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Within- and between-day reliability of laboratory-based body composition assessment methods

Carina M. Velasquez[1], Christine M. Florez[1], Christian Rodriguez[2], Madelin R. Siedler[3], Matthew T. Stratton[4], Patrick S. Harty[5], Ainsley E. Way[1], Madison H. Sullivan[1] and Grant M. Tinsley[1]

[1]Department of Kinesiology & Sport Management, Texas Tech University, USA; [2]LSU Pennington Biomedical Research Center, USA; [3]College of Saint Benedict and Saint John's University, USA; [4]JDS Therapeutics LLC, USA and [5]Lindenwood University, USA

Research Article

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Abbreviations:
ADP, air displacement plethysmography; BF%, body fat percentage; BIA, bioelectrical impedance analysis; BIS, bioimpedance spectroscopy; DXA, dual-energy X-ray absorptiometry; FFM, fat-free mass; FM, fat mass; ICC, intraclass correlation coefficient; MFBIA, multi-frequency bioelectrical impedance analysis; ROI, regions of interest; SFBIA, single-frequency bioelectrical impedance analysis; TEM, technical error of measurement; TGV, thoracic gas volume

Corresponding author:
Grant M. Tinsley;
Email: grant.tinsley@ttu.edu

Abstract

This study examined the within- and between-day reliability of commonly employed laboratory-based body composition assessment methods. Eighteen healthy adults reported to the laboratory on two occasions, separated by 1–2 d, and were assessed with multiple methods under standardised conditions. These included two dual-energy X-ray absorptiometry (DXA) scanners with manual or automated regions of interest, air displacement plethysmography (ADP) with measured or estimated thoracic gas volume (TGV), two multi-frequency bioelectrical impedance analysers (MFBIA), single-frequency BIA (SFBIA) and bioimpedance spectroscopy. Within-day reliability was established via immediate test–retest assessments at the first visit (technical error) and between-day reliability by repeating assessments at the second visit (technical plus biological error). Within- and between-day measures were evaluated using technical error of measurement (TEM) and intraclass correlation coefficients (ICC). For body fat percentage, within-day TEM ranged from 0·03 to 0·70 %, with ICC of 0·993–1·000, while between-day ranged from 0·37 to 1·24 %, with ICC of 0·965–0·998. For fat and fat-free mass (FM and FFM), within-day TEM ranged from 0·02 to 0·53 kg, with ICC of 0·998–1·000 for FFM and 0·992–1·000 for FM. Between-day TEM ranged from 0·26 to 0·90 kg for FM and FFM, with ICC of 0·995–0·999 for FFM and 0·955–0·998 for FM. Across metrics, DXA demonstrated the best reliability, followed by one MFBIA and ADP with predicted TGV. Overall, laboratory-based body composition devices provide excellent within- and between-day reliability under standardised conditions, though observed differences in error may influence method selection when tracking small body composition changes.

Body composition estimation is an important component of assessing health and disease risks in a clinical setting. However, these estimates can be influenced by normal physiological variations that occur on a daily basis[1]. A variety of laboratory-based methods have been utilised to assess body composition, with bioelectrical impedance analysis (BIA), dual-energy X-ray absorptiometry (DXA) and air displacement plethysmography (ADP) being among the most widely used. In the general population, the reliability (i.e. reproducibility) of these methods has been examined, typically through simple within-day test–retest assessments[2–6]. However, reliability is known to vary when based on within-day *v.* between-day assessments, and this variability may not be uniform across assessment technologies. This was observed by McLester *et al.*[7], who examined the between-day reliability of three multi-frequency BIA (MFBIA) devices as compared with DXA in healthy young adults. While all methods in this study generally displayed strong reliability, the standard error of the measurement values were about 2 to 3 times larger for MFBIA as compared with DXA in males, while females displayed more similar reliability between these methods. Additional technical factors, such as manual *v.* automated regions of interest (ROI) selection for DXA assessments and electrode placement for bioimpedance devices, have also been shown to influence reproducibility[8,9].

Although the validity of individual methods like DXA, BIA and ADP has been examined in previous studies[10–12], limited information about the within-day reliability and between-day reliability of these devices has been reported. When repeated measures are conducted immediately back-to-back within the same day (i.e. immediate test–retest), the observed within-day reliability primarily reflects technical error (i.e. error attributable to the device and the assessor), as detectable biological changes do not occur in the negligible time between assessments. Ideally, these measures are performed under standardised conditions (e.g. fasted state, refraining from recent exercise), further minimising biological variation relative to a person's resting state. In contrast, when reliability is established from repeated assessments

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taken on different days (i.e. between-day reliability), the total error observed is a combination of technical and biological error (i.e. errors attributable to the device, assessor and biological variation in the body being assessed). Even when assessments are conducted in standardised conditions on the separate days, some degree of day-to-day biological variability is expected. Based on these considerations, the purpose of this study was to examine the test–retest reliability of body fat percentage (BF%), fat-free mass (FFM) and fat mass (FM) estimates from within-day and between-day comparisons utilising a variety of commonly employed laboratory-based methods of body composition assessment.

