.61	0.11
		BIA	26.6 ± 7.5[e]	0.89	3.5	3.08 ± 6.87	0.03

Abbreviations: 3C, 3-compartment; 4C, 4-compartment; BIA, bioelectrical impedance analysis; NA, not available; NR, not relevant (correlation with the same variable); SF, skinfold thicknesses.

[a] Determined using mean difference + (1.96 × SD).

[b] The equation of Siri[21] using body volume (underwater weighing), predicted total body water (bioelectrical impedance spectroscopy), and body mass.

[c] Criterion.

[d] Determined using field methods.

[e] $P < .05$ versus criterion within the study.

[f] Adaptation of the equation of Brozek[20] using body volume (underwater weighing), total body water (bioelectrical impedance analysis), and bone mineral content (dual energy x-ray absorptiometry).

[g] The Lohman 1992 equation presented by Wang et al[13] using body volume (air- displacement plethysmography), total body water (D_2O dilution), and bone mineral content (dual energy x-ray absorptiometry).

0.76; Table 3); all were significant. The SEEs were 2.8%, 3.5%, and 3.8% for the 3C model, BIA, and SF, respectively. The mean differences between each field method and the criterion were >0 (overestimating body fat), but the correlations for the Bland-Altman plots were not different, suggesting consistency in the prediction for these female athletes as %Fat varied (Tables 3 and 4).

The mean MW estimated using the 4C criterion (55.3 ± 4.9 kg) tended to be 1.4 kg more than the mean estimated using the 3C method (53.9 ± 5.4 kg, $P = .09$) and was 2.2 kg more than the mean estimated using the BIA method alone (53.1 ± 5.6 kg, $P < .05$). The mean estimated MW using SF (55.0 ± 5.8 kg) differed by 0.3 kg but was not different from the criterion ($P > .99$). The descriptive statistics for MW and the relationships between the criterion and each field method for MW are presented in Table 4. All correlations were significant ($P < .05$), with the highest *r* and lowest SEE values for 3C prediction of the criterion. Correlations for the Bland-Altman plots were not different and did not show bias in the methods, as %Fat (Figure 1) and MW (Figure 2) varied among the participants.

DISCUSSION

Combining anthropometric and bioelectrical impedance technology might be a practical means of increasing the accuracy and strength of prediction of assessing the athlete's body composition to determine a safe body weight for competition. The combination provides additional information with SF founded on adiposity and electrical impedance analysis largely determined by body water that is almost exclusively in the lean tissues. Because the water content can change abruptly and alter BM independent of fat mass or SF thickness, an accounting of hydration variability could help prevent overestimating the amount of weight that could be lost by the athlete, as previously explained.[23] Somewhat in contrast to our primary hypothesis, the addition of BIA information to the SF data resulted in a mean value that was 2 %Fat units more than the criterion variable ($P < .05$). However, the combination directionally increased the predictability ($r^2 = 0.87$), decreased the prediction error (2.8%), and produced lower limits of agreement (Table 3) compared with outcomes for SF or BIA used individually. This is consistent with the findings of

Table 4. Minimal Weight (kg) Comparisons

Method	Mean ± SD	*r* versus 4-Component Criteria	Standard Error of Estimate, kg	Limits of Agreement, kg	*r* for Bland-Altman
Minimal weight 4-component criteria	55.3 ± 4.9	NR	NR	NR	NR
Minimal weight 3-component model	53.9 ± 5.4	0.92[b]	2.01	−1.36 ± 4.22	0.24
Minimal weight skinfolds	55.0 ± 5.8	0.89[b]	2.34	−0.32 ± 6.00	0.30
Minimal weight bioelectrical impedance analysis	53.1 ± 5.6[a]	0.85[b]	2.67	−2.17 ± 5.14	0.29

Abbreviation: NR, not relevant (correlation with the same variable).

[a] $P < .05$ versus minimal weight 4-component criteria (analysis of variance and post hoc).

[b] $P < .05$.

