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Original article

Accuracy and precision of multiple body composition methods and associations with muscle strength in athletes of varying hydration: The Da Kine Study

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SUMMARY

Background: Athletes vary in hydration status due to ongoing training regimes, diet demands, and extreme exertion. With water being one of the largest body composition compartments, its variation can cause misinterpretation of body composition assessments meant to monitor strength and training progress. In this study, we asked what accessible body composition approach could best quantify body composition in athletes with a variety of hydration levels.

Methods: The Da Kine Study recruited collegiate and intramural athletes to undergo a variety of body composition assessments including air-displacement plethysmography (ADP), deuterium-oxide dilution (D_2O), dual-energy X-ray absorptiometry (DXA), underwater-weighing (UWW), 3D-optical (3DO) imaging, and bioelectrical impedance (BIA). Each of these methods generated 2- or 3-compartment body composition estimates of fat mass (FM) and fat-free mass (FFM) and was compared to equivalent measures of the criterion 6-compartment model (6CM) that accounts for variance in hydration. Body composition by each method was used to predict abdominal and thigh strength, assessed by isokinetic/isometric dynamometry.

Results: In total, 70 (35 female) athletes with a mean age of 21.8 ± 4.2 years were recruited. Percent hydration (Body $\text{Water}_{6CM}/\text{FFM}_{6CM}$) had substantial variation in both males (63–73 %) and females (58–78 %). ADP and DXA FM and FF M had moderate to substantial agreement with the 6C model (Lin's Concordance Coefficient [CCC] = 0.90–0.95) whereas the other measures had lesser agreement (CCC <0.90) with one exception of 3DO FFM in females (CCC = 0.91). All measures of FFM produced excellent precision with %CV < 1.0 %. However, FM measures in general had worse precision (% CV < 2.0 %). Increasing quartiles (significant $p < 0.001$ trend) of 6CM FFM resulted in increasing strength measures in males and females. Moreover, the stronger the agreement between the alternative methods to the 6CM, the more robust their correlation with strength, irrespective of hydration status.

Conclusion: The criterion 6CM showed the best association to strength regardless of the hydration status of the athletes for both males and females. Simpler methods showed high precision for both FM and FFM and those with the strongest agreement to the 6CM had the highest strength associations.

Summary box: This study compared various body composition analysis methods in 70 athletes with varying states of hydration to the criterion 6-compartment model and assessed their relationship to muscle strength. The results showed that accurate and precise estimates of body composition can be determined in athletes, and a more accurate body composition measurement produces better strength estimates. The best laboratory-based techniques were air displacement plethysmography and dual-

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Abbreviations: 3DO, 3-dimensional optical; 6CM, 6-compartment model; ADP, air displacement plethysmography; BIA, bioelectrical impedance analysis; BM, body mass; BMC, bone mineral content; BV, body volume; CCC, Lin's concordance correlation coefficient; D_2O, deuterium dilution; DXA, dual-energy X-ray absorptiometry; FFM, fat-free mass; FM, fat mass; kg, kilogram; L, liter; NHOPI, Native Hawaiian or Pacific Islander; NH, non-Hispanic; RMSE, root mean square error; (RMS-CV%), root-mean-square coefficient of variation; SD, standard deviation; TBW, total body water.

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energy x-ray absorptiometry, while the commercial methods had moderate-poor agreement. Prioritizing accurate body composition assessment ensures better strength estimates in athletes.

What is already known on this topic – Body composition and muscle strength are significant predictors of athletic performance.

What this study adds – An ideal body composition assessment approach would provide valid estimates to the criterion and strongly link to a functional component such as muscle strength. This study provides validations of assessment methods for fat and fat-free mass and evaluates their associations with isokinetic and isometric muscle strength.

How this study might affect research, practice, or policy – This investigation provides clinicians and coaches with information vital to identifying the optimal tool for monitoring body composition and strength in athletes.

1. Introduction

Fat-free mass (FFM) represents functional, metabolically active tissue that contributes to strength and force production and plays a key role in sports performance [1]. When fat mass (FM) is in excess, it can hinder performance and adversely affect physiological systems, such as the endocrine system (by increasing the production of cortisol and leptin) as well as the immune system through heightened inflammation [2]. Body composition assessment in sport is consequently critically important for the qualification of athletes as well as monitoring the extreme conditions surrounding sports participation including continuous dieting, energy deficits, and/or extreme weight-loss practices [3]. Similarly, accurate body composition tracking can help identify and monitor relative energy deficiency (RED-S) risk and other injuries or illnesses, as well as enable athletes to adjust their training and nutritional habits to the demands of their sport [4,5].

The relationship between body composition and muscle strength remains unclear due to FFM's complex composition (i.e. water, protein, minerals, and others) that varies between participants and populations [6–8]. An ideal body composition method would be accurate/precise and provide the highest muscle strength/performance associations. Multiple studies have explored absolute or relative proportions of body composition and their associations with muscle strength, though not comprehensively comparing multiple systems, muscle groups, or other predictive factors in athletes of varying states of hydration [9,10].

Furthermore, Nickerson and Gudivaka emphasized the importance of considering skin hydration/temperature status in athletic populations to obtain accurate measurements of body composition estimates [11,12]. Nickerson found that both single-frequency bioelectrical impedance analysis (BIA) and bioelectrical impedance spectroscopy (BIS) devices reported an increase in body water values by approximately 5 % after a brief exposure to heat, despite a slight reduction in body mass. Gudivaka revealed that proximal impedance changes were approximately half as sensitive to alterations in skin and ambient temperature compared to distal impedance, underlining the significance of precise temperature control for obtaining valid and reproducible measurements.

The reference method to assess body composition in vivo is the 6-compartment model (6CM), which provides an estimate of the hydration of FFM that overcomes the limitation of assumed hydration in many commercial body composition methods [13,14]. Because it does not rely on assumptions of constancy in the FFM compartment, it is an ideal candidate for body composition assessment in athletes [8,15,16]. Despite the well-known strengths of multicompartment modeling, time, cost, and equipment costs preclude its routine use in sports settings [17]. Few studies have examined a variety of clinical body composition assessment techniques to the multicompartment models in athletics, where the sample sizes have been small, non-sex-specific, and including limited device comparisons [18–20]. Additionally, rapid commercial techniques such as bioelectrical impedance analysis (BIA) and 3D-optical imaging (3DO) are becoming more accessible in athletic training facilities [21–23]. In performance assessment studies, accuracy is crucial, but the relationship between body composition measures and sport-specific performance outcomes like muscle strength in athletes is not fully understood.

Therefore, this study aimed to examine the accuracy of different laboratory and commercial body composition methods to a criterion model and show their associations to muscle strength within a collegiate athlete population. Additionally, we explored the impact of skin hydration and temperature variations to create a more accurate body composition model to improve strength predictions. We hypothesized that commercial methods, when evaluated, would offer similar accuracy and precision of body composition estimates in their associations to muscle strength over the laboratory-based methods.

