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Foot-to-Foot Bioelectrical Impedance, Air Displacement Plethysmography, and Dual Energy X-ray Absorptiometry in Resistance-Trained Men and Women

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ABSTRACT

International Journal of Exercise Science 11(4): 1145-1155, 2018. Accurate assessment of body composition is important to athletic performance goal setting and nutritional program design. Dual-energy x-ray absorptiometry (DXA) is considered the "gold standard" in body composition assessment, yet the cost renders DXA unfeasible for many. Therefore, it is of interest to compare other body composition assessment methods to DXA in resistance-trained individuals whose focus is athletic performance. The purpose of the current study was to determine the agreement in estimates of body composition ((body fat (BF%); fat mass (FM); fat free mass (FFM)) by bioelectrical impedance analysis (BIA; Tanita SC-331S) and air displacement plethysmography (ADP; BODPOD) compared to DXA (Hologic Horizon A) in 31 resistance-trained adults (men=15, women=16; mean±SD: 23.6±4.7years). Differences were found in BF% and FM between BIA and DXA. Regression analysis showed BF% and BMI to explain 24% and 29.9% of the variance in BF% measurements between DXA and BIA, respectively. The results of the Bland-Altman plot indicate a poor level of agreement between BIA and DXA for BF%, FM, and FFM (-4.56±8.82 %, -3.48±7.04 kg, 4.59±7.33 kg, respectively). ADP had wide limits of agreement for all variables (BF: 1.85±4.83 %, FM: 1.54±3.72 kg, FFM:-0.22±4.15 kg). BIA and ADP showed increasing variance in all measures as levels of fatness increased, with the exception of FFM for ADP. Compared to DXA, BIA overestimated BF% and FM, and underestimated FFM. Although wide individual errors were noted, no differences were found between ADP and DXA. The magnitude of inaccuracies between methods may be dependent upon individual body fatness.

KEY WORDS: Body fat, fat free mass, lean body mass, muscle strength

INTRODUCTION

In competitive athletes and strength sport participants, body composition measures determine training goals, serve as progress markers, and guide nutrition program design (1). The ability to accurately measure body composition provides valuable information for nutrition education, identifying malnourishment, and preventing undesirable loss of FFM (8). Practitioners commonly assess body composition ((body fat (BF%), fat mass (FM), fat-free mass (FFM)) in their performance-focused clientele such as, competitive athletes and strength sport participants. Therefore, determination of the accuracy of different assessment methods in the aforementioned populations is warranted.

The 4-compartment model ((4C); fat, protein, water, mineral)), is considered the criterion method for assessing body composition, (16). Availability of 4C models outside of clinical and research settings is narrow due to expense and data processing limitations (16). When compared to body composition estimates from 4C models, the 3C model (fat, fat-free, mineral) of dual-energy x-ray absorptiometry (DXA) has been shown to be valid (r = 0.87-0.94; standard error of the estimate = 2.6-2.9%) in collegiate athletes (24). DXA's 3C model is based on the different x-ray beam attenuations of fat, bone mineral content, and lean tissue (16). However, the limitations of DXA (required certified technician, equipment size, cost) result in decreased availability to intercollegiate athletic programs and performance-based training facilities. More affordable, space-friendly methods like air displacement plethysmography (ADP) and bioelectrical impedance analysis (BIA) are more commonly used.

The ADP method is a 2C model (FM, FFM), in which body density is calculated from mass and volume, with volume measured by air displacement (16). Body composition estimates via ADP have been shown to be valid and reliable in untrained adults when compared to DXA (2,5,7,22). However, validation of ADP in resistance trained, collegiate athletic populations is inconclusive (10,29,30). Utter et al. found ADP to be a valid measure of BF% and FFM in collegiate wrestlers (29), while others found ADP to underestimate BF% by 2% in football players (10) and overestimate BF% by 2% in women athletes (track and field, volleyball, softball, soccer, crew)(30). The inconsistencies in previous findings highlight the need for further analysis of ADP's validity in resistance- trained, athletic populations.

