

Original Article

Body density estimates from upper-body skinfold thicknesses compared to air-displacement plethysmography[☆]

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SUMMARY

Background & aims: Determine the accuracy of body density (Db) estimated with upper-body skinfold thickness (SFT) measurements compared to air-displacement plethysmography (ADP) and ascertain whether body mass index (BMI) impacts the accuracy of SFT to assess Db.

Methods: We estimated Db with SFT and ADP in 131 healthy men and women with normal (N; 18.5–24.9 kg/m²), overweight (OW; 25–29.9 kg/m²), and obese (OB; 30–39.9 kg/m²) BMI.

Results: Compared with ADP, SFT overestimated ($p < 0.05$) Db in OW and OB females and in OB males (−0.0047, −0.0164 and −0.0119 g/cc, respectively), and underestimated ($p < 0.05$) Db in N females and males (0.0050 and 0.0068 g/cc, respectively) but did not differently estimate Db in OW males. The gender by BMI group interaction was not significant. SFT underestimated ($p < 0.05$; 0.0058 g/cc) Db in the N and overestimated ($p < 0.05$; 0.0113 g/cc) Db in the OB BMI groups. The error in predicting Db did not change significantly over the range of Db within the N ($r = 0.239$, $p = 0.06$) and OB ($r = 0.160$, $p = 0.934$) BMI groups. Limits of agreement were −0.0165 to 0.0284 g/cc and −0.0365 to 0.0085 g/cc for the N and OB BMI groups, respectively. The error of estimating Db with SFT was correlated with mean Db in the aggregate sample ($r = 0.495$, $p < 0.0001$) and the OW group ($r = 0.394$, $p < 0.009$). The regression-based limits of agreement were ± 0.0226 g/cc in the total group and ± 0.0168 g/cc in the OW group.

Conclusions: Although SFT offer practical advantages, the validity of SFT to estimate Db among individuals with N and OB BMI is adversely affected.

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1. Introduction

Determination of body density (Db) is a fundamental measurement in the assessment of human body composition. Body density is inversely related to body fatness (% fat) and, thus, is used in the two-component (fat and fat-free) model of body composition.^{1,2} Although hydrodensitometry (HD) is the classical method to estimate body volume and to calculate Db, air-displacement plethysmography (ADP) is a popular option.³ ADP is a safe,

non-invasive alternative to HD and overcomes many of the difficulties of the procedures of underwater weighing and certain methodological issues.³ The need for costly equipment and trained staff to obtain reliable and accurate determinations of Db with ADP and HD limits their general use.

The measurement of upper-body skinfold thickness (SFT) is a practical, cost-effective alternative to estimate Db, and relies on a logarithmic relationship between SFT and body fat to estimate Db.⁴ Comparisons of SFT and ADP estimates of Db are limited with recent data suggesting that body mass index (BMI) influences the results. Compared to ADP, SFT overestimated Db of adults with low BMI, but underestimated Db in men with normal BMI.^{5,6} Thus, BMI or body size may affect the validity of SFT to predict Db in adults.

This study compared estimates of Db determined with SFT and ADP in healthy adults with varying levels of BMI. The goal was to determine whether the most commonly used SFT model is a valid surrogate for ADP in the estimation of Db in healthy adults. We hypothesized that SFT and ADP would yield similar Db values regardless of BMI groups.

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2. Materials and Methods

2.1. Subjects

One hundred thirty-two healthy adults were recruited for this cross-sectional study; one subject was unable to complete the assessments. The goal was to study 40 subjects in each of three BMI groups [normal (N; 18.5–24.9 kg/m²), overweight (OW; 25–29.9 kg/m²), and obese (OB; 30–39.9 kg/m²).⁷ Inclusion criteria were: ≥ 18 years; BMI ≥ 18.5 and < 40 kg/m²; absence of self-reported chronic disease; no use of medication that could influence body water balance; and absence of pregnancy or lactation. Two, 7 and 10 women were post-menopausal in the N, OW, and OB groups, respectively; none of the women were on estrogen treatment. The study was approved by the Institutional Review Board at the University of North Dakota. Subjects provided written informed consent after receiving oral and written descriptions of the study protocol.