2. Methods

2.1. Experimental design

The Da Kine Study is a cross-sectional observational study of athletes to examine the association of body composition estimates to muscle strength. This study was approved by the University of Hawai'i Research Compliance and Institutional Review Board (IRB), protocol #2018-01102. Participants provided written consent at recruitment.

2.2. Participants

Between April 2019–March 2020, eighty healthy male and female collegiate and intramural athletes (>18 years) representing various BMI ranges and sports were enrolled. Sample size estimates were based on a previous validation study of body composition assessment methods to the multicompartment model ($n = 29$ females), attempting to increase recruitment to account for potential data loss and to include an equal stratification of males [24]. Athletes were recruited during their in-season or off-season strength and conditioning routines, with investigators approaching coaches and trainers during practice. Exclusions included pregnancy/breastfeeding, metal implants, or recent body composition-altering procedures. Participants fasted and abstained from alcohol for at least 8 h before testing and avoided moderate-intensity exercise for 24 h. On the testing day, participants arrived at the University of Hawaii Cancer Center adhering to pretesting protocols and underwent anthropometry (height and weight measurements on a stadiometer [Seca264, Chino, CA]), body composition assessments, and thigh and trunk strength tests. Ethnicity was self-reported. Supplemental Table 1 shows all methods obtained and an encompassing comparison of devices and their assumptions. All methods were taken in duplicate to calculate precision.

2.3. Laboratory-based methods

2.3.1. Air displacement plethysmography (ADP)

Measurements were taken using ADP in a BodPod (v5.4.1, COSMED, Concord, CA) to provide body volume (BV) measurements required for 6CM, along with the standard output of body composition. Measurements were taken via the manufacturer's standard protocol, where participants dressed in form-fitting attire, with a hair cap. The BodPod measures BV with corrections for residual lung volume and surface area artifacts (SAA) [25]. Thoracic gas volume (TGV) was measured by breathing through a tube connected to a filter and reference chamber, following the manufacturer's instructions, or estimated if participants could not obtain a valid measurement directly due to the inability to achieve consistency over the three repeated TGV measurements ($n = 26$). The BodPod software automatically calculated the SAA. These two adjustments (TGV and SAA) were factored into the overall BV calculation.

2.3.2. Dual-energy X-ray absorptiometry (DXA)

Whole-body DXA scans were performed using a Hologic Discovery/A system (Hologic, Marlborough, MA) to provide bone mineral content (BMC) for 6CM as well as DXA body composition. Scans were analyzed by a trained technologist using Hologic Apex version 4.5. National Health and Nutrition Examination Survey Body Composition Analysis (NHANES BCA) calibration option was disabled. DXA systems were calibrated according to standard Hologic procedures and all scans were taken by standard procedures [26].

2.3.3. Deuterium oxide dilution (D_2O)

Total body water (TBW) for 6CM was determined using the D_2O protocol defined in the International Atomic Energy Agency (IAEA) standards [27]. A high-precision scale was used for D_2O dosing (Denver Instrument M−310). All study participants provided the required two post-dose saliva samples. Based on previous research using multiple samples and technologies, saliva was chosen as the criterion [17]. The saliva data was interrogated with a quality control method of a 5 % difference between time points of three and 4 h. If the difference was higher than 5 %, the saliva samples were deemed to not have reached equilibrium and were excluded. Participants were provided with a measured dose of 30 g (99.9%pure) D_2O (Cambridge Isotope Laboratories, Tewksbury, MA) and 100 mL local drinking water as a rinse to ensure the entire dose was consumed. During the 4-h D_2O equilibration period, participants were allowed to consume up to 500 mL of water which was recorded. To estimate body composition directly from D_2O measures, TBW was divided by the assumed FFM hydration of 0.732.

2.3.4. Underwater weighting (UWW)

UWW measured BV and estimated body composition. On land, participants were weighed in their form-fitting suit caps, then entered the temperature-stable water with a nose clip. Immersed weight was measured using an electronic weighing system (EXERTECH, Dresbach, MN), transmitting data to a computer and providing continuous recording. Trials were performed at residual volume after maximal expiration. Participants sat on the UWW scale, slowly submerged, fully exhaled, and remained still for underwater weight measurement. This procedure was repeated three times and averaged. The underwater weight is directly proportional to the volume of water displaced by the BV.

2.3.5. Bioelectrical impedance analysis/spectroscopy (BIA/BIS)

Body composition was estimated in participants by three different systems: SOZO (BIS; ImpediMed, Carlsbad, CA), SFB7 (BIS; ImpediMed, Carlsbad, CA), and S10 (BIA; InBody, Cerritos, CA). Each method was performed as per their respective manufacturer recommendations. The S10 and SFB7 scans were performed in an order of convenience approaching a random order immediately following DXA to allow for proper fluid normalization in the supine position [28]. Before each scan, participants cleaned their ankles, hands, and feet with alcohol wipes. For the SFB7 system, participants were tested using single-tab adhesive electrodes after lying supine for 10 min. SOZO measures were performed after a minimum of 5 min of standing to allow for fluid normalization.

2.3.6. Three dimensional optical (3DO) scans

Each participant underwent 3DO whole-body surface scans, with repositioning, on a Fit3D Proscanner with software version 4.1 (Fit3D, Inc., Redwood City, CA). The 3DO scanner provided FM and FFM for analysis. The 3DO scanner is comprised of light-coding depth sensors, a rotating platform, and analysis software [29]. Participants stood on the turntable with legs separated and arms extended and holding the positioning handles following the protocol from the manufacturer. During the scans, the platform rotates 360° over a period of 30–40 s, with the camera system emitting light and reflections being recorded by the camera.

2.3.7. Skin moisture and temperature

A moisture meter (Moisture-Meter-D, Delfin Technologies) assessed cutaneous water content using a control unit transmitting a 300 MHz signal to a skin probe, functioning as an open-ended coaxial transmission line [30,31]. The reflected wave depended on tissue dielectric constant, shown on the unit (range:1–80, pure water ≈ 80). Medium probes assessed tissue water at 1.5 mm depth. Skin temperature was recorded using an infrared temperature scanner (Dermatemp DT-1001, Exergen, Newton, MA) prior to BIA scans. After supine equilibration, measurements were taken twice at three sites on the right side (forehead, dorsal hand, foot).