The 2C BIA method estimates an individual's total body water via resistance to the flow of electrical current. The FM has minimal water content and creates increased resistance to electrical current (12). Body composition measures estimated by BIA have shown a strong relationship to DXA (4,15,20,25,28). However, studies have suggested that BIA underestimates BF% and FM at higher levels of adiposity (4,20,25), while others found BIA to underestimate BF% (29) and FFM (23,27,28) as participants levels of FFM increased. Other findings conflict and suggest BF% to be overestimated in lean individuals (men, <15%; women, <25%)(4). While BIA measurements may show a strong relationship to DXA measures, the wide range of individual error indicates further evaluation in resistance-trained, athletic populations is needed.

Differences in physical activity (29) and adiposity can affect the accuracy of body composition estimates when using ADP and BIA. Further, sex (4, 24), BMI (24), and age (21) have been shown to improve the explained variance between measures significantly. Currently, no studies have validated BIA and ADP to DXA in resistance-trained men and women. Thus, the purpose was to determine the agreement in estimates of body composition (BF%, FM, and FFM) by BIA and ADP compared to DXA in resistance-trained individuals.

METHODS

Participants

Demographic information for all participants is included in Table 1. In addition to the current study, participants simultaneously took part in a bench press study that required ≥ one consecutive year of resistance training with a minimum of 3 sessions per week. Further inclusion criteria were minimum strength requirements determined by one repetition maximum bench press per body weight (1RM/BW) 1.0 for men and 0.70 for women. Participants were instructed to refrain from exercise, eating, and drinking for at least 2 hours prior to body composition testing. In addition, participants were asked to prohibit alcohol and excessive dietary habits the day before testing and urinate within 30 minutes of the testing. ADP testing was completed within 48-72 hours from BIA and DXA. The time of day for all testing was constant for each participant. Prior to participation, all associated risks, procedures and purposes of the study were explained and written informed consent was obtained. The study was approved by the University's Institutional Review Board and conducted in accordance with the Declaration of Helsinki guidelines.

Table 1. Descriptive information of participants.

	Whole Cohort (n=31)	Men (n=15)	Women (n=16)
Age (y)	23.6 ± 4.7	22.3 ± 3.6	22.6 ± 5.3
Training Years (y)	3.4 ± 1.5	3.6 ± 1.7	3.2 ± 1.3
Height (m)	1.69 ± 0.11	1.77 ± 0.08	1.62 ± 0.09
Weight (kg)	73.0 ± 17.5	87.5 ± 12.8	59.4 ± 7.1
1RM: BW (kg/kg)	1.16 ± 0.23	1.32±0.12	1.00±0.22
BMI (kg/m^2) [2]	25.1 ± 3.5	27.7 ± 2.9	22.6 ± 1.8
DXA BF%	19.7 ± 4.5	16.6 ± 2.7	22.6 ± 3.9
Gynoid BF%	23.6 ± 5.7	19.1 ± 3.5	27.8 ± 4.0
Android BF%	20.0 ± 3.8	18.6 ± 3.1	21.3 ± 4.0
Android/Gynoid[1]	0.87 ± 0.13	0.98 ± 0.07	0.77 ± 0.07

Data reported as mean ± SD. Body fat percentage (BF%). [1] Calculated as the ratio of Android / Gynoid BF% estimated by DXA. [2] Body mass index (BMI) was calculated using the formula ($height/weight^2$).

Protocol

Air Displacement Plethysmography (ADP): Upon arrival to the laboratory, height and body mass were recorded to the nearest 0.01 cm and 0.02 kg, respectively using a stadiometer (Detecto, Webb City, MO) and digital scale (BOD POD; Cosmed USA, Concord, CA) calibrated according to manufacturer guidelines with participants' bare foot. Body composition was then assessed using ADP (BOD POD model 2000A; BOD POD; Cosmed USA, Concord, CA) The FM and FFM values were determined based upon the body densities obtained from the BOD POD. Thoracic lung volume was predicted due to time constraints, and the lack of difference in BF% estimates compared to measured thoracic lung volume (18). Prior to each testing session, calibration procedures were completed according to the manufacturer guidelines using an empty chamber and a calibrating cylinder of a standard volume (49.55 L). Participants were instructed to wear a formfitting sports bra (women), spandex shorts, swim cap, and remove all jewelry, in accordance with standard operating procedures, in order to reduce air displacement. A trained technician performed BOD POD testing. Participants were instructed to enter the BOD POD and sit in an erect position with their hands folded in their laps. Two tests were performed to ensure reliability of the assessment. If the tests results were not within 150 mL of each other, two more tests were executed. Test to test reliability of performing this body composition assessment in the Sports Performance laboratory has yielded high reliability for body mass (r=1.0), BF% (0.997), and FFM (1.0).