2.2. Protocol

Standing height (± 2 mm) was measured with a wall-mounted stadiometer (Holtain Ltd, Crymmych, Pembrokeshire, UK) and weight (± 0.1 kg) was determined with a calibrated, digital scale (Fairbanks model 50735; Kansas City, MO). Subjects wore spandex clothing without shoes and socks, and were instructed to abstain from caffeine, physical activity, showering/bathing/sauna within four hr of testing; refrain from food within two hr of testing; and avoid alcohol 24 h prior to testing. Females were tested during the 6–10th d of their menstrual cycle to minimize the effects of fluid retention.

2.3. Air-Displacement Plethysmography (ADP)

Body volume and Db were estimated by using ADP (Bod Pod, model 2000A, Body Composition System; Life Measurement Inc, Concord, CA). The device is a dual-chamber unit consisting of a testing chamber where the subject sits, and a reference chamber, where the breathing circuit, electronics, and pressure transducers are located.⁸ Five consecutive measurements of the test cylinder volume were taken daily before the start of testing. Manufacturer criteria for an acceptable calibration of the five measurements were a mean difference of ± 100 mL in cylinder volume and standard deviation ≤ 75 mL.⁹ The within and between day coefficients of variation (CV) in volume measurements of the cylinder were 0.08% and 0.31%, respectively. The Bod Pod device also was calibrated using a three-step procedure before each subject entered the chamber.³ The within subject CV for ADP % fat based on repeated measures in our laboratory was 3.2%, which is within the range of within subject CV (2.3–4.5%) for % fat.^{3,10} Subjects wore spandex t-shirt and shorts (men wore shorts only) and a swim cap during ADP.³

Subjects received instructions and had a practice simulation to familiarize them with the procedure. Two trials, lasting approximately 50 sec each, were conducted during which raw body volume was measured. The two raw body volumes were averaged if they differed by ≤ 150 mL.³ A third trial was performed and the closest two body volumes were averaged if the difference in the first two raw volumes was > 150 mL. In the event that the three raw body volumes were not within 150 mL, the unit was recalibrated and each trial repeated. During lung volume measurement, subjects wore a nose clip, breathed through a tube and breathing valve, and performed the recommended breathing maneuver.⁸ A measured thoracic gas volume was obtained by using the

manufacturer software program (version 2.14) and was used to calculate Db.

2.4. Skinfold Thickness Measurements (SFT)

Skinfold thickness was measured with a calibrated, Harpenden skinfold caliper (Holtain Ltd, Crosswell, Crymmych, UK) to the nearest 0.5 mm at the biceps, triceps, subscapular and supra-iliac sites on the right side of the body with the volunteer standing.¹¹ SFT at each site was measured twice by an experienced anthropometrist. The values were averaged unless a difference > 1 mm was found then the measurement was repeated. The intra-class correlations and technical error of measurement for each of the four SFT were ≥ 0.995 and $\leq 3\%$, respectively. The sum of the four SFT was logarithmically transformed and then appropriate age- and sex-adjusted regression coefficients were applied to calculate Db for each subject.¹¹ Body fatness was calculated from Db using the Siri equation¹ to highlight the practical impact of observed differences in Db values by method.

2.5. Statistical analysis

Power analysis indicated that a sample of 120 subjects, 40 in each BMI group, would provide 90% power to detect a mean difference of 0.0111 g/cc between the methods within each BMI range. A within group standard deviation of 0.0111 g/cc for Db and alpha of 0.05 were used.