2.3.8. Strength assessments

Whole-body muscle strength was evaluated using an isokinetic dynamometer (Humac NORM, Computer Sports Medicine, Stoughton, MA). Participants were positioned at 95° trunk-to-thigh angle and secured with straps to stabilize their lower leg, thigh, and waist. They underwent warm-up, practice, and then performed five isometric and concentric repetitions of knee extension/flexion. After resting, they completed five maximal effort repetitions of trunk flexion/extension, followed by 15 consecutive repetitions. Data collection followed the Humac NORM manual protocol without gravity correction. Participants were instructed to exert maximum force rapidly, receiving verbal encouragement but without real-time feedback. The primary measure of strength was isokinetic leg and trunk extension, which maximized whole-body strength assessment by involving multiple muscles and producing a mean peak force.

2.3.9. Multicompartment body composition models

6CM body composition model described by Wang was used as our criterion method [14]. What makes the 6CM unique from the 2- and 3-compartment models discussed above is that it utilizes criterion measures of BV, TBW, and BMC to derive a more accurate measure of body composition without relying on the assumption of constant hydration of FFM. Though the multicompartment models can be expressed in multiple ways, the 6CM derives body composition using four measures: BV by ADP, TBW by D_2O, BMC by DXA, and BM from scale weight. The inclusion of each measure into the final 6CM is shown in Equation (1):

$$FM_{6CM} = 2.748 * BV - 0.699 * TBW + 1.178 * DXA\ BMC - 2.051 * BM \qquad \text{Equation 1}$$

For reporting FFM_{6CM}, BM was subtracted from FM_{6CM} as outlined in Equation (2):

$$FFM_{6CM} = BM - FM \qquad \text{Equation 2}$$

For clarity, all FFM measures include BMC, which differs from lean soft tissue (which excludes BMC) [32]. Hydration of FFM was calculated in Equation (3) to compare to the standard reference value (73.2 %) reported in the literature [33]:

$$Hydration_{FFM} = \left(TBW_{D2O} / FFM6_{CM}\right) * 100\% \qquad \text{Equation 3}$$

2.4. Statistical analysis

Data was initially assessed for normality using Shapiro–Wilks's test. To compare the accuracy between each of the commercial body composition modalities and the criterion 6CM, a one-way within-subjects ANOVA with post-hoc comparisons was performed to assess for significant mean differences. Average error and agreement between measures and the criterion 6CM were calculated using the root mean square error (RMSE), coefficient of determination (R2), intercept values, and Lin's concordance correlation coefficient (CCC). The CCC agreement cutoffs are defined as follows: poor (<0.90), moderate (0.90–0.95), substantial (0.95–0.99), and almost perfect (>0.99) [39]. Specifically, we sought to explore the overall group agreement (as opposed to individual agreement) of methods to determine: (1) which methods provide the strongest group agreement to the criterion and (2) whether those methods with greater agreement had improved predictions of muscle strength.

Test-retest precision for devices with repeated measures was calculated as root-mean-square coefficient of variation (RMS-CV%). Precision was also calculated for D_2O duplicate (separate) samples. Stepwise linear regression was used to determine if TBW/FFM, skin temperature, or moisture improved the prediction of TBW by BIA to the criterion. For the predictor variable (BIA TBW), TBW/FFM, skin temperature, and moisture were used to predict TBW and strength estimates by using a $p < 0.10$ to enter the model $p < 0.05$ to stay in the model. Bootstrapping (n = 1000) 95 % confidence intervals for the R2 of each model using the percentile method was used to compare model performance. To compare each body composition modality to strength, Pearson's correlation was performed between FFM and the corresponding strength measurement. All statistical calculations were performed using SAS 9.4 (SAS, Cary, NC).

3. Results

In this study, 70 participants (35 females) had valid tests for all methods and were included in the final analysis, where Supplemental Fig. 1 provides details of the data that was included and excluded. Due to a malfunction of the UWW device during data collection, only 24 participants (14 females) completed the test, necessitating the use of the n = 24 matched comparisons for all analyses relating to the UWW device (reported separately in Table 2). Descriptive statistics are found in Table 1 and were normally distributed, including the strength measures. Males' BMI ranged from 20.2 to 32.8 kg/m2 and 17.8–30.9 kg/m2 in females, whereas the FM ranged from 3.2 to 22.9 kg in males to 3.4–26.4 kg in females. Compared to Brozek (1963) reference body, the hydration of FFM (TBW/FFM) in males (70.04 ± 2.08 %) and females (69.75 ± 2.92 %) significantly ($p < 0.05$) differed from the assumed constant of 73.2 %.

Because the hydration status (TBW/FFM) of the athletes was significantly outside of the normal range for both males (0.63–0.73 %) and females (0.58–0.78 %), an attempt was made to increase the accuracy of each BIA device's TBW estimation to the criterion by using measures of skin temperature and moisture by using step-forward linear regression including each estimate of TBW along with the skin temperature and moisture variables from all locations (head, hand, and foot). However, none of the candidate variables of skin moisture or temperature were selected in the final model to increase the performance of the BIA-reported TBW values. None of the candidate variables improved the correlations to muscle strength.

Table 2 presents the results of comparisons of FM and FFM measurements to the criterion 6CM, along with their agreement

Table 1
Descriptive statistics of demographics, whole body composition and muscle strength in male and female athletes (n = 70).

	Variable	Units	Male (N = 35)		Female (N = 35)	
			Mean ± SD)	Min - Max)	Mean ± SD)	Min - Max)
Demographics	Weight	kg	[a]82.27 ± 10.09	61.9–102.5	62.97 ± 10.44	43.9–92.4
	Height	cm	[a]180.99 ± 10.26	159.3–203	168.04 ± 8.86	154.7–188.1
	Age	years	24.43 ± 5.11	18–37	21.86 ± 4.19	18–35
	BMI	kg/m^2	[a]25.2 ± 3.21	20.15–32.79	22.25 ± 2.89	17.79–30.94
Skin	Temperature	deg.	34.17 ± 0.83	32.5–35.6	33.97 ± 1.14	31.1–35.6
	Moisture	F/m	[a]42.17 ± 7.75	31–53.4	37.16 ± 4.84	27.6–46.1
ISOK Strength	LEG Ext	Nm	[a]139.08 ± 34.44	67–200	94.11 ± 27.94	54–155
	TRK Ext	Nm	[a]188.14 ± 61.68	75–306	93.09 ± 38.2	40–214
Whole Body	ADP BV	L	[a]77.42 ± 10.16	57.31–96.94	60.11 ± 10.44	40.26–88.27
	D_2O TBW	L	[a]49.94 ± 6.42	36.3–60	34.14 ± 6.01	22.8–49.03
	DXA BMC	kg	[a]3.09 ± 0.38	2.38–3.91	2.33 ± 0.4	1.7–3.53
6CM	6CM FM	kg	11.58 ± 5.9	3.18–22.87	14.36 ± 5.66	3.39–26.36
	6CM FFM	kg	[a]71.25 ± 8.53	54.79–84.33	48.87 ± 7.92	33.87–69.48
	TBW/FFM	%	[b]70.04 ± 2.08	62.69–73.16	69.75 ± 2.92	58.22–78.12

Abbreviations: 6CM – 6 Compartment model, ADP – Air displacement plethysmography, BMC – bone mineral content, BV – body volume, cm: centimeter, D_2O – deuterium dilution, deg: degrees, DXA: Dual energy X-ray absorptiometry, Ext – extension, FFM: fat-free mass, FM: fat mass, ISOK – isokinetic, kg: kilogram, L: liter, m: meter, NM: Newton meter, TBW – total body water.