Bioelectrical Impedance Analysis (BIA): Foot-to-foot BIA was performed on a pressure contact electrode system (Tanita SC-331S; Tanita, Inc., Arlington Heights, IL). Prior to testing, participants were asked to remove jewelry, accessories and to stand erect with bare feet on the footpads. Body height, sex, age, activity level (standardized to "normal" for all participants), and estimated clothing weight (-1 kg) were manually entered. Previous research with NCAA-DI baseball players determined that using the athlete mode resulted in a 5.7% mean difference in BF% estimation when using a Tanita foot to foot BIA (1). Therefore, the authors decided to evaluate the normal setting.

Body mass was measured to the nearest 0.1 kg while the measurement of impedance was made. The BF%, FM, and FFM were estimated using manufacturer predictive equations. In order to reduce possible errors from alterations in body fluid distribution, participants stood for at least 10 minutes prior to testing (26).

Dual-energy X-ray Absorptiometry (DXA): All participants underwent a full body scan using fan beam DXA (Hologic, Horizon A model Belford, MA, USA; APEX software 13.5.3.1:3). To determine if fat distribution had an effect on the accuracy of BIA and ADP, measurements of android/gynoid ratio were collected. Participants wore standardized clothing with no metal parts (drawstring pants, T-shirt) and were instructed to remove jewelry. The whole body scan consists of ~3 minutes x-ray time, of low radiation (~3.4 mSV) and does not exceed exposure limits (3). During the scan, participants lay supine, laterally centered on the table with the palms facing down and feet 45° inward. A Certified Bone Densitometry Technologist supervised all scans. DXA is a reliable and valid measure of body composition (19). Daily calibration of the equipment was performed using a manufacturer-provided phantom spine (Hologic #26436) with a coefficient of variation (CV); bone mineral density, 0.75%; bone mineral content, 6.94%. Weekly calibration for body composition measures was performed using a whole body phantom (Hologic #1104). The CV for DXA assessment of whole body composition in our laboratory was 2.45%, 2.56%, and 2.04% for BF%, FM, and FFM, respectively.

Statistical Analysis
Visual inspection of histograms and the Shapiro-Wilks test for normality showed data were normally distributed for men and women. Analyses were conducted to compare BF (%), FM (kg), and FFM (kg) from BIA and ADP to DXA. Descriptive statistics are presented as Mean ± SD. Overall mean body composition results were compared between body composition methods using the MANOVA procedure. Bonferroni Post-hoc analyses were performed when

a significant finding ($p \leq 0.05$) was identified. Pearson's correlation coefficients were calculated to examine the comparability and agreement of the different methods' mean results. Moderate correlations were defined as R-values of 0.41 to 0.70, and strong correlations were considered to be between 0.71 and 0.90 (9). Regression analyses evaluated the difference between BIA and DXA in measurements of BF% by using age, sex, DXA BF%, BMI, and A/G ratio as explanatory variables. In order to evaluate individual agreement of these methods, Bland-Altman plots were created (6). All statistical procedures were conducted using the Statistical Package for the Social Sciences (SPSS version 24; IBM, Somers, NY, USA).

RESULTS

ADP and DXA Comparisons: No differences in BF% were found between ADP and DXA for the overall cohort, men, or women (Table 2). Strong, significant ($p<0.001$) correlations were observed between ADP and DXA in BF% for the overall cohort (r = 0.909), men (r = 0.875), and women (r = 0.900). The results of the Bland Altman plot indicate ADP underestimated BF% (1.85 ± 4.83%) (Figure 1). There were no differences in FM between ADP and DXA for the overall cohort, men, or women (Table 2). Strong, significant ($p<0.001$) correlations were observed between ADP and DXA in FM for the overall cohort (r = 0.920), men (r = 0.936), and women (r = 0.912). The results of the Bland-Altman plot showed ADP underestimated FM (1.54 ± 3.72) (Figure 2). No differences in FFM existed between ADP and DXA for the overall cohort, men, or women (Table 2). Strong, significant ($p<0.001$) correlations were observed between ADP and DXA in FFM for the overall cohort (r = 0.991), men (r = 0.966), and women (r = 0.970). The results of the Bland-Altman plot revealed strong mean agreement between ADP and DXA for FFM (Figure 3).