Methods

Participants and design

A convenience sample of generally healthy adults (defined as having no known disease or other condition that could be negatively affected by participating in the study) were recruited for participation in Lubbock, Texas, USA. Prospective participants were excluded from the study if they were taller than 193 cm or were heavier than 159 kg (due to the limitations of one DXA scanner), were missing any limbs or parts of limbs, had implanted metal due to previous medical procedure, had a pacemaker or electrical implant, had undergone a body-altering surgery (i.e. breast augmentation, liposuction, etc.) or were currently pregnant or trying to become pregnant. Eighteen adults, including eleven females (mean (SD); age = 25·7 (SD 7·5) years; body mass = 63·1 (SD 7·0) kg; height = 167·9 (SD 6·0) cm; BMI = 22·4 (SD 2·3) kg/m^2; eight non-Hispanic Caucasian, two Hispanic Caucasian and one Asian) and seven males (age = 30·3 (SD 9·0) years; body mass = 74·2 (SD 12·7) kg; height = 176·4 (SD 9·4) cm; BMI = 23·7 (SD 2·5) kg/m^2; four non-Hispanic Caucasian, two Hispanic Caucasian and one Hispanic Black) reported to the laboratory two times, separated by 24–48 h. Within-day reliability was established at the first laboratory visit utilising immediate test–retest assessments for each method under the standardised conditions. Based on the immediate test–retest nature of these assessments, within-day reliability was considered indicative of technical error only. Between-day reliability was established by repeating all the assessments under standardised conditions at the second laboratory visit, conducted on a separate day from the first visit. Between-day reliability was considered indicative of technical plus biological error due to day-to-day biological variation in addition to technical errors of separate assessments. For both visits, participants arrived after following overnight (≥ 8 h) abstention from eating, drinking, exercising and ingesting any alcohol or caffeine. Upon arrival, urine specific gravity was assessed using a digital refractometer (PA201X-093, Misco). Mean (SD) urine specific gravity values were 1·019 (SD 0·004) for visit 1 and 1·019 (SD 0·005) for visit 2. This study was reviewed and approved by the Texas Tech University Institutional Review Board (protocol no: IRB2019-730), and all participants provided written informed consent prior to participation.

Dual-Energy X-ray absorptiometry

DXA scans were performed on GE Lunar iDXA and Lunar Prodigy scanners (GE Healthcare). Nine participants were assessed with each DXA scanner to limit cumulative radiation exposure, with participants randomly assigned to either the iDXA or Prodigy scanner. Both scanners were calibrated daily prior to scanning using the manufacturer-supplied calibration block. Custom-made foam blocks were used to position the participants and ensure consistency for all measures[13]. Foam blocks were placed bilaterally between the hands and the hips, while a strapped block at the feet maintained consistent foot positioning with a perpendicular orientation to the table. At the first visit, participants moved completely off the scanning table between duplicate scans. For each scan, a copy of DXA reports with automated ROI was saved. Thereafter, the same trained operator manually adjusted ROI lines within the software to indicate body segments (i.e. arms, trunk and legs). The automated and manual versions were analysed separately. DXA has previously been validated against a criterion four-compartment model for body composition, demonstrating strong group-level agreement[14].

Multi-Frequency bioelectrical impedance analysis

Two MFBIA analysers were used (mBCA 515/514, Seca® GmbH & Co.; InBody 770, Biospace Co.). The Seca® analyser utilised a 19-frequency, eight-point design, with contact electrodes for the hands and bare feet, and was conducted in the standing position. The frequencies utilised for this device ranged from 1 to 1000 kHz, along with a measuring current of 100 μa. This analyser has been validated against a four-compartment model for body composition[15]. For the InBody analyser, participants stood barefoot with their feet positioned on the contact electrodes, while subjects held the designated handles with additional contact electrodes in both hands. Thirty impedance measurements with frequencies ranging from 1 to 1000 kHz were employed. The InBody 770 has previously demonstrated good test–retest reliability for BF%, FFM and FM in healthy men and women[7]. At the initial visit, the Seca MBFIA analyser was first performed twice in a row, without moving the participant, to determine the error derived from the device itself. The participant was then repositioned (i.e. stepped off and then stepped back on the device), and the test was repeated to determine the additional error of repositioning. This procedure was not possible for the InBody analyser due to the requirement to clear the scale before each test.

Bioimpedance spectroscopy

Bioimpedance spectroscopy (BIS; SFB7, ImpediMed) was utilised in conjunction with the manufacturer-specified hand-to-foot electrode arrangement and was calibrated daily using a manufacturer-supplied testing cell. Each participant remained supine for approximately three minutes immediately prior to BIS assessment. Before placing the electrodes, the electrode sites on the hands, wrist, foot and ankle were cleaned with alcohol pads. In accordance with the manufacturer guidelines, the BIS electrodes were placed unilaterally on the right side of the body. Before beginning the assessment, the participants' limbs were spread apart to ensure there was no contact with other parts of the body. During the assessment, participants remained motionless in the supine position. Bioelectrical output was processed using manufacturer-provided software, and Cole-Cole plots were reviewed for quality assurance. The coefficients utilised for males ($\rho_e = 273{\cdot}9$, $\rho_i = 927{\cdot}2$) and females ($\rho_e = 235{\cdot}5$, $\rho_i = 894{\cdot}2$), as well as body density, body proportion and hydration values (1·05, 4·30 and 0·732, respectively), were the same utilised in previous investigations[16–18]. At the first visit, duplicate assessments were performed with the same set of adhesive electrodes, without removing the electrodes, to establish the technical error of the analyser itself. Then, the first set of electrodes was discarded and replaced with a new set, and the test was repeated to determine the additional error

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derived from a second set of adhesive electrodes (i.e. a new set of electrodes plus positioning by the researchers). Studies[16,17] utilising the same analyser have demonstrated the validity of BIS, which estimates total body water through Cole modelling[19] and mixture theories[20], as compared with deuterium dilution.

Single-Frequency bioelectrical impedance analysis

The single-frequency BIA (SFBIA) analyser (Quantam V, RJL Systems) was tested daily before any measurement using a manufacturer-supplied testing cell. The total body water estimates from this SFBIA analyser, which are subsequently used to estimate body composition, have been validated against a deuterium oxide criterion[21]. Participants rested in the supine position for approximately 5 min prior to the assessment. The SFBIA analyser used an eight-point bilateral, hand-to-foot electrode configuration. Prior to placing the electrodes, the electrode sites on the hands, wrist, foot and ankle were cleaned with alcohol pads. In accordance with the manufacturer guidelines, the electrodes were placed on the dorsal surface of both hands and feet. Before beginning the assessment, the participants' limbs were spread apart to ensure there was no contact with other parts of the body. During the assessment, participants remained motionless in the supine position and bioelectrical output was processed using manufacturer-provided software. At the first visit, duplicate assessments were performed with the same set of adhesive electrodes, without removing the electrodes, to establish the technical error of the analyser itself. Then, the first set of electrodes was discarded and replaced with a new set, and the test was repeated to determine the additional error derived from a second set of adhesive electrodes (i.e. a new set of electrodes plus positioning by the researchers).