[a] Significant ($p < 0.05$) sex differences.

[b] Differs significantly from the value calculated based on Brozek's assumed hydration of 73.2 %.

Table 2
Agreement between different body composition methodologies to the criterion 6 compartment model (n = 70).

Method	Male								Female							
	Precision				Accuracy				Precision				Accuracy			
	Mean	RMS-CV	CCC	R^2	RMSE	Slope	Int	Slope Int = 0	Mean	RMS-CV	CCC	R^2	RMSE	Slope	Int	Slope Int = 0
Full sample (n = 70)																
Fat mass																
Criterion 6CM FM	11.58	3.80							14.36	2.99						
ADP	11.87	1.58	^{b}0.96	0.91	1.73	1.01	−0.37	0.98	13.98	1.05	^{c}0.93	0.87	2.03	0.93	0.97	0.99
D_2O	14.61	1.39	0.86	0.92	1.66	0.87	−1.24	0.80	16.60	0.58	0.89	0.90	1.70	0.95	−1.29	0.88
DXA	11.42	1.43	^{c}0.90	0.88	2.01	1.24	**−2.59**	1.04	13.68	1.26	^{c}0.91	0.87	2.08	1.08	−0.81	1.03
Fit3D	14.92	5.82	0.66	0.64	3.56	0.98	−3.35	0.78	15.04	4.57	0.86	0.78	2.70	1.02	−1.50	0.93
S10	13.22	0.94	0.72	0.55	3.95	0.50	**5.37**	0.83	14.97	1.10	0.80	0.64	3.40	0.72	**2.78**	0.87
SFB	12.34	3.33	0.56	0.28	4.99	0.61	**4.71**	0.86	15.00	3.19	0.80	0.64	3.39	0.86	1.38	0.95
SOZO	15.07	2.32	0.57	0.44	4.43	0.68	1.36	0.76	15.56	4.45	0.80	0.65	3.32	0.88	0.53	0.91
Fat-free mass																
Criterion 6C FFM	71.25	0.11							48.87	0.10						
ADP	70.66	0.07	^{b}0.96	0.93	2.12	0.93	3.47	0.99	49.05	0.07	^{b}0.97	0.95	1.95	0.96	3.64	1.00
D_2O	68.22	0.08	^{c}0.94	0.95	1.74	0.95	**4.21**	1.04	46.64	0.07	^{c}0.92	0.95	1.84	0.95	**6.28**	1.04
DXA	71.50	0.10	^{b}0.96	0.93	2.14	0.98	0.80	0.98	49.72	0.05	^{b}0.96	0.92	2.37	1.01	−0.80	0.99
Fit3D	67.42	1.02	^{c}0.91	0.85	3.03	1.02	0.76	1.03	47.89	1.02	0.81	0.82	3.59	1.02	2.90	1.06
S10	69.59	0.12	0.88	0.78	3.70	0.86	7.87	1.01	48.22	0.04	0.86	0.76	4.22	0.85	12.43	1.01
SFB	70.20	0.34	0.89	0.81	3.48	0.94	3.53	1.00	48.33	0.04	0.78	0.62	5.23	0.84	12.47	1.01
SOZO	67.76	0.52	0.88	0.82	3.36	1.02	0.53	1.02	47.66	0.12	0.78	0.71	4.56	0.84	**14.45**	1.05
UWW sample (n = 24)																
Fat mass																
Criterion 6CM FM	8.61	3.67							13.25	2.83						
UWW	9.01	1.25	0.89	0.84	1.91	0.70	2.22	0.88	10.74	1.49	0.68	0.53	3.89	0.79	4.80	1.15
Fat-free mass																
Criterion 6CM FFM	75.68	0.10							51.34	0.12						
UWW	75.30	0.41	0.79	0.58	2.32	0.74	19.87	1.00	53.84	0.44	0.82	0.74	3.58	0.77	10.03	0.95

Abbreviations: 6CM: 6-Compartment model, ADP: Air displacement plethysmography, CCC: Lin's concordance correlation coefficient, D_2O: deuterium dilution, DXA: Dual energy X-ray absorptiometry, Int – intercept, UWW: Underwater weighing.
3DO device: Fit3D; BIA devices: S10 (InBody S10), SFB (ImpediMed SFB7), SOZO (ImpediMed SOZO).
Note: R^2 is adjusted, (Slope Int = 0) is the slope, when the intercept is equal to zero. Bolded text indicates Significant Intercept. ^{a} = >0.99 'almost perfect' equivalence, ^{b} = 0.95 to 0.99: 'substantial' equivalence, ^{c} = 0.90 to 0.95: 'moderate' equivalence, otherwise unmarked is considered <0.90 poor equivalence.

and test-retest precision. The results reveal that ADP and DXA demonstrated the highest agreement in FM to the criterion (CCC = 0.90–0.99), with ADP exhibiting substantial agreement (CCC = 0.96) in FM for males. ADP also showed substantial agreement in FFM both sexes, while DXA and D_2O had moderate agreement. D_2O produced the lowest RMSE in males (1.66 kg) and females (1.70 kg), which was lower than ADP or DXA. The 3DO method had a moderate agreement in females FFM (CCC = 0.91),