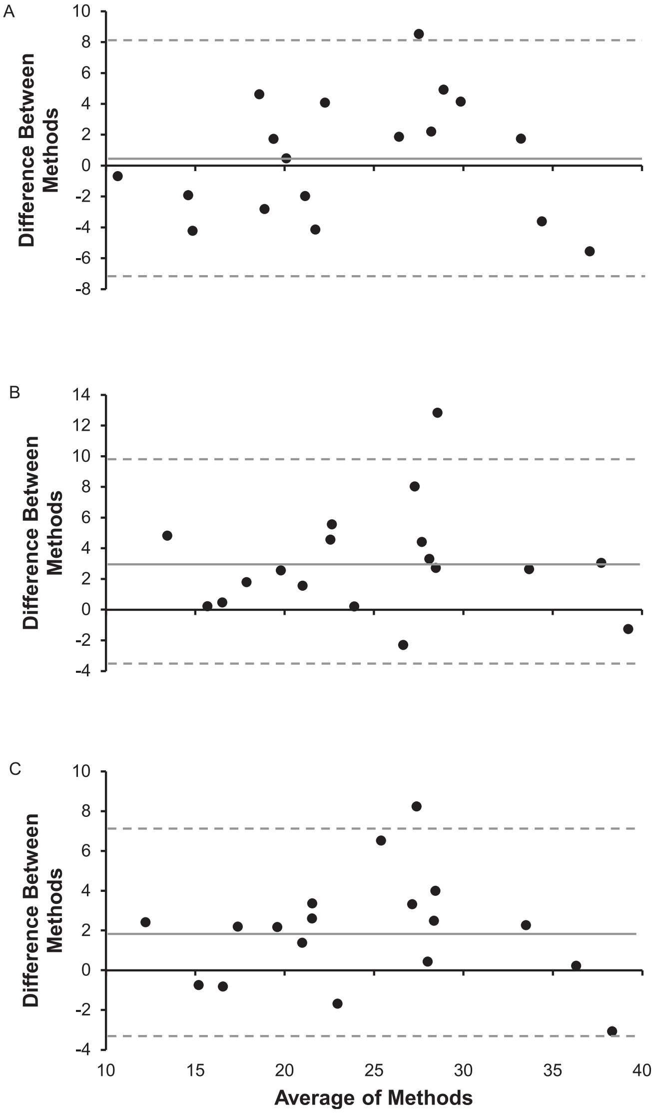

Figure 1. Bland-Altman plots for percentage of fat comparisons of the average of 2 methods (x-axis) and the difference between 2 methods (y-axis). A, Skinfold methods and the 4-compartment (4C) criterion ($r = 0.11$, $P > .05$). B, Bioelectrical impedance analysis method and the 4C criterion ($r = 0.03$, $P > .05$). C, The 3-compartment method and the 4C criterion ($r = 0.05$, $P > .05$).