Repeated measures analysis of variance using the Proc Mixed procedure in SAS 9.1¹² was used to compare Db estimated with ADP and SFT between genders and among BMI groups. Differences in Db and %fat estimated by the two methods then were calculated for each subject. A two-way analysis of variance using the Proc GLM procedure¹² was used to determine the effect of gender and BMI group on these differences. In addition, t-tests were used to determine whether the difference in Db or %fat differed from 0 within a gender and BMI group. Tukey–Kramer contrasts were used for post hoc pair-wise comparisons of means when appropriate. The significance level was $p < 0.05$. Data are reported as mean \pm SD, unless otherwise indicated.

We also determined the error in estimating Db with SFT compared to ADP by using the Bland-Altman method.¹³ When the bias was significantly related to the magnitude of the Db measurement ($p < 0.05$), regression-based limits of agreement were calculated, and are shown on the corresponding figures.

3. Results

Table 1 shows the physical characteristics of the subjects listed by gender and BMI groups. Body volume was less ($p < 0.05$) in the females than the males, and increased ($p < 0.05$) with increasing BMI in each gender group. Compared with ADP, SFT overestimated ($p < 0.05$) Db in OW and OB females and in OB males (Table 2). SFT, compared to ADP, underestimated ($p < 0.05$) Db in both female and male N but did not differently estimate Db in OW males. The gender by BMI group interaction was not significant.

Assessment of bias in the aggregate data showed that the error of estimating Db with SFT compared with ADP was high and negative at low values of Db and high and positive at high values of Db ($r = 0.495$, $p < 0.0001$; Fig. 1A). Thus, SFT overestimated Db at low Db and underestimated Db at high Db. The regression-based limit of agreement [$2 \times$ root mean square error (RMSE)] was ± 0.0226 g/cc in the total group. A similar pattern was observed in the OW BMI group ($r = 0.394$, $p < 0.009$; Fig. 1C) with regression-based limits of agreement of ± 0.0168 g/cc. No statistically

Table 1Descriptive characteristics of participants by gender and Body Mass Index (BMI) Group. Values are mean \pm SD.

	<i>n</i>	Age, y	Height, cm	Weight, kg	BMI, kg/m ²	Volume, ^a L	Σ 4SFT, ^b mm
Females							
Normal	26	36.2 ^a \pm 13.2	165.9 \pm 6.3	62.0 ^a \pm 6.3	22.5 \pm 1.9	59.5 ^a \pm 6.4	51.9 \pm 14.8
Overweight	22	49.9 ^b \pm 12.2	162.5 \pm 5.8	71.8 ^b \pm 5.8	27.2 \pm 1.3	70.5 ^b \pm 5.6	69.1 \pm 18.8
Obese	20	44.2 ^{ab} \pm 12.3	159.5 \pm 4.6	86.7 ^c \pm 7.3	34.1 \pm 2.0	86.4 ^c \pm 7.5	80.3 \pm 24.9
Males							
Normal	20	35.0 ^a \pm 13.7	180.1 \pm 6.5	74.2 ^b \pm 7.3	22.8 \pm 1.5	69.5 ^b \pm 7.4	42.6 \pm 15.2
Overweight	22	39.8 ^{ab} \pm 16.4	179.4 \pm 5.6	88.4 ^c \pm 7.0	27.4 \pm 1.3	84.2 ^c \pm 6.4	58.7 \pm 15.7
Obese	21	49.7 ^b \pm 12.2	179.5 \pm 5.9	107.4 ^d \pm 10.0	33.3 \pm 2.7	104.8 ^d \pm 10.1	70.4 \pm 23.5
All Participants							
Normal	46	35.6 \pm 13.3	172.1 ^A \pm 9.5	67.3 \pm 9.0	22.6 ^A \pm 1.7	63.9 \pm 8.4	47.9 \pm 15.5
Overweight	44	44.9 \pm 15.2	171.0 ^{AB} \pm 10.2	80.1 \pm 10.5	27.3 ^B \pm 1.3	77.3 \pm 9.1	63.9 \pm 17.9
Obese	41	47.2 \pm 12.4	169.7 ^B \pm 11.4	97.3 \pm 13.6	33.7 ^C \pm 2.4	95.8 \pm 12.8	75.2 \pm 24.4
Analysis of variance (<i>p</i> -values)							
Gender		0.39	0.0001	0.0001	0.85	0.0001	0.004
BMI Group		0.0002	0.02	0.0001	0.0001	0.0001	0.0001
Gender * BMI Group		0.03	0.07	0.03	0.31	0.03	0.99