Air displacement plethysmography

ADP (BOD POD Cosmed USA) was performed in accordance with manufacturer recommendations and default software. ADP has previously demonstrated similar body density values to that of hydrostatic weighing and is generally considered a valid technique when compared with a four-compartment model[22–24]. To ensure that values were consistent, two to three volume measurements were obtained and used for analysis. Thoracic gas volume (TGV) was measured using the manufacturer's procedures. Versions of the results with measured and predicted TGV were used for analysis. The Siri[25] equation was used to estimate body composition through the manufacturer's software. Due to technical problems or missing data for some assessments, the sample size for the ADP analysis was 14.

Statistical analysis

Data analysis was performed using R (v. 4.5.1). Test–retest reliability was established using intraclass correlation coefficients (ICC; model 2,1 from the DescTools package (v. 0.99.60)), the absolute technical error of measurement (TEM; i.e. precision error) and the relative TEM (i.e. root-mean-square CV). The absolute TEM was calculated as $\sqrt{\frac{\sum D^2}{2n}}$ where D is the difference between repeated measurements and n is the sample size. The relative TEM was calculated as the absolute TEM divided by the grand mean for the variable in question, multiplied by 100. To determine the within-day errors (i.e. technical error), the differences between consecutive tests at the first laboratory visit were used to calculate the aforementioned metrics. To determine the between-day errors (i.e. technical plus biological error), the differences between tests conducted at the first (i.e. the first measurement from the first visit) and second laboratory visits were used. All reliability metrics were calculated for BF%, FM and FFM, except that relative TEM values are not presented for BF% due to this variable already being presented in percentage units.

Results

A combined visual summary of each method's performance, including within-day (technical error) and between-day (technical plus biological error) measurement error, is displayed in Figure 1.

Body fat percentage

Across all within-day results for BF%, the SFBIA and BIS analysers with the same electrodes for duplicate assessments exhibited the lowest absolute TEM of 0·03–0·06 % (Table 1). Absolute TEM for within-day BF% errors ranged from 0·03 to 0·70 % across methods (Figure 2(a)). All within-day BF% measures demonstrated high reliability based on their ICC (ICC = 0·993–1·000). Moreover, for between-day errors in BF%, the iDXA with manual or automatic ROI exhibited the lowest absolute TEM of 0·37–0·38 %, while BIS displayed the greatest absolute TEM of 1·24 % (Table 1; Figure 2(a)). Between-day ICC for BF% ranged from 0·980 to 0·998 (Table 1).

Fat-Free mass

For FFM, absolute TEM for within-day measures ranged from 0·02 to 0·53 kg (Table 2), with the SFBIA and BIS analysers with the same electrodes for duplicate assessments exhibiting the smallest amount of error (0·02–0·04 kg) and BIS with different electrodes displaying the largest amount of error (0·53 kg). The within-day relative TEM for FFM ranged from 0·04 to −1·01 % (Table 2). All methods exhibited high within-day reliability (ICC = 0·992–1·000).

The lowest absolute TEM for FFM between days was observed for iDXA with manual or automatic ROI (0·26–0·28 kg), and the largest error was observed for BIS (0·90 kg; Figure 2(b)). The relative TEM for FFM between days ranged from 0·53 to 1·73 % with ICC of 0·995–0·999.

Fat mass

For within-day FM comparisons, absolute TEM ranged from 0·02 to 0·53 kg, while between-day values ranged from 0·28 to 0·83 kg (Table 3; Figure 2(c)). The relative TEM for within-day measurements ranged from 0·15 to 3·49 % and from 1·61 to 5·75 % for between-day measures (Table 3). Both between-day and within-day measures exhibited high ICC (0·992–1·000; 0·955–0·998) for all methods.

Discussion

The purpose of this study was to examine the within-day and between-day test–retest reliability of body composition estimates using a variety of commonly employed laboratory-based methods. Prior studies have typically examined the reliability of laboratory-based body composition devices within a single day[4–6] or between days[7,9,26], but few studies have incorporated both, thereby allowing for the separation of technical error (variability attributable to the device and assessor) from biological errors (variability due to biological variation in the body being assessed).

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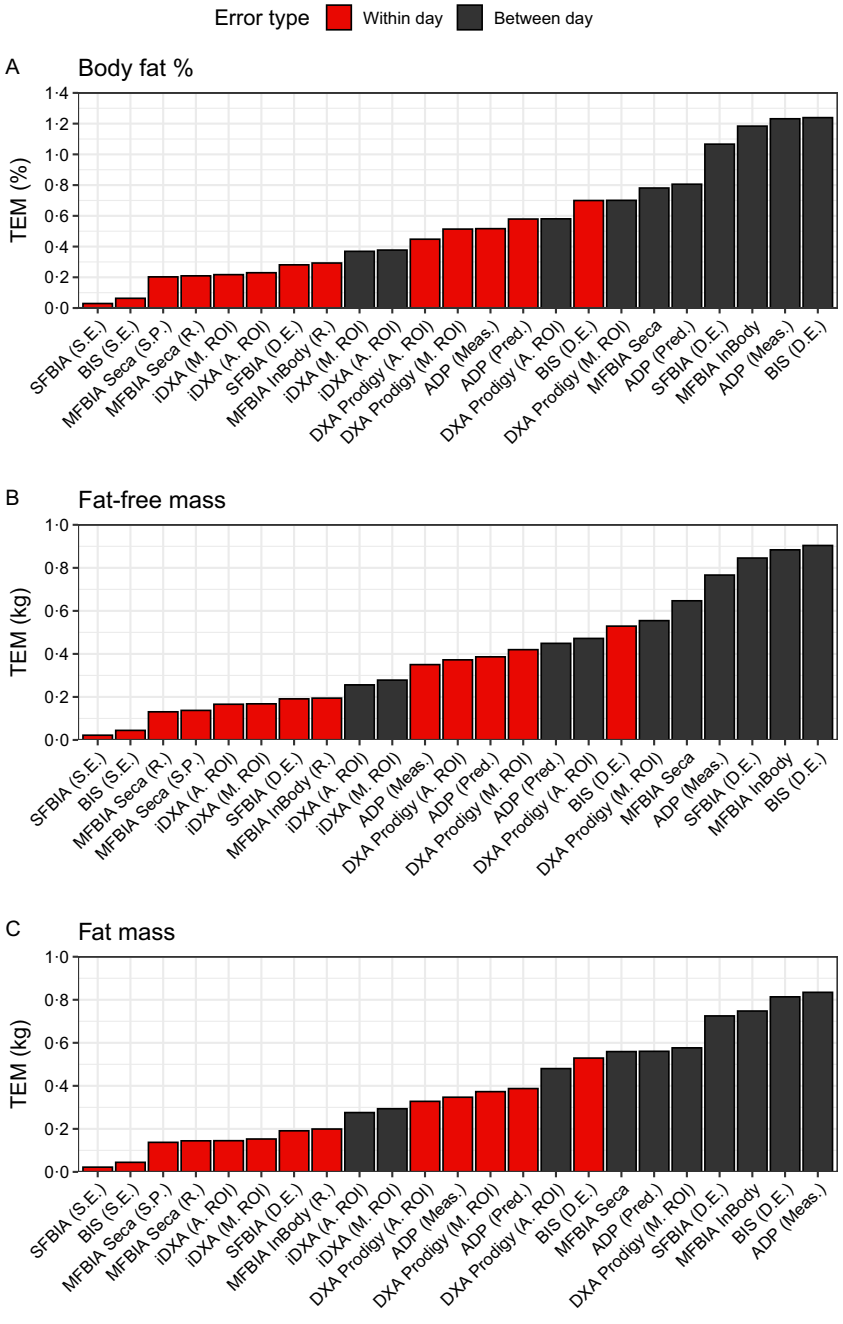