BIA and DXA Comparisons: BF% determined from BIA was greater than DXA BF% values for the entire cohort (24.26 ± 4.69 vs.19.70 ± 4.79, p=0.002) and for men (22.03 ± 4.31 vs. 16.63 ± 2.71, p=0.015) (Table 2). Moderate correlations existed between BIA and DXA for the entire cohort (r = 0.519, p=0.003) and for men (r = 0.610, p=0.016). When compared to DXA, Bland-Altman plots indicated BIA had errors of agreement to DXA of -4.56 ± 8.82 % (Figure 1). The FM determined from BIA was greater than DXA FM for the entire cohort (17.70 ± 5.62 vs. 14.21 ± 3.32, p=0.010) (Table 2). Strong correlations existed between BIA and DXA measured FM for entire whole cohort (r = 0.795, $p<0.001$) and for men (r = 0.870, $p<0.001$) while the correlation for women was moderate (r = 0.655, p=0.006). The Bland-Altman plot (Figure 2) indicated BIA overestimated FM with errors of agreement to DXA of -3.48 ± 7.04. There were no differences in FFM between BIA and DXA for the overall cohort, men, or women (Table 2). Strong, significant ($p<0.001$) correlations were observed between BIA and DXA in FFM for the overall cohort (r = 0.981), men (r = 0.948) and women (r = 0.938). Bland-Altman analysis indicated BIA underestimated FFM (Figure 3).

Table 2. Body composition estimates from BIA, ADP, and DXA (Mean values with standard deviations).

		DXA		ADP			BIA		
	n	Mean	SD	Mean	SD	%Diff	Mean	SD	%Diff
Overall									
BF%	31	19.70	4.79	17.86	5.67	1.85	24.26	4.69	-4.56*
FM (kg)	31	14.21	3.32	12.67	4.44	1.54	17.70	5.62	-3.48*
FFM (kg)	31	59.95	15.66	60.17	16.10	-0.22	55.36	13.82	4.59
Women									
BF%	16	22.59	3.86	20.69	5.12	1.90	26.36	4.15	-3.77
FM (kg)	16	13.61	2.84	12.24	3.27	1.37	15.88	4.38	-2.27
FFM (kg)	16	46.67	6.34	47.02	6.34	-0.35	43.39	3.17	3.29
Men									
BF%	15	16.63	2.71	14.84	4.69	1.79	22.03	4.31	-5.40*
FM (kg)	15	14.86	3.76	13.13	5.50	1.73	19.64	6.26	-4.78
FFM (kg)	15	74.12	1010	74.19	10.19	-0.08	68.13	7.74	5.99

Mean values were significantly different from those for DXA * P < 0.05
DXA, Dual Energy X-ray Absorptiometry; BIA, Bioelectrical Impedance Analysis; ADP, Air Displacement Plethysmography; BF%, body fat percentage; FM, fat mass; FFM, fat free mass