^{a,b,c,d} Within a column, Gender * BMI group means with different superscripts were statistically different ($p < 0.05$).^{A,B,C} Within a column, BMI group means with different superscripts were statistically different ($p < 0.05$).^a Body volume corrected for surface area artifact and thoracic gas volume.^b Skinfold thickness (SFT) at biceps, triceps, subscapular, and supra-iliac sites.¹¹

significant trends in error were identified in the N ($r = 0.239$, $p = 0.06$) and OB ($r = 0.160$, $p = 0.934$) BMI groups (Fig. 1B and D).

Significant errors (Table 2) were found between methods used to estimate Db in the N (mean difference: 0.0058 g/cc) and OB BMI groups (mean difference: -0.0141 g/cc), and the bias did not change significantly over the range of % body fat within the N and OB BMI groups. Limits of agreement were -0.0168 to 0.0284 g/cc and -0.0365 to 0.0085 g/cc for the N and OB BMI groups (Fig. 1B and D), respectively.

These observed differences in Db translated into important differences in % fat (Table 3). SFT significantly underestimated % fat in the females (mean difference: 2.21%) and the OB BMI group (mean difference: 6.72%), and overestimated it in the N BMI group (mean difference: 2.57%). Limits of agreement were -10.95 to 15.37% , -12.79 to 7.65% , -4.06 to 17.50% for the females, and N and OB BMI groups, respectively, and -7.71 to 9.41% for the OW BMI group.

4. Discussion

The challenge of establishing valid methods for field assessment of human body composition persists. The need to balance the practicality and feasibility of performing measurements in a non-laboratory environment with the goal to minimize prediction error emphasizes anthropometric approaches, notably SFT measurements. Epidemiological surveys, which encounter diversity in body size or BMI, utilize SFT to characterize the body composition of population groups.¹⁴ However, the effect of body size on the accuracy of SFT predictions of body composition variables remains uncertain.^{4,15,16} The present study was designed to address this issue; it showed that BMI group classification impacts the validity of the four-site SFT¹¹ to estimate Db and predict %fat. We found no significant difference in Db by method in men and the OW BMI group. Errors in the estimated Db and %fat values in the men and

Table 2Comparison of Body Density (Db) by Gender and Body Mass Index (BMI) Group. Values are mean \pm SD.

	<i>n</i>	Db-ADP, ^a g/cc	Db-SFT, ^b g/cc	Db difference (ADP-SFT)
Females				
Normal	26	1.0379 \pm 0.0132	1.0329 \pm 0.0084	0.0050 ^a \pm 0.0112
Overweight	22	1.0154 \pm 0.0106	1.0201 \pm 0.0093	-0.0047^a \pm 0.0077
Obese	20	1.0019 \pm 0.0093	1.0183 \pm 0.0100	-0.0164^a \pm 0.0130
Males				
Normal	20	1.0628 \pm 0.0151	1.0560 \pm 0.0132	0.0068 ^a \pm 0.0115
Overweight	22	1.0454 \pm 0.0157	1.0441 \pm 0.0133	0.0013 \pm 0.0097
Obese	21	1.0218 \pm 0.0094	1.0337 \pm 0.0122	-0.0119^a \pm 0.0089
All Participants				
Normal	46	1.0487 ^A \pm 0.0187	1.0429 ^B \pm 0.0157	0.0058 ^E \pm 0.0113
Overweight	44	1.0304 ^C \pm 0.0201	1.0320 ^C \pm 0.0166	-0.0017^F \pm 0.0092
Obese	41	1.0121 ^D \pm 0.0137	1.0262 ^C \pm 0.0135	-0.0141^G \pm 0.0133
Analysis of variance (<i>p</i> -values)				
Density			Db difference	
Gender		0.0001	Gender	0.001
BMI Group		0.0001	BMI Group	0.03
Method		0.0004	Gender * BMI Group	0.62
Gen * BMI Group		0.12		
Gen * Method		0.03		
BMI Group * Meth		0.0001		
Gen * Meth * BMI Group		0.63		