Figure 1. The technical and biological errors of each body composition estimation method, as indicated by the technical error of measurement (TEM), for body fat percentage (a), fat-free mass (b) and fat mass (c). The technical plus biological error, indicated by the total height of each bar, was established from between-day comparisons, while the technical error was established from within-day comparisons. DXA, dual-energy X-ray absorptiometry; A.ROI, automated regions of interest; M.ROI, manual regions of interest; MFBIA, multi-frequency bioelectrical impedance analysis; S.P., same placement; R., repositioned; BIS, bioelectrical impedance spectroscopy; S.E., same electrode; D.E., different electrode; SFBIA, single-frequency bioelectrical impedance analysis; ADP, air displacement plethysmography; Meas., measured; Pred., predicted.

Distinguishing between these sources of measurement error allows for a clearer determination of whether body composition changes are likely due to true physiological changes or measurement error (i.e. data 'noise'). In the present study, an overall comparison of between-day reliability reflective of technical plus biological errors indicated that reliability was highest for the iDXA scanner (TEM < 0·4 % for BF% and < 0·3 kg for FM and FFM), followed by the Prodigy DXA scanner, the Seca MFBIA analyser and ADP with predicted TGV (TEM ≤ 0·81 % for BF% and ≤ 0·65 kg for FM and FFM) – in varying order depending on the body composition variable. The InBody MFBIA analyser, ADP with measured TGV, SFBIA and BIS displayed the highest TEM values for all variables (< 1·25 % for BF% and ≤ 0·9 kg for FM and FFM), although these were still relatively low. Additional findings were as follows: (1) for DXA, ADP with predicted TGV and BIS, more of the overall error was classified as technical as opposed to biological; in contrast, more error was attributed to biological factors for both MFBIA analysers, SFBIA and ADP with measured TGV; (2) bioimpedance analysers with adhesive electrodes (SFBIA and BIS) displayed the smallest absolute and relative TEM for BF%, FFM and FM for within-day measurements when the electrodes were not replaced, indicating negligible error of the analysers themselves; (3) BIS with different electrodes displayed the highest TEM for within-day measurements, indicating that the adhesive electrodes and their placement may be an important source of technical error for this technique; (4) measured TGV for ADP slightly decreased TEM values for within-day measurements, but between-day TEM values were lower when using predicted TGV and (5) manual *v.* automated ROI segmentation for DXA minimally influenced reliability.

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Table 1. Reliability of body fat percentage estimates from laboratory-based body composition methods for within- and between-day measures

	Within-day		Between-day	
Device	Absolute TEM (%)	ICC	Absolute TEM (%)	ICC
$iDXA_{autoROI}$	0·23	0·999	0·38	0·998
$iDXA_{manROI}$	0·22	0·999	0·37	0·998
DXA $Prodigy_{autoROI}$	0·45	0·997	0·58	0·996
DXA $Prodigy_{manROI}$	0·51	0·996	0·70	0·993
MFBIA $Seca_{same\ position}$	0·20	0·999	–	–
MFBIA $Seca_{reposition}$	0·21	0·999	0·78	0·992
MFBIA $InBody_{reposition}$	0·29	0·999	1·18	0·980
$BIS_{diff\ electrode}$	0·70	0·994	1·24	0·981
$BIS_{same\ electrode}$	0·06	1·000	–	–
$SFBIA_{diff\ electrode}$	0·28	0·999	1·07	0·985
$SFBIA_{same\ electrode}$	0·03	1·000	–	–
$ADP_{measured}$	0·52	0·993	1·23	0·965
$ADP_{predicted}$	0·58	0·994	0·81	0·988

TEM, technical error of measurement; ICC, intraclass correlation; DXA, dual-energy X-ray absorptiometry; autoROI, automated regions of interest; manROI, manual regions of interest; MFBIA, multi-frequency bioelectrical impedance analysis; BIS, bioelectrical impedance spectroscopy; SFBIA, single-frequency bioelectrical impedance analysis; ADP, air displacement plethysmography.
Relative TEM values were not calculated since body fat percentage is already expressed in percentage units. Between-day assessments for select variables were not possible (i.e. duplicate assessments with the same pair of electrodes or without repositioning).