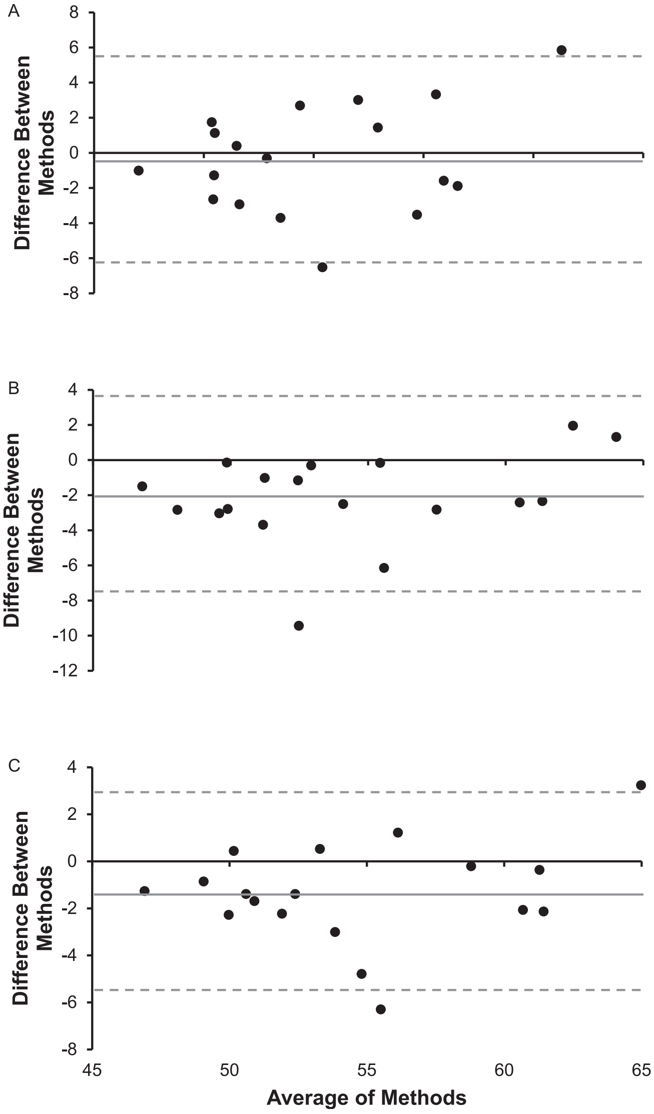

Figure 2. Bland-Altman plots for minimal weight comparisons of the average of 2 methods (x-axis) and the difference between 2 methods (y-axis). A, Skinfold method and the 4-compartment (4C) criterion ($r = 0.30$, $P > .05$). B, Bioelectrical impedance analysis method and the 4C criterion ($r = 0.29$, $P > .05$). C, The 3-compartment method and the 4C criterion ($r = 0.24$, $P > .05$).

others[11,12] who have reported improved prediction when combining SF and BIA to predict body fat in other populations. Translating the body fat from the 3C model into MW also resulted in stronger predictions with less error compared with SF or BIA alone, and the mean value was not different from the 4C criterion, although a tendency to a difference existed.

Field methods designed to assess athletes' body composition commonly assume a 2-compartment (2C) model and have often relied on densitometric methods such as hydrostatic weighing or air-displacement plethysmography as the criterion measure for male populations.[4–6] The model conceptually divides BM into fat mass (FM) and FFM.[24] The 2C model uses a constant density of 0.9 g/mL for human fat and 1.1 g/mL for FFM based on adult cadaveric analyses[21] or the reference human.[20] For the adult FFM, 73.8% is assumed to be water; 6.8%, mineral; and the balance, protein.[20] The density of FM is constant among individuals. Density of FFM can deviate appreciably from reference values due to variations in water and minerals from assumed percentages in FFM, invalidate the assumed FFM density of 1.1 g/mL, and bias the estimate of %Fat for the 2C model.[9,13,25] For this study, we purposely recruited female athletes from sports that have previously been reported to have a high degree of variability in bone mineral density and TBW.[9] Comparisons of the FFM compartments among our participants (Table 2) were consistent with earlier reports for female swimmers and gymnasts,[9,26] and the ratios of the fat-free components varied from the standards typically assumed for TBW : FFM (73.8%) and Mo : FFM (6.8%) when a 2C model is used.[20] Therefore, we believe our study design was valid for exploring how violations of fixed assumptions about FFM translate into errors in body fat determination using traditional field methods; the combination of SF and BIA could help mitigate prediction errors.

Previous researchers[9,10,27,28] have assessed body composition in college-aged female athletes using multicomponent models, but none have specifically investigated the predictability of a multicomponent outcome variable using combined anthropometry and BIA for this population. The 2 published studies[11,12] that have involved the combined field methods are summarized in Table 3, which includes our results. Our observation that the 3C model produced a higher coefficient of determination and lower prediction error compared with the individual methods was consistent with the findings of others.[11,12] In comparing the mean values, however, no consistent pattern emerged. Esco et al[12] reported that on average in females, SF underestimated %Fat, BIA overestimated %Fat, and the combination was not different from the criterion method. Their criterion method was based on a 3C model that did not account for BMC and only estimated TBW using bioelectrical impedance spectroscopy (BIS) independent from the BIA field method. In adult males only, no difference was reported between predictions using anthropometry or BIA individually or when combined and those using a multicomponent criterion that did include total body mineral assessment (DEXA) but only estimated TBW using BIS.[11] Given that BIS and BIA rely on similar principles of current flowing through the body to predict TBW, an inherent bias for elevating the correlations with the 4C criterion could be present. In addition, BIA has been shown to be unreliable for predicting TBW compared with direct analysis.[29] Yet our study, in which we directly measured TBW using deuterium dilution, provided findings consistent with those of earlier studies,[11,12] showing that predictability improves with SF and BIA combined, and suggested that a recalibration or correction factor may be justifiable in aligning the combined field methods for accuracy.