^a Difference score was statistically different than zero ($p < 0.05$).^{A,B,C,D} BMI group by Db method means with different superscripts were statistically different ($p < 0.05$).^{E,F,G} Difference scores with different superscripts were statistically different ($p < 0.01$).^a Air-displacement plethysmography.^b Skinfold thickness.¹¹

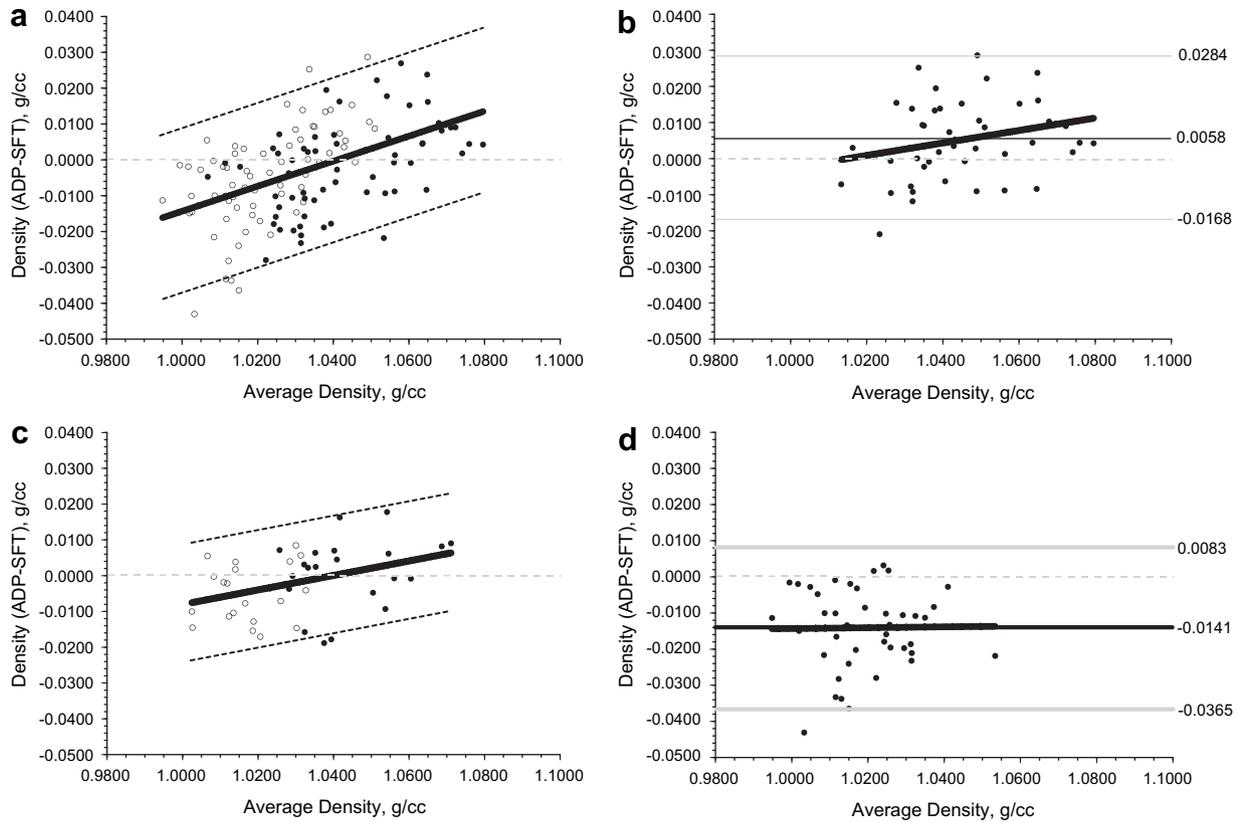


Fig. 1. Agreement between body densities determined with air-displacement plethysmography (ADP) and upper-body skinfold thickness (SFT). Open circles represent data from females, and solid circles are data from men. Solid line represents the linear relationship between mean differences in body density (ADP–SFT) and average body density [(ADP + SFT)/2]. Panel A presents data for the entire sample ($n = 131$; $R^2 = 0.245$, $p < 0.0001$, $RMSE = 0.0116$) and Panel C shows the data for the overweight BMI (25–29 kg/m²) group ($n = 44$; $R^2 = 0.154$, $p < 0.009$, $RMSE = 0.0086$) including the regression-based limits (2 X RMSE) for the regression line shown in abbreviated lines. Panel B shows data for the normal BMI (18–25 kg/m²) group ($n = 46$; $R^2 = 0.078$, $p < 0.06$, $RMSE = 0.0109$). Panel D presents data for the obese BMI (30–40 kg/m²) group ($n = 41$; $R^2 = 0.002$, $p = 0.93$, $RMSE = 0.0113$).

Table 3