In a previous study conducted by Schubert *et al.*[26] in predominantly normal-weight and overweight young adults, the authors examined the between-day reliability of laboratory-based body composition devices (i.e. DXA (Lunar Prodigy), ADP with predicted TGV and MFBIA (InBody 720)) compared with a four-compartment model of estimating body composition. This study displayed high between-day reliability for each device when estimating BF%, FFM and FM, with ICC ranging from 0·973 to 0·997. In our current investigation, DXA was the best-performing technology based on the absolute TEM for between-day reliability of all body composition estimates (absolute TEM of 0·26–0·58 kg for FM and FFM and 0·37–0·70 % for BF%), followed by ADP with predicted TGV (absolute TEM of 0·45–0·56 kg for FM and FFM and 0·81 % for BF%), with InBody MFBIA exhibiting the largest amount of error of these three methods (absolute TEM 0·75–0·88 kg for FM and FFM and 1·18 % for BF%). A similar pattern was also observed when examining ICC values for each method and body composition outcome. Previous studies that have examined the technical plus biological error (i.e. between-day error) of body composition techniques have reported DXA having a low amount of estimation error for FFM and FM in a variety of populations, including healthy young adults, resistance-trained individuals and individuals across the age span[1,26–28]. Similarly, in our current investigation, the iDXA scanner displayed the lowest errors for FFM and FM estimates, and both the iDXA and Prodigy scanners displayed a low amount of biological error for BF% estimates. For DXA, it has been hypothesised that the reliability may depend on the method of ROI analysis. Lohman *et al.*[8] reported that manual ROI improved between-day reproducibility of appendicular values compared with automated ROI in healthy males. In our present analysis of the reliability of total body values, differences between manual and automated ROI were small. For FM and FFM, the automated ROI produced marginally lower between-day TEM values for both DXA scanners. For BF%, the TEM were virtually identical for the iDXA scanner, with the automated ROI demonstrating a slightly lower TEM for the Prodigy scanner. Collectively, these results indicate that the choice of automated *v.* manual ROI may not meaningfully influence the reliability of DXA total body composition estimates, although the additional consideration of the reliability of segmental estimates may be warranted for studies tracking changes in specific body regions.

In addition to DXA, two MFBIA devices – the InBody770 and Seca 515/514 – were included in the present investigation. A previous study directly comparing GE iDXA to an InBody analyser found that the InBody 770 demonstrated high between-day reliability for BF%, FFM and FM for both males and females with ICC ranging from 0·98 to 1·00, although the standard error of the measurement values were larger for the InBody 770 as compared with iDXA[7]. In the current analysis, the Seca 515/514 MFBIA displayed smaller errors across both within- and between-day measures, as compared with the InBody MFBIA analyser, with minimal differences when performing assessments without participant repositioning *v.* repositioning (for the within-day analysis). Moreover, a prior investigation using the Seca mBCA 515/514 reported that the device demonstrated good within-session reliability with a CV of 0·99 for BF%[6]. Overall, the modern vertical bioimpedance analysers with contact electrodes evaluated in the present study generally demonstrated strong reliability, with some differences in performance between specific models.

Prior research has also examined the performance of traditional supine SFBIA devices, like the RJL Quantum analyser included in the present study. Based on the technical differences as compared with MFBIA (e.g. supine *v.* standing body position and adhesive *v.* contact electrodes), the reliability of such SFBIA analysers may be expected to differ. In a study performed by Vasold *et al.*[9], the authors reported that the RJL SFBIA displayed a high reliability for between-day measures of FFM estimates (ICC = 0·994), which was similar to the ICC in our current investigation for between-day measures (ICC = 0·996). However, we observed notably higher errors for between-day assessments compared with within-day assessments (within-day absolute TEM BF% = 0·28 %, FFM = 0·19 kg, FM = 0·19 kg; between-day absolute TEM BF% = 1·07 %, FFM = 0·85 kg, FM = 0·73), highlighting the contribution of biological errors when using this method. Interestingly, although the BIS analyser used in the present study exhibits similar characteristics to SFBIA (i.e. supine body position and adhesive electrodes), more of the cumulative error for BIS was categorised as technical rather than biological. From within-day evaluations, it was evident that the BIS analyser itself was responsible for very limited technical error, indicating the important contribution of the electrodes and their placement to the error of this method. Since longitudinal assessments will inherently require different electrodes, it is important to note the relatively large amount of technical error from this source, which will increase the magnitude of change in BF%, FFM and FM that must be observed to exceed the method's error. Collectively, the SFBIA and BIS analysers themselves produced little error, but biological factors and the placement of new electrodes contributed varying amounts of error across these seemingly similar technologies.

Unlike SFBIA and BIS, where electrode placement can significantly affect the outcomes, ADP offers a non-contact