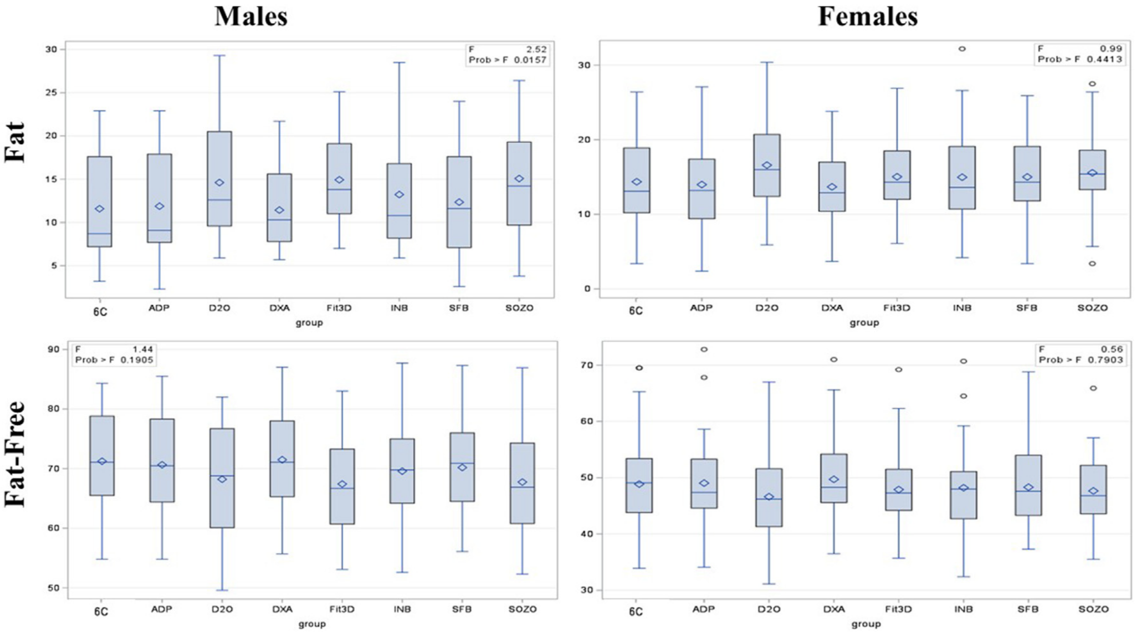


Fig. 1. Fat and fat-free mass mean difference in all methods (n = 7).

the only commercial method to produce such an agreement in body composition. However, the 3DO had the worst precision among all methods, for both males (5.8 %) and females (4.6 %). Similarly, the SFB7 (3.3–3.2 %) and the SOZO (2.3–4.5 %) had poor precision estimates in males and females. All measures of FFM had excellent precision of <1.0 %, whereas only ADP, DXA, D_2O, UWW, and S10 had <2.0 %. The lowest precision estimates were the S10 (0.09 %) in males and D_2O (0.06 %) in females. Ultimately, the 6CM precision (3.8–2.9 % in males and females) was similar to previously reported multicompartment modeling [34]. All other methods (UWW and BIA did not produce high equivalence in any category (all CCC<0.90).

Figure 1 provides the group comparisons for FM and FFM estimates. No significant (all $p > 0.05$) mean differences were observed between devices for FM or FFM in either sex. Despite a lack of a significant mean differences, Figs. 2 and 3 represent the individual agreement to 6CM, illustrating that devices show large individual errors. Large regression offsets from the line of identity and wide limits of agreement show that some of these devices did not provide equivalence to the criterion. Although the S10, SFB, and SOZO methods all had a CCC = 0.88–0.89, approaching moderate equivalence, the figure shows considerable underestimation of FM in athletes, though less so for females. Specifically, D_2O tended to underestimate FM in almost all cases, and to a lesser extent, the 3DO device. A similar divergence was present in the FM for DXA in males, where it tended to overestimate in the lower ranges and underestimate in the higher ranges.

The estimation of muscle strength via isokinetic movements of the thigh and trunk as predicted by measured FFM are shown in Table 3. Height and weight were chosen as the base model for

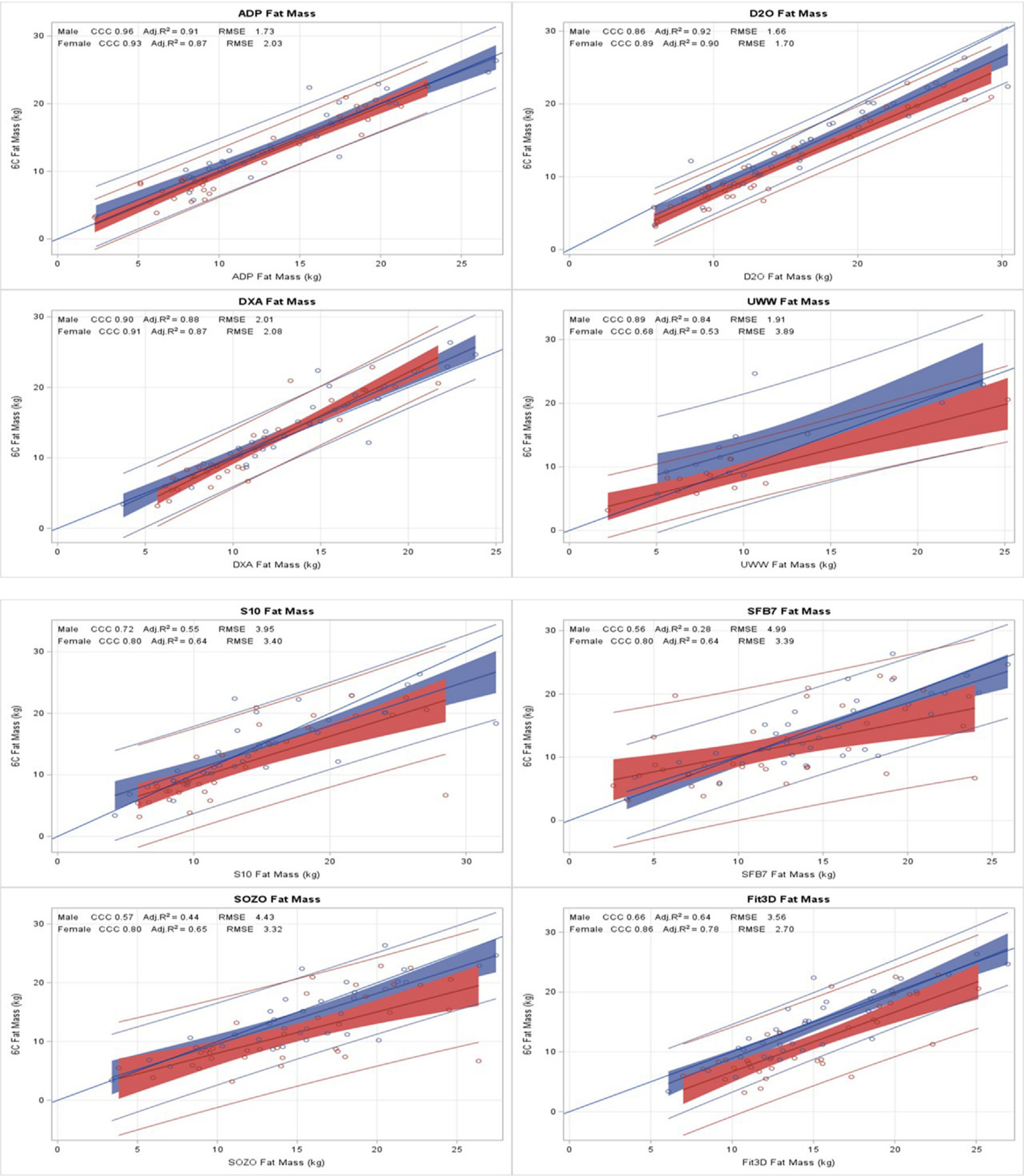


Fig. 2. Fat mass agreement to the 6-compartment model (n = 70).