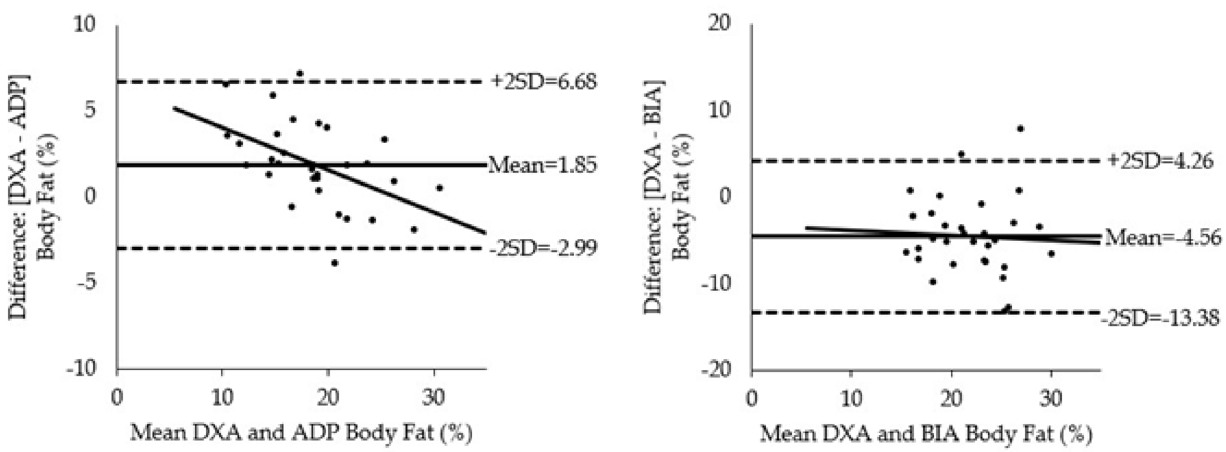

Figure 1. Bland-Altman plots to determine systematic differences in body composition measures of air displacement plethysmography (ADP; left) and bioelectrical impedance analysis (BIA; right) to dual energy X-ray absorptiometry (DXA) for body fat % (BF%) in resistance trained men and women. Lines are the regression slope and bias ± 2 SD of residuals.

The results of the regression analysis are in Table 3. There were no significant differences in regression analyses models 1 (sex and age) and 4 (sex, age, and A/G ratio). Regression model 2 (sex, age, BF%) and 3 (sex, age, BMI) explained 24.0% and 29.9%, respectively. In model 2 BF% was the significant predictor (p=0.015) while sex (p=0.312) and age (p=0.717) had no significant effect. Likewise, the significant predictor in model 3 was BMI (p=0.005), but sex (p=0.093) and age (0.159) had no effect. The results should be reported in a logical sequence, giving the main findings first.

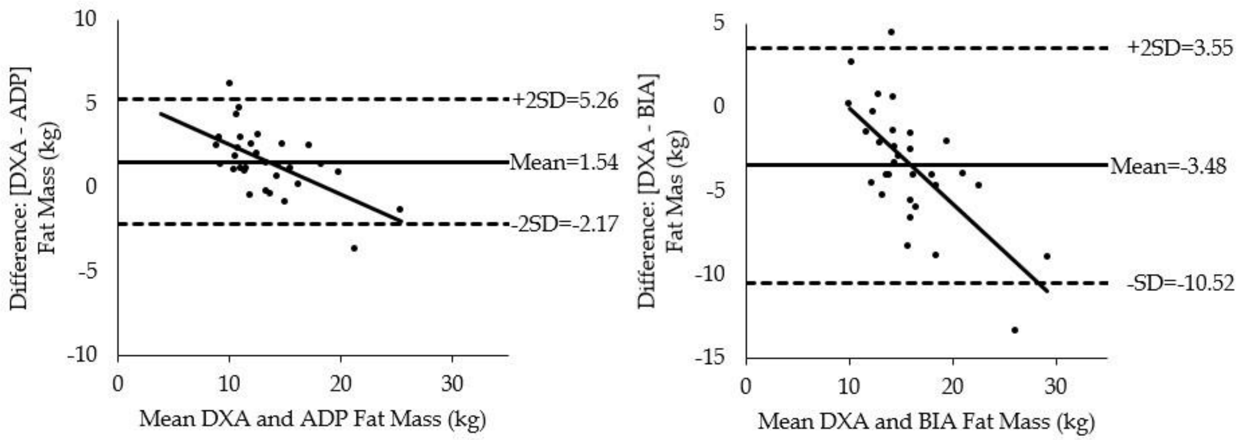

Figure 2. Bland-Altman plots to determine systematic differences in body composition measures of air displacement plethysmography (ADP; left) and bioelectrical impedance analysis (BIA; right) to dual energy X-ray absorptiometry (DXA) for fat mass (FM) in resistance trained men and women. Lines are the regression slope and bias ± 2 SD of residuals.