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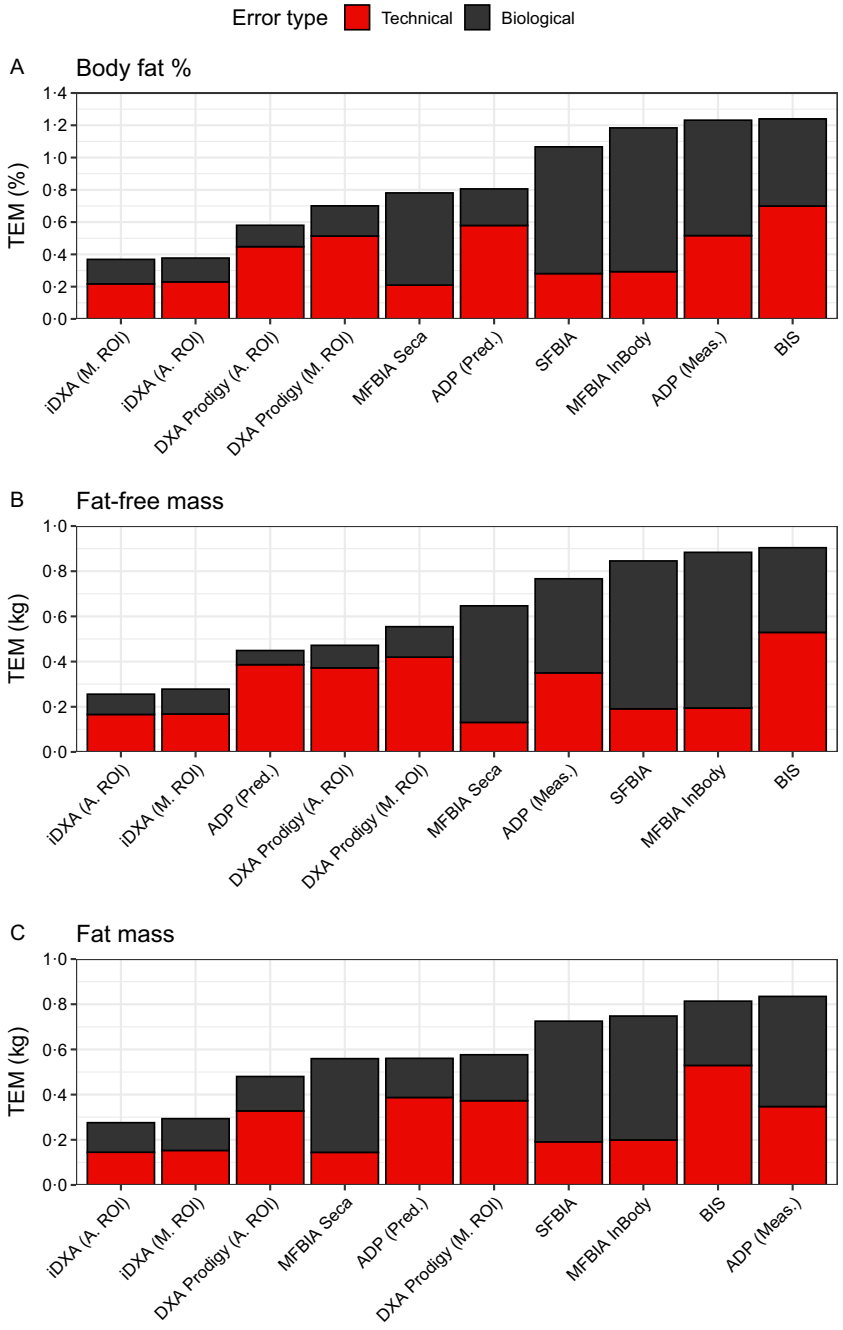


Figure 2. The within-day and between-day technical error of measurement (TEM) for body fat percentage (a), fat-free mass (b) and fat mass (c) for all body composition estimation techniques. DXA, dual-energy X-ray absorptiometry; A.ROI, automated regions of interest; M.ROI, manual regions of interest; MFBIA, multi-frequency bioelectrical impedance analysis; S.P., same placement; R., repositioned; BIS, bioelectrical impedance spectroscopy; S.E., same electrode; D.E., different electrode; SFBIA, single-frequency bioelectrical impedance analysis; ADP, air displacement plethysmography; Meas., measured; Pred., predicted.

alternative that has been evaluated for its within- and between-day reliability[26]. In a prior study, ADP demonstrated good within-day reliability for estimates of BF%, FFM and FM, with ICC of 0·973, 0·992 and 0·975, respectively. Similarly, another investigation that examined between- and within-day reliability of ADP demonstrated trivial typical error for FFM (relative TEM of 0·5–1·5 %) and moderate to substantial typical error for FM (relative TEM 3·4–3·6 %)[27] – values that are generally comparable to the present investigation. Moreover, Tucker *et al.*[5] assessed the within-day test–retest reliability of BF% estimates from ADP in a large sample of middle-aged women, and the results indicated good test–retest reliability with an ICC of 0·998. Overall, the present results indicate that ADP demonstrates generally strong reliability, with superior between-day consistency observed when using predicted rather than measured TGV.

From a practical perspective, individuals performing body composition assessments should consider calculating and reporting the TEM, or a similar metric, for all devices within their own facility to better contextualise longitudinal changes in body composition. Establishing these facility-specific error thresholds can help determine whether observed changes in body composition reflect meaningful physiological adaptations or fall within the expected measurement variability. In this respect, the between-day error – including technical and biological errors – could be conceptualised as the magnitude of change that would need to be exceeded for a change to be considered meaningful. While the values presented in the current study provide some context for these values for several common assessment methods, the generally strong reliability displayed in the current investigation may not be reflective of performance in other settings, particularly when

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Table 2. Reliability of fat-free mass estimates from laboratory-based body composition methods for within- and between-day measures

	Within-day			Between-day		
Device	Absolute TEM (kg)	Relative TEM (%)	ICC	Absolute TEM (kg)	Relative TEM (%)	ICC
$iDXA_{autoROI}$	0·17	0·35	0·999	0·26	0·53	0·999
$iDXA_{manROI}$	0·17	0·35	0·999	0·28	0·58	0·998
DXA $Prodigy_{autoROI}$	0·37	0·67	0·999	0·47	0·85	0·999
DXA $Prodigy_{manROI}$	0·42	0·76	0·999	0·55	1·00	0·999
MFBIA $Seca_{same\ position}$	0·13	0·25	1·000	–	–	–
MFBIA $Seca_{reposition}$	0·14	0·26	1·000	0·65	1·23	0·997
MFBIA $InBody_{reposition}$	0·19	0·37	1·000	0·88	1·67	0·995
$BIS_{diff\ electrode}$	0·53	1·01	0·998	0·90	1·73	0·995
$BIS_{same\ electrode}$	0·04	0·09	1·000	–	–	–
$SFBIA_{diff\ electrode}$	0·19	0·36	1·000	0·85	1·59	0·996
$SFBIA_{same\ electrode}$	0·02	0·04	1·000	–	–	–
$ADP_{measured}$	0·35	0·64	0·999	0·77	1·41	0·997
$ADP_{predicted}$	0·39	0·71	0·999	0·45	0·82	0·999

TEM, technical error of measurement; ICC, intraclass correlation; DXA, dual-energy X-ray absorptiometry; autoROI, automated regions of interest; manROI, manual regions of interest; MFBIA, multi-frequency bioelectrical impedance analysis; BIS, bioelectrical impedance spectroscopy; SFBIA, single-frequency bioelectrical impedance analysis; ADP, air displacement plethysmography.