Whereas our study was preliminary and involved a small sample size, a secondary purpose was to evaluate the SF prediction equation of Slaughter et al[7] specifically applied to female athletes. This was important because use of the equation has been mandated by various SGBs in determining the lowest safe competitive weight for females in weight-category sports[2,3] but without validation in female athletes. The Slaughter equation[7] was calibrated to a 4C model that corrected the FFM for deviations from the assumed mineral and water contents due to sex, maturation, and ethnicity in nonathletes.[7] Total body mineral content was extrapolated from scans of only a cross-section of the ulna and radius and not the entire body, as obtained using DEXA. Present-day methods allow for more accurate assessments by obtaining total body mineral using DEXA. To determine TBW, Slaughter et al[7] used infrared spectroscopy to quantify dilution of relatively high doses of deuterium, 6- to 30-fold higher than those in our study. The measurement of TBW has been improved by quantifying proton ratios in the tracer dilution space using much lower doses of tracer (ie, less likely to equilibrate incompletely) and quantification methods of greater sensitivity and precision[18,30]: isotope ratio mass spectrometry or CRDS, both of which reduce errors produced by the higher doses of deuterium used in the past. Although our sample size was relatively small, the lack of a difference between SF prediction and our 4C criterion suggested that the Slaughter equation[7] may be valid as currently applied in college-aged female athletes. With that stated, we believe there is still room to improve the accuracy and reliability of the methods using the additional BIA data due to prediction strengthening (higher r^2, lower SEE) when using the 3C approach.

In our study, the large and statistically significant discrepancy between the mean %Fat for the 4C model and either method involving BIA was perplexing. The electrical resistance value obtained from BIA was used to predict TBW by applying the equation of Chumlea et al,[19] who measured a sample of >12 000 participants with a high degree of variability as a consequence of age, maturation, and ethnicity. The prediction error for their equation for females was quite large (±2.6 L) and could translate into a large error in predicting %Fat. Our BIA-predicted TBW was consistent with and nearly identical to directly measured TBW, suggesting that the BIA data might not have been the source of variability. However, translating TBW to FFM using the standard value of 0.738 would have introduced error. This suggests the need for a criterion that accounts for FFM compartment differences if BIA alone is developed to be used for MW estimation. In contrast, the SF prediction equation of Slaughter et al[7] alone may have fared better in yielding results closer to and not different from our 4C criterion because it was originally calibrated to a 4C criterion that accounted for total body mineral and body water variations.[7]

In athletics, %Fat values are commonly used to calculate MW of participants for competition and provide guidance for reasonable and safe weight management. Minimal weight is not necessarily the ideal performance weight but rather a guide for managing the expectations of athletes who plan and want to lose weight for competition. The calculation is predicated on reducing fat mass and preserving fat-free tissue, with the lowest safe %Fat set at 12% for females.[1,2] Yet athletes, with encouragement from their coaches, may latch on to the MW value as the ideal and strive to achieve it. The implications of our findings are that the SF method, which was originally calibrated to a 4C criterion in nonathlete females,[7] produced an MW that was not different from the 4C criterion value in our female collegiate athletes, different by 0.3 kg on average. In contrast, using the mean values, either method involving BIA differed for MW by 1.4 kg (3C method; $P = .09$) to 2.2 kg (BIA alone; $P < .05$). In other words, either of these methods might allow female athletes to lose an additional 3.1 to 4.8 pounds (1.4 to 2.2 kg), which could place them below the MW and jeopardize their health and performance.

CONCLUSIONS

Despite the inaccuracy suggested by a difference in the means for %Fat and a tendency for a difference in MW when comparing 3C and 4C methods, a strong relationship existed such that the 3C method might improve the prediction (r^2) and lower the prediction error (SEE) of the 4C criterion compared with prediction using SF or BIA separately. This suggests that with recalibration to adjust the intercept of the regression equation, the 3C model could be applied as an accurate and strong predictor of %Fat in female athletes in whom body water and Mo vary considerably and thereby improve identification of MW. The SF equation originally developed by Slaughter et al[7] in nonathlete females appeared to be accurate for use in college-aged female athletes who varied widely in the composition of the FFM, although the prediction error was still moderately high. To arrive at an improved method of predicting an equitable and safe estimate of MW, we encourage future research on larger samples of female athletes from early adolescence to young adulthood who voluntarily manipulate weight for competition. In such a population, combining SF and BIA might be of value to eventually increase accuracy and reduce prediction error. We highly encourage the use of a 4C model as the criterion with each compartment assessed independently of the field methods to account for variability in FFM due to the biological maturation level, adaptations from training, and history of weight manipulation. In the interim, athletic trainers can be confident in using SF to obtain accurate assessments of body fat in order to guide female athletes to a safe and reasonable MW.

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