Comparison of Body Fatness (%fat) by Gender and BMI Group. Values are mean \pm SD.

	<i>n</i>	%Fat, ADP ^a	%Fat, SFT ^b	%Fat difference, (ADP–SFT)
Females				
Normal	26	26.99 \pm 6.12	29.25 \pm 3.92	–2.26 ^a \pm 5.20
Overweight	22	37.55 \pm 5.06	35.27 \pm 4.45	2.29 ^a \pm 3.70
Obese	20	44.10 \pm 4.58	36.15 \pm 4.76	7.95 ^a \pm 6.33
Males				
Normal	20	15.86 \pm 6.72	18.84 \pm 5.88	–2.98 ^a \pm 5.11
Overweight	22	23.63 \pm 7.05	24.17 \pm 6.02	–0.55 \pm 4.41
Obese	21	34.50 \pm 4.45	28.94 \pm 5.67	5.55 ^a \pm 4.13
All Participants				
Normal	46	22.15 ^A \pm 8.42	24.72 ^B \pm 7.11	–2.57 ^E \pm 5.11
Overweight	44	30.58 ^C \pm 9.29	29.73 ^C \pm 7.66	0.85 ^F \pm 4.28
Obese	41	39.18 ^D \pm 6.59	28.83 ^C \pm 7.73	6.72 ^G \pm 5.39
Analysis of Variance (p-values)				
%Fat		%Fat difference		
Gender	0.0001	Gender	0.0001	
BMI Group	0.0001	BMI Group	0.02	
Method	0.0002	Gender * BMI Group	0.55	
Gen * BMI Group	0.16			
Gen * Method	0.03			
BMI Group * Meth	0.0001			
Gen * Meth * BMI Group	0.55			

^aDifference score was statistically different than zero ($p < 0.05$).

^{A,B,C,D}BMI group by %Fat method means with different superscripts were statistically different ($p < 0.05$).

^{E,F,G}Difference scores with different superscripts were statistically different ($p < 0.01$).

^a Air-displacement plethysmography.