Table 3. Reliability of fat mass estimates from laboratory-based body composition methods for within- and between-day measures

	Within-day			Between-day		
Device	Absolute TEM (kg)	Relative TEM (%)	ICC	Absolute TEM (kg)	Relative TEM (%)	ICC
$iDXA_{autoROI}$	0·15	0·84	0·999	0·28	1·61	0·998
$iDXA_{manROI}$	0·15	0·89	0·999	0·29	1·71	0·998
DXA $Prodigy_{autoROI}$	0·33	2·11	0·996	0·48	3·06	0·990
DXA $Prodigy_{manROI}$	0·37	2·40	0·994	0·58	3·68	0·985
MFBIA $Seca_{same\ position}$	0·14	0·92	0·999	–	–	–
MFBIA $Seca_{reposition}$	0·14	0·96	0·999	0·56	3·77	0·991
MFBIA $InBody_{reposition}$	0·20	1·32	0·999	0·75	5·09	0·982
$BIS_{diff\ electrode}$	0·53	3·49	0·992	0·81	5·39	0·980
$BIS_{same\ electrode}$	0·04	0·29	1·000	–	–	–
$SFBIA_{diff\ electrode}$	0·19	1·32	0·999	0·73	5·10	0·983
$SFBIA_{same\ electrode}$	0·02	0·15	1·000	–	–	–
$ADP_{measured}$	0·35	2·42	0·992	0·83	5·75	0·955
$ADP_{predicted}$	0·39	2·71	0·993	0·56	3·90	0·984

TEM, technical error of measurement; ICC, intraclass correlation; DXA, dual-energy X-ray absorptiometry; autoROI, automated regions of interest; manROI, manual regions of interest; MFBIA, multi-frequency bioelectrical impedance analysis; BIS, bioelectrical impedance spectroscopy; SFBIA, single-frequency bioelectrical impedance analysis; ADP, air displacement plethysmography.

there is less control over pre-assessment standardisation of patients. Each method used within the current investigation is potentially susceptible to additional measurement error that may occur in a real-world environment. All methods are subject to greater technical error when inconsistent quality control (e.g. calibration), positioning and testing procedures are employed. All may also be subject to biological variability due to food and fluid ingestion and recent exercise, although the extent to which this impacts estimates can vary by method[29,30]. Some biological factors – such as skin temperature, clothing and body hair – may affect ADP in particular[31]. BIA methods are particularly sensitive to hydration status, recent food or fluid intake when analysers include a built-in scale, and skin or environmental temperature, among other factors[32,33]. For practitioners and clinicians, this information highlights the importance of patients adhering to pre-testing standardisation procedures whenever possible, including reporting for evaluation after an overnight fast or consistent time of day, refraining from physical activity and controlling fluid consumption to promote appropriate hydration status while avoiding errors from recent intake. Less consistent implementation

of pre-testing guidelines, such as may occur in real-world testing environments, is expected to introduce more variability in each assessment, thereby worsening the between-day reliability of the techniques. Likewise, any individuals incorporating body composition methods (i.e. practitioners, clinicians and scientist), should be properly trained to ensure consistent device operation and reduce technical errors. Ultimately, facility-specific testing under realistic testing conditions, even when these conditions do not meet the typical best practices, is the best way to obtain reliability information to inform what constitutes a meaningful change in the specific testing context.

Some additional considerations should be taken into account when interpreting the results of the present study. The menstrual cycle was not controlled when scheduling study visits. However, a previous study[34] has noted the menstrual cycle having no significant influence on body composition results obtained by DXA, ADP and BIA. Additionally, the very short duration of the present study minimised the influence of potential changes for the between-day assessments. Nonetheless, the menstrual cycle may be a scheduling consideration for future longitudinal work. Additional research under less controlled field conditions and in populations with differing health status and clinical characteristics is warranted, as both considerations may further influence measurement error. These investigations should include an examination of the performance of methods across a diversity of body sizes and demographic characteristics due to the potential impact of these factors on method reliability. While the present sample included individuals with BMI values of 18·5–28·0 kg/m^2, future work in those defined as having obesity based on BMI would further inform body composition assessment in this population. In general, some body composition methods demonstrate relative stability of performance across a wide range of body sizes, while others may be more susceptible to errors based on body size. These differences may be attributable to the different biophysical principles leveraged by each technique, as well as differences in manufacturer-specific algorithms. The present findings help establish the relevance of inter-device variability, but the findings should be further confirmed in individuals with obesity.

In conclusion, generally strong reliability of laboratory-based body composition methods was demonstrated for both within- and between-day estimates of BF%, FFM and FM. Differences in the amount of technical and biological error across broad technologies and specific devices were observed. Several methodological considerations and procedural variations were examined, and it was determined that some had measurable impacts on error (e.g. placement of adhesive electrodes for bioimpedance techniques and use of measured *v.* predicted TGV for ADP), while others exerted minimal impact (e.g. manual *v.* automated ROI for DXA). Importantly, the present results may represent a 'best-case' scenario, indicative of controlled research settings but not all real-world clinical environments. Investigators should employ appropriate caution when interpreting longitudinal body composition changes, considering the technical and biological errors of the specific technology being used. Ultimately, while some methods demonstrated superior between-day performance (e.g. iDXA and Prodigy DXA scanners, Seca MFBIA and ADP with predicted TGV), the choice of method should also be guided by the practicality of implementing these devices in the selected clinical or research setting.