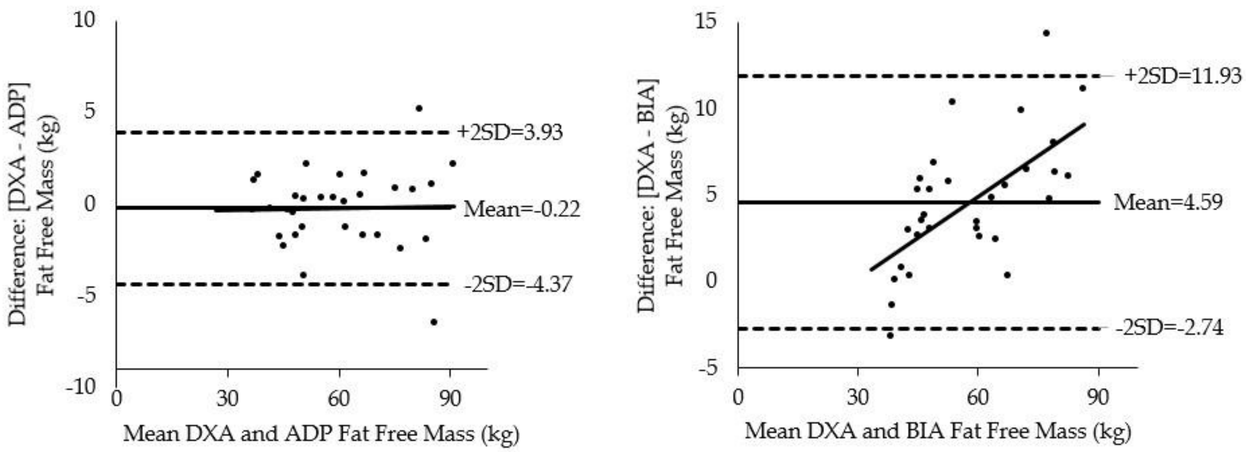

Figure 3. Bland-Altman plots to determine systematic differences in body composition measures of air displacement plethysmography (ADP; left) and bioelectrical impedance analysis (BIA; right) to dual energy X-ray absorptiometry (DXA) for fat free mass (FFM) in resistance trained men and women. Lines are the regression slope and bias ± 2 SD of residuals.

Table 3. Regression analyses of the difference between DXA and BIA in measurements of BF% using sex, age, DXA BF%, BMI and A/G ratio as predictor variables (n = 31).

Predictor	Model 1 R^2= 0.05		Model 2 R^2= 0.240		Model 3 R^2= 0.299		Model 4 R^2= 0.093	
	Beta	95% CI	Beta	95% CI	Beta	95% CI	Beta	95% CI
Sex	-1.32	-4.8, 2.2	2.10	-2.1, 6.3	3.92	-0.7, 8.5	1.48	-4.6, 7.6
Age, years	0.13	-0.3, 0.5	0.06	-0.3, 0.4	0.24	-0.10, 0.58	0.10	-0.3, 0.5
BF, %	n/a	n/a	0.60*	0.1, 1.1	n/a	n/a	n/a	n/a
BMI, kg/m²	n/a	n/a	n/a	n/a	-0.97*	-1.6, -0.3	n/a	n/a
A/G Ratio	n/a	n/a	n/a	n/a	n/a	n/a	-13.19	-36.9, 10.6

DXA, Dual Energy X-ray Absorptiometry; BIA, Bioelectrical Impedance Analysis; ADP; BF%, body fat percentage; A/G Ratio, ratio of Android / Gynoid BF% estimated by DXA. Body mass index (BMI) was then calculated using the formula (height/weight^2)

DISCUSSION

The purpose was to determine the agreement in BIA and ADP estimates of body composition (BF%, FM, FFM) compared to DXA in resistance-trained individuals. ADP and DXA had strong relationships across BF%, FM, and FFM, while the relationship between BIA and DXA was mixed. Further, Bland-Altman plots indicated an overestimation of FM and an underestimation of FFM for BIA compared to DXA.

The strong relationship of body composition estimates from ADP and DXA supports previous findings (7). The results of the Bland-Altman analysis indicated that ADP underestimated BF% at low levels of fatness and overestimated BF% at high levels compared to DXA. This finding from the current study is in agreement with results in an older population of higher body fatness (BF%: 33.1 ± 8.6)(7) as well as results from lean, collegiate football players (BF%: 12.9 ± 1.2%) (10). However, previous research has indicated that ADP overestimates BF% in collegiate women athletes from track and field, volleyball, softball, soccer, and crew (30,32), a finding that was not observed with the resistance-trained women in the current study. However, this may be a result of the aforementioned studies comparing ADP to hydrostatic weighing rather than DXA. Further, we found no mean difference in FFM estimation but there were wide limits of agreement, which holds clinical significance in regard to accurate assessment of muscle mass in the resistance-trained and for subsequent nutritional program design.