^b Skinfold thickness.¹¹

the OW BMI group (0.0014–0.0017 g/cc and <1%, respectively) were within the limits of error of the SFT and ADP methods (0.0010 g/cc and 2%, respectively).^{3,11,17} In contrast, SFT significantly overestimated Db in women and the OB BMI groups (0.0044 and 0.0141 g/cc, respectively) and significantly underestimated Db in the N BMI group (0.0058 g/cc). These errors in Db resulted in significant underestimation of mean %fat of the women and the OB BMI group (2.21 and 6.7%, respectively), and overestimation of %fat (2.57%) in the N BMI group. Thus, the errors of estimating %fat by using SFT in these BMI groups exceed the reported mean error of the SFT and ADP methods, particularly in the OB BMI group.^{3,11,17} These findings emphasize the importance of examining the effect of body size in validation of methods of body composition assessment.¹⁸

Preliminary findings suggest that BMI classification affects the validity of the four-site SFT¹¹ to estimate body composition relative to ADP. Among patients with pulmonary disease and low BMI values (16–19 kg/m²), SFT¹¹ significantly overestimated HD-determined Db compared to ADP in patients depleted (1.0527 vs 1.0313 g/cc) or adequate (1.0332 vs 1.0148 g/cc) in fat-free mass.⁵ Compared to ADP, SFT¹¹ tended to underestimate Db (1.0668 vs 1.0679 g/cc) of male athletes with OW BMI.⁶ Thus, the findings of the present study confirm that SFT overestimates Db in adults with low and N BMI and, importantly, provide the first evidence that BMI group affects estimates of Db in a study powered to identify differences in SFT-predicted Db among BMI groups.

The systematic overestimation of Db and associated underestimation of %fat in the OB BMI group (6.72%) is important (Fig. 1D). Difficulties in accurately measuring SFT in obese adults^{19,20} and inaccuracies in the assumptions of the two-component model^{20,21} contribute to discrepancies in the estimation of body composition of obese individuals.²² As shown in the present study (Table 3), errors in the prediction of %fat with SFT also occur in other groups, females and the N BMI group, because BMI is neither a specific nor sensitive indicator of body composition.^{23,24} Thus, SFT underestimates %fat in individuals with excess fat that is expressed principally in the OB but also in the female and N BMI groups (Fig. 1B).

Use of ADP as a reference method requires attention to potential sources of measurement error particularly in obese subjects. Moderating factors, including inaccurate estimates of thoracic gas volume and body surface area, can produce errors of 2% body fatness in obese individuals.^{3,25} Thus, measurement of individual thoracic lung volumes, wearing tight-fitting attire and swim cap, minimizing facial and body hair, maintenance of room temperature within 21–32 °C with minimal air flow, and restricting body weight of subjects to less than 200 kg optimized validity of the Db determinations with ADP in the present study.

A potential limitation of the present work is the use of SFT from only upper-body sites to estimate Db. Strong associations between lower limb SFT and total subcutaneous adipose tissue mass in cadavers²⁶ supported the inclusion of thigh SFT in seven-site SFT models to predict Db.^{27,28} Recent cross-validation studies in diverse samples of healthy adults reported errors of 3% in body fatness estimates compared to dual x-ray absorptiometry without attention to body size.²⁹ More recently, lower limb SFT sites including the thigh and calf were incorporated into body composition prediction models with reported reductions in the estimation of %fat in young and middle-aged adults.^{30,31} Thus, there is a need to determine whether body size affects the validity of these new prediction models.

In conclusion, the findings of this study indicate that four-site SFT significantly overestimated Db in females and underestimated Db in N BMI group that translates into differences of 2–3% body fat and is at the limit of the accuracy of the SFT and ADP methods. Among adults with BMI classified as OW, SFT significantly underestimated Db at high Db and overestimated Db at lower Db levels. However, SFT significantly overestimated Db and underestimated body fatness by 6–7% in adults classified as obese. Thus, SFT are an acceptable surrogate for ADP in estimating Db among adults with BMI classified as normal or overweight. Future research should determine whether new SFT prediction models that include measurements of lower limb improve the accuracy of body composition prediction among children and adults with diverse body sizes.

Conflict of interest statement

None of the authors have a financial conflict of interest in this research.

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