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References

1. Rose GL, Farley MJ, Slater GJ, *et al.* (2021) How body composition techniques measure up for reliability across the age-span. *Am J Clin Nutr* **114**, 281–294.
2. Siedler MR, Rodriguez C, Stratton MT, *et al.* (2023) Assessing the reliability and cross-sectional and longitudinal validity of fifteen bioelectrical impedance analysis devices. *Br J Nutr* **130**, 827–840.
3. Shiel F, Persson C, Simas V, *et al.* (2018) Reliability and precision of the nana protocol to assess body composition using dual energy X-ray absorptiometry. *Int J Sport Nutr Exerc Metab* **28**, 19–25.
4. Fornetti WC, Pivarnik JM, Foley JM, *et al.* (1999) Reliability and validity of body composition measures in female athletes. *J Appl Physiol* **87**, 1114–1122.
5. Tucker LA, Lecheminant JD & Bailey BW (2014) Test-retest reliability of the Bod Pod: the effect of multiple assessments. *Perceptual Motor Skills* **118**, 563–570.
6. Merrigan J, Stute N, Eckerle J, *et al.* (2022) Reliability and validity of contemporary bioelectrical impedance analysis devices for body composition assessment. *J Exerc Nutr* **5**, 103133.
7. McLester CN, Nickerson BS, Kliszczewicz BM, *et al.* (2020) Reliability and agreement of various InBody body composition analyzers as compared to dual-energy X-ray absorptiometry in healthy men and women. *J Clin Densitometry* **23**, 443–450.
8. Lohman M, Tallroth K, Kettunen JA, *et al.* (2009) Reproducibility of dual-energy X-ray absorptiometry total and regional body composition measurements using different scanning positions and definitions of regions. *Metabolism* **58**, 1663–1668.
9. Vasold KL, Parks AC, Phelan DM, *et al.* (2019) Reliability and validity of commercially available low-cost bioelectrical impedance analysis. *Int J Sport Nutr Exerc Metab* **29**, 406–410.
10. Tinsley GM (2021) Five-component model validation of reference, laboratory and field methods of body composition assessment. *Br J Nutr* **125**, 1246–1259.
11. Blue MN, Tinsley GM, Hirsch KR, *et al.* (2023) Validity of total body water measured by multi-frequency bioelectrical impedance devices in a multi-ethnic sample. *Clin Nutr ESPEN* **54**, 187–193.
12. Brewer GJ, Blue MN, Hirsch KR, *et al.* (2021) Validation of InBody 770 bioelectrical impedance analysis compared to a four-compartment model criterion in young adults. *Clin Physiol Funct Imaging* **41**, 317–325.
13. Nana A, Slater GJ, Hopkins WG, *et al.* (2012) Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people. *Med Sci Sports Exerc* **44**, 180–189.
14. Williams JE, Wells JCK, Wilson CM, *et al.* (2006) Evaluation of Lunar Prodigy dual-energy X-ray absorptiometry for assessing body composition in healthy persons and patients by comparison with the criterion 4-component model. *Am J Clin Nutr* **83**, 1047–1054.

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15. Bosy-Westphal A, Schautz B, Later W, *et al.* (2013) What makes a BIA equation unique? Validity of eight-electrode multifrequency BIA to estimate body composition in a healthy adult population. *Eur J Clin Nutr* **67**, S14–S21.
16. Moon JR, Smith AE, Tobkin SE, *et al.* (2009) Total body water changes after an exercise intervention tracked using bioimpedance spectroscopy: a deuterium oxide comparison. *Clin Nutr* **28**, 516–525.
17. Moon JR, Tobkin SE, Roberts MD, *et al.* (2008) Total body water estimations in healthy men and women using bioimpedance spectroscopy: a deuterium oxide comparison. *Nutr Metab* **5**, 7.
18. Tinsley GM, Moore ML, Benavides ML, *et al.* (2020) 3-dimensional optical scanning for body composition assessment: a 4-component model comparison of four commercially available scanners. *Clin Nutr* **39**, 3160–3167.
19. Cole KS (1940) *Permeability and Impermeability of Cell Membranes for Ions. Cold Spring Harbor Symposia on Quantitative Biology*. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press.
20. Hanai T (1968) Electrical properties of emulsions. In *Emulsion Science*, pp. 353–478 [P Sherman, editor]. London; New York: Academic Press.
21. Tinsley GM, Park KS, Saenz C, *et al.* (2023) Deuterium oxide validation of bioimpedance total body water estimates in Hispanic adults. *Front Nutr* **10**, 1221774.
22. Fields D, Wilson G, Gladden L, *et al.* (2001) Comparison of the BOD POD with the four-compartment model in adult females. *Med Sci Sports Exerc* **33**, 1605–1610.
23. Fields DA, Goran MI & McCrory MA (2002) Body-composition assessment via air-displacement plethysmography in adults and children: a review. *Am J Clin Nutr* **75**, 453–467.
24. Millard-Stafford M, Collins M, Evans E, *et al.* (2001) Use of air displacement plethysmography for estimating body fat in a four-component model. *Med Sci Sports Exerc* **33**, 1311–1317.
25. Siri WE (1956) The gross composition of the body. *Adv Biol Med Phys* **4**, 239–280.
26. Schubert MM, Seay RF, Spain KK, *et al.* (2019) Reliability and validity of various laboratory methods of body composition assessment in young adults. *Clin Physiol Funct Imaging* **39**, 150–159.
27. Kerr A, Slater GJ & Byrne N (2017) Impact of food and fluid intake on technical and biological measurement error in body composition assessment methods in athletes. *Br J Nutr* **117**, 591–601.
28. Zemski AJ, Hind K, Keating SE, *et al.* (2019) Same-day *v.* consecutive-day precision error of dual-energy X-ray absorptiometry for interpreting body composition change in resistance-trained athletes. *J Clin Densitometry* **22**, 104–114.
29. Tinsley GM, Harty PS, Stratton MT, *et al.* (2022) Tracking changes in body composition: comparison of methods and influence of pre-assessment standardisation. *Br J Nutr* **127**, 1656–1674.
30. Rodriguez C, Florez CM, Prather J, *et al.* (2023) Influence of upper-extremity and lower-extremity resistance exercise on segmental body composition and body fluid estimates. *J Strength Cond Res* **37**, 1042–1051.
31. Higgins PB, Fields DA, Hunter GR, *et al.* (2001) Effect of scalp and facial hair on air displacement plethysmography estimates of percentage of body fat. *Obes Res* **9**, 326–330.
32. Kyle UG, Bosaeus I, De Lorenzo AD, *et al.* (2004) Bioelectrical impedance analysis