When compared to DXA, BIA resulted in significantly higher estimates of BF% and FM for the entire cohort. Further, we observed a significant overestimation of BF% in men. Previous research that compared BF% from BIA and DXA in healthy individuals (19-60 years) reported an underestimation by BIA across the entire cohort as well as in men and women separately (25). The level of body fatness of the current study's participants, which was classified as low to moderate, may partially serve to explain the difference between our results and those of Sun et al. When Sun et al.'s participants were classified by BF% levels, BF% was reportedly overestimated in the low BF% group (BF% <20%), similar in the moderate BF% group (BF% 20-30), and underestimated in the high BF% group (BF% >30) (25). Other literature evaluating overweight and obese participants (range: 36.1-54.7 BF%) also found BIA to underestimate BF%, and proposed that BIA resulted in increasing underestimations with increasing fat levels (20,21). Therefore, it is suggested that BIA using the normal activity level overestimates BF% in leaner, athletic populations such as the one in the current study.

Furthermore, the separate models from our regression analyses suggest that BF% (24%) or BMI (29.9%) partly explain the variance between BIA and DXA for measures of BF%. The relationship of BIA to DXA consisted of a moderate correlation for BF% and strong correlations for FM and FFM. These findings differ from previous research in which a strong correlation for BF% between the two methods was reported (21,25). In part, this discrepancy may be explained by the BIA measurement method. The aforementioned studies (21,25) used a hand-to-foot measurement method where the flow of electrical current is about the entire body rather than remaining in the higher relative adiposity of the lower body as in the foot-to-foot method employed in the current study. Further, previous literature that compared BF% estimates of foot-to-foot BIA to DXA reported moderate correlations in overweight (BMI: 25-30 kg/m^2) or obese (BMI: 25-30 kg/m^2) men (29), yet no relationship was observed in young, overweight or obese women (mean ± SD; 36.4 ± 4.3 kg/m^2) (27). This is in agreement with the current findings of moderate correlations of BF% estimates by BIA and DXA in men, but not women.

Moreover, when evaluating the results of the Bland-Altman plots, the current study found BIA to overestimate FM and underestimate FFM compared to DXA, which is in support of previous findings (4,27,28). Also similar to previous findings, the FM and FFM estimates showed wide levels of individual agreement (25,31). The overestimations of FM and underestimations of FFM measures deviated in their absolute level of agreement with increasing FM and FFM, respectively (20). Previously, in NCAA-D1 baseball players, foot-to-foot BIA resulted in greater mean differences when using "athlete mode" (5.7 ± 4.8%) compared to "normal settings (0.6 ± 4.9%). However, even the most valid estimates of body composition from BIA resulted in unacceptable total error (17). The persistent findings of large variance shown by wide levels of individual agreement or total error (25,31) may suggest that, when assessing resistance-trained populations, the use of BIA is not a desirable method for evaluating FM and FFM.

We acknowledge potential limitations. Participants were asked to refrain from water consumption, yet hydration levels were not documented prior to testing. When young athletic men consumed water prior to BIA testing, BF% increased by 0.5%, which was attributed to weight increase rather than hydration (11). In the current study, body mass measures did not differ and DXA testing immediately followed BIA in the same experimental session. Hydration levels have shown no impact on ADP body composition estimates in collegiate wrestlers (29). Lastly, it is important to note that DXA measures can be affected by different DXA models (13) and subject's trunk thickness (14,16).

In conclusion, there is a wide range of individual error when assessing body composition (BF%, FM, FFM) in the resistance-trained population with BIA or ADP compared to DXA. Our findings, from regression analyses, suggest differences between methods to be associated with increasing body fatness, not sex or age. When testing the agreement of these particular body composition assessments, it is recommended that future research involve a large sample of the aforementioned population and use a 4C model as the reference in a longitudinal study with several time points of body composition evaluations.

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