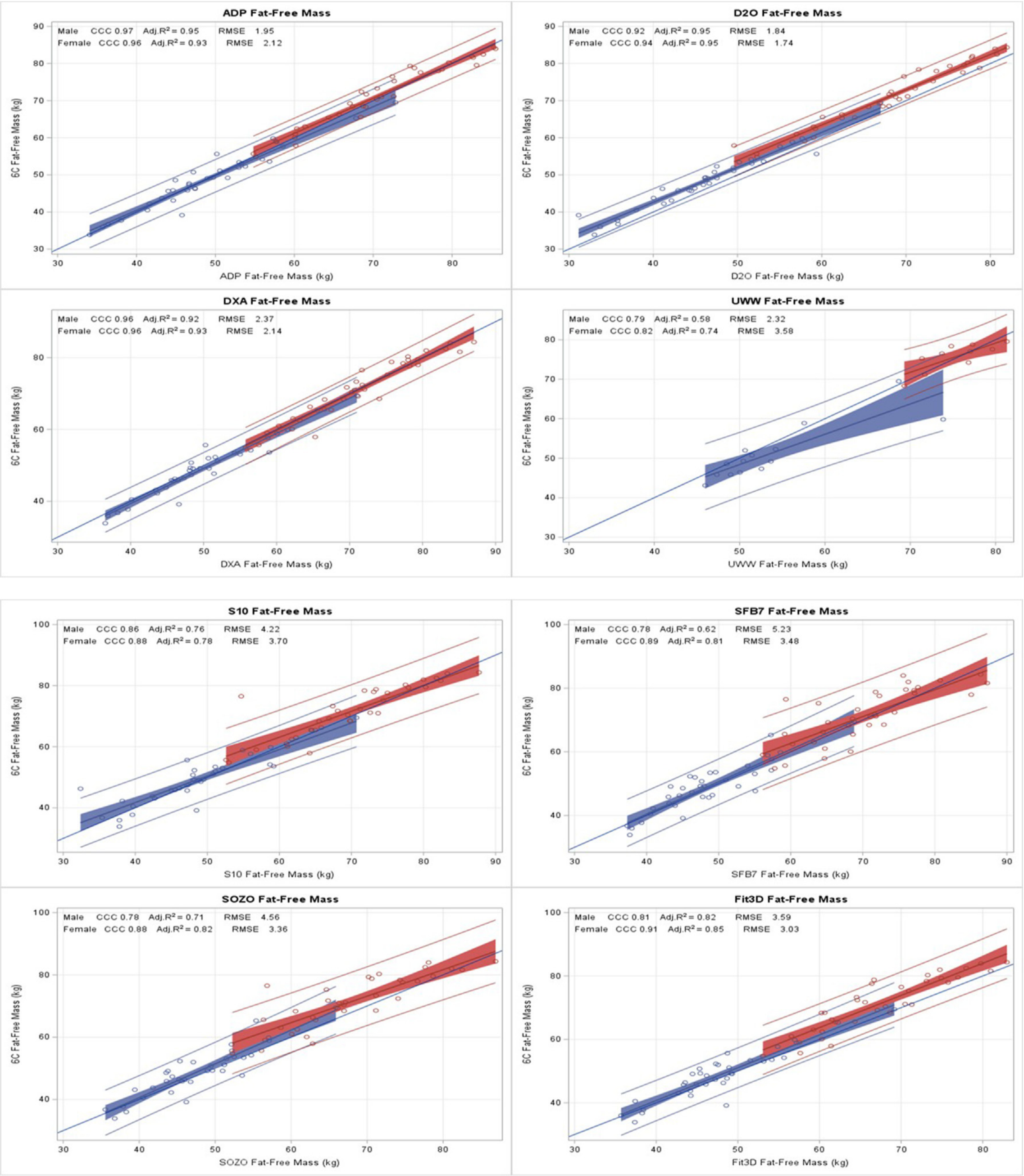


Fig. 3. Fat-free mass agreement to the 6-compartment model ($n = 70$).

comparison, derived using stepwise forward regression of demographic information. Although skin temperature and moisture variables were considered, they were not significant (both $p > 0.05$) for the model. The different methods of FFM from each device produced varying estimates of muscle strength (r^2 range 0.31–0.55 in males, 0.38–0.71 in females), and no single predictor of strength was significant over the other methods for males and females due to large confidence intervals and overlapping effects including the base model. However, the 6CM had the highest overall performance in each category of isokinetic leg and trunk strength for both sexes. The 6CM FFM was moderate in males and females for leg strength ($r^2 = 0.46, 0.58$, respectively), and male and female trunk strength was best predicted by the 6CM FFM ($r^2 = 0.55, 0.71$, respectively). Methods such as ADP, DXA, and D_2O showed strongest associations to muscle strength, while 3DO FFM also showed one of the highest associations to muscle strength ($r^2 = 0.69$).

Furthermore, knee isometric extension/flexion and trunk/knee isokinetic flexion comparisons were conducted, and the Pearson's correlation of each FFM estimate result is reported in Supplemental Table 2. Overall, females showed significant ($p < 0.05$) stronger associations than males in all methods. The sex-specific FFM quartiles were assessed for trends in relationship to strength, with the p-trend association with leg and thigh muscle strength represented in Fig. 4. All FFM methods had significant p-trend associations ($p < 0.05$), with increasing FFM quartiles associated with greater strength.

Because athletes of different sports have different size, strength, and body composition demands, they will oftentimes be incorrectly

Table 3
Highest ranking determination of leg and trunk strength by FFM and body composition methods of males and females (n = 70).

FFM	Leg ISOK Ex			FFM	Trunk ISOK Ex		
	R^2	95 % CI	RMSE		R^2	95 % CI	RMSE
Male							
6CM	0.46	0.23–0.69	25.5	6CM	0.55	0.35–0.77	47.2
D_2O	0.42	0.18–0.67	26.3	DXA	0.53	0.30–0.74	45.2
DXA	0.40	0.15–0.62	29.3	S10	0.51	0.29–0.73	47.4
ADP	0.40	0.18–0.64	26.9	D_2O	0.49	0.22–0.74	50.0
UWW	0.40	0.18–0.64	27.8	ADP	0.48	0.23–0.73	48.8
SFB	0.35	0.14–0.63	30.5	UWW	0.48	0.23–0.73	49.2
SOZO	0.32	0.12–0.61	30.3	SOZO	0.46	0.22–0.71	48.8
S10	0.31	0.11–0.61	30.4	Fit3D	0.46	0.19–0.73	48.1
Fit3D	0.31	0.14–0.68	29.7	SFB	0.40	0.16–0.68	54.6
Base Model	*0.25*	0.05–0.54	*31.3*	*Base Model*	*0.38*	0.13–0.66	*49.1*
Female							
6CM	0.58	0.33–0.75	21.3	6CM	0.71	0.43–0.87	23.7
D_2O	0.56	0.31–0.78	21.4	ADP	0.69	0.43–0.88	22.7
Fit3D	0.50	0.23–0.76	21.2	DXA	0.69	0.43–0.88	18.3
DXA	0.47	0.05–0.57	24.2	Fit3D	0.69	0.29–0.91	18.9
ADP	0.46	0.24–0.7	21.9	D_2O	0.66	0.39–0.86	25.0
UWW	0.46	0.24–0.7	25.1	S10	0.64	0.33–0.88	25.4
SOZO	0.45	0.19–0.72	22.1	SOZO	0.64	0.32–0.86	25.8
SFB	0.39	0.11–0.68	23.6	SFB	0.62	0.30–0.85	28.5
S10	0.38	0.10–0.69	24.1	UWW	0.61	0.36–0.8	17.4
Base Model	*0.18*	0.02–0.49	*24.4*	*Base Model*	*0.49*	0.20–0.73	*19.7*

Abbreviations: 6CM- 6-Compartment model, ADP- air displacement plethysmography, D_2O- deuterium dilution, Ext – extension, FFM-fat-free mass, – ISOK – isokinetic, UWW: underwater weighing.
3DO device: Fit3D; BIA devices: S10 (InBody S10), SFB (ImpediMed SFB7), SOZO (ImpediMed SOZO).
Note: R^2 is adjusted. The base model was derived using demographic information on height and weight. All RMSE are in Nm. UWW was calculated on the sample with matched 6CM comparisons where n = 24.

categorized using BMI alone. Differences in body composition are ultimately important to understand the relationship between FFM and strength This is highlighted in Fig. 5 using 3D images from the current study comparing sex-based differences in five athletes with similar FM ranges (males = 9–10 kg, females = 19–20 kg) but varying BMI categories. The predictive values of BMI for estimating FM were poor in both males and females (r^2 = 0.42, 0.41, respectively), indicating a low level of accuracy in using BMI as a predictor of FM in both sexes. Furthermore, BMI is not a better determinant of muscle strength than FFM. On the contrary, those in the ~25 BMI range had the highest strength results over other BMI categories. These findings further support the utility of accurate body composition assessment for monitoring training and strength in sport.

4. Discussion

This study aimed to compare various methods of body composition analysis in athletes who exhibit varying levels of hydration. By using a criterion 6CM, we were able to explore the accuracy of these commercial devices, as well as evaluate their relationship with muscle strength. The 6CM method exhibited the strongest correlation with muscle strength among all body composition analysis techniques. The most reliable laboratory-based techniques were ADP and DXA, while commercial assessments had moderate to poor agreement. Methods that showed significant agreement with body composition tended to produce a more valid determination of muscle strength in both male and female athletes. These findings demonstrate that precise and accurate estimates of body composition can be obtained in athletes, and a more precise measurement of body composition results in better muscle strength estimates. Accurate body composition estimates produce more precise muscle strength estimates in athletes, irrespective of their hydration status. ADP and DXA are trustworthy approaches for evaluating body composition and muscle strength compared to the criterion approach.

Our study contrasts studies performed by others on the validity of different laboratory methods (DXA, ADP, UWW) for estimating body composition in athletes using criterion multicompartment modeling [18,19,35]. In a study of exclusively female athletes, acceptable error ranges of percent fat for all devices (except DXA) were observed, while our study found that ADP and DXA had better agreement with the line of identity in females. Silva concluded that DXA and ADP were imprecise and invalid for individual body fat prediction in young athletes, but our study found moderate to

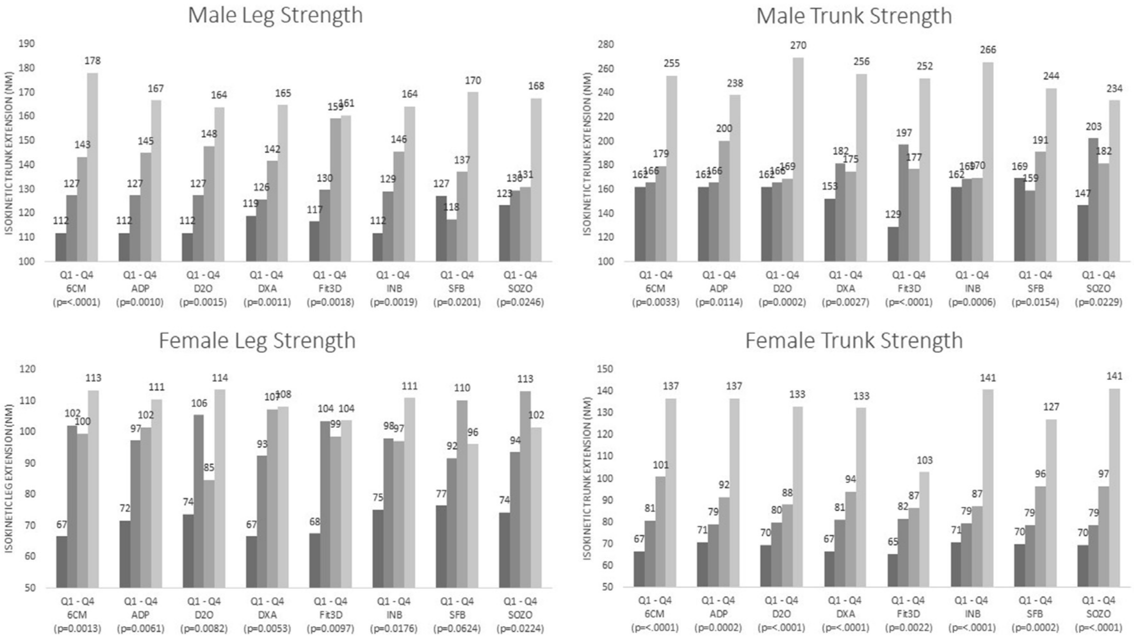
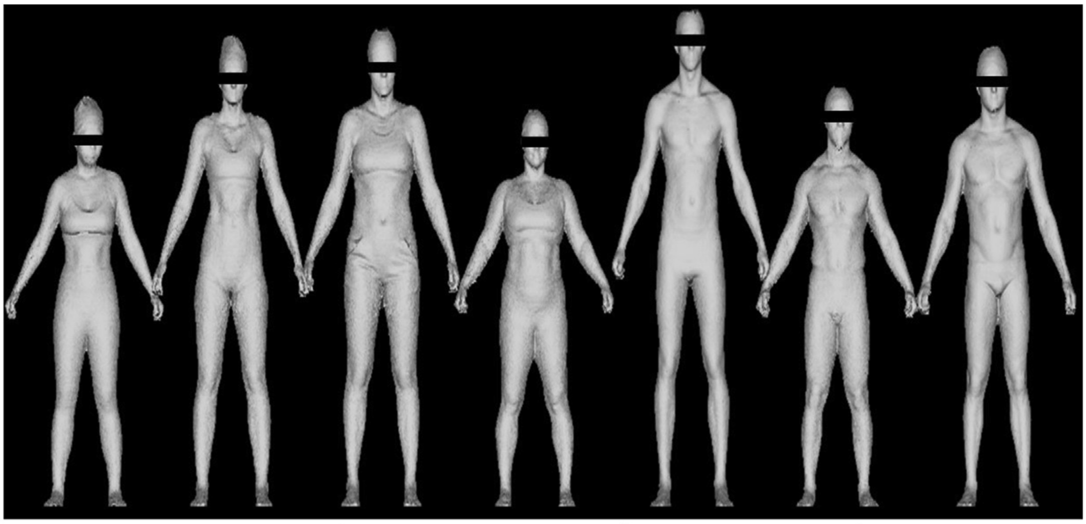


Fig. 4. Quartile p-trend Associations of FFM Estimates Leg to Trunk Strength in Males and Females (n = 70).



	Female				Male		
BMI	18.2	23.4	26.1	30.9	21.6	26.8	32.8
Height(cm)	185.3	180.7	188.1	154.7	197.2	165.3	159.3
Weight(kg)	62.4	76.5	92.4	74.1	83.9	73.3	83.2
Fat Mass(kg)	18.9	20.4	21.2	21.4	11.8	11.2	10.9
Sport	MMA	Volley Ball	Water Polo	Gymnastics	Volley Ball	Power Lifting	Diving

Fig. 5. A comparative analysis of sex-based differences in fat mass and BMI among five athletes with a fat mass range of 9–10 kg for males and 19–20 kg for females.

substantial agreement for both sexes with DXA and ADP, and poor agreement with UWW. Kendall found poor agreement (CCC = 0.84) between ADP and modified multicompartment estimates for FFM in male athletes, while our study found substantial agreement (CCC = 0.97) for ADP. Many factors may contribute to differences with previous research, such as population variations (youth or exclusively female populations versus our sex-stratified adult population), device specifications (use of BIA as the TBW criterion versus a true criterion multicompartment model), and participant training (diet/exercise confounding variables). Future work should aim to explore these factors to advance the findings presented here.

Monitoring of muscle mass throughout a competitive season is common to identify changes in body composition that impact athletic performance [36–38]. The findings regarding the prediction of muscle strength agrees with other studies that support the assessment of body composition as a proxy for strength [9,39,40]. However, considerable sex differences related to body size are relevant when predicting muscle strength with body composition. In our study, DXA FFM was associated with leg strength ($r^2 = 0.40$ males, $r^2 = 0.47$ females). An issue with other analyses regarding strength prediction is the combining of sexes in the modeling, where the poor linear relationships may be masked by an improved correlation given the trend over the entire dataset [41]. The combined association for males and females for whole body FFM and leg strength was $r^2 = 0.64$, highlighting how this relationship appears stronger when sexes are combined. We recommend reporting sex-specific muscle strength associations to avoid this type of correlation inflation and to not overestimate the muscle-strength relationship due to these factors. While improved correlations were observed when combining sexes in all methods, the lower prediction ability of commercially available assessment methods is likely the result of these methods being doubly-indirect estimation methods, often calibrated to DXA as their “criterion” [42,43]. While these devices offer alternative measures that may improve strength estimations (3DO: circumference/volume, BIA: resistance, phase angle), we elected to compared FFM across systems. Future studies should assess the impact of these other factors on the relationship to strength in athletes.

To our knowledge, this is the first investigation evaluating the body composition agreement between criterion multicompartment modeling and other laboratory and commercial methods, specifically the associations of each device-reported FFM estimate to muscle strength in a collegiate athletic population. A strength of our study is that the criterion of muscle strength was measured in large muscle groups like the legs and trunk in multiple movements of isokinetic and isometric. Males and females were explored separately, showing that further work is necessary to understand the sex-specific FFM to strength associations observed in athletes.

Although measurement of the thigh and abdominal/back muscles are more functionally relevant than grip strength, we were unable to directly compare our results to much of the muscle strength literature that reports on this metric. One factor not fully explored in this study is the composition and impact of muscle glycogen on strength. Changes in muscle glycogen can occur as a result of changes to diet and exercise and are therefore common in athletes, therefore more work is necessary to understand the role of between-day precision of devices and their capabilities of predicting strength change resulting from small changes in FFM (glycogen and water) composition over time. Similarly, differences in body composition between athletes in- and off-season are expected, which would ultimately benefit from a further assessment of the relationship between body composition and strength based on training period [36–38]. The superior strength prediction by females raises questions about whether the sports chosen by female participants may be more leg-centric or driven by other unidentified factors. Due to the small sample size, we were unable to explore this further through the use of a withhold dataset for model testing. We also could not stratify the analyses to determine the impact of race/ethnicity on strength relationships. Increasing the sample size should improve our ability to discern statistically significant differences by technique to strength.

5. Conclusion

From this investigation, we conclude that when assessing body composition and estimates of muscle strength, researchers and clinicians should evaluate which device is to be used based on its accuracy in comparison to a criterion method, such as the 6CM. This is due to the results demonstrating that the more advanced methods of body composition analysis tend to demonstrate a stronger association with muscle strength than more cost-effective methods and therefore may be more important for guiding nutritional interventions to maintain strength and performance. Furthermore, the 6CM is particularly effective in estimating isokinetic and isometric muscle strength, further supporting its utility, when available. Future research in athletes should examine the effects of changes in FFM due to training, weight loss, and/or gain on functional measures when compared to a criterion method.

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Data share statement

Data described in the manuscript, codebook, and analytic code will be made available upon request pending an application and approval, payment, and or other.

Conflict of interest

JS received an investigator-initiated grant from Hologic, Inc. to fund the larger study and other grants on body composition from Hologic and GE Healthcare. SH is on the Medical Advisory Board for Tanita Corporation. TK is a current employee at Hologic. The remaining authors report no conflicts of interest.

Author contributions

John Shepherd, Steven B. Heymsfield, and Thomas Kelly: Design study, conceptualization, funding acquisition. Brandon Quon and Devon Cataldi: Practical performance, data analysis/curation, formal analysis. John A Shepherd and Devon Cataldi: Investigation, validation, visualizations. Devon Cataldi, Jonathan Bennett, Michael Wong, Nisa Kelly, and Yong En Liu: Preparation manuscript, methodology, project administration, resources, software, supervision. Devon Cataldi, John Shepherd, Steven B. Heymsfield, Dale A. Schoeller and Jonathan Bennett: Critical review of manuscript, roles/writing - original draft, review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clnu.2023.11.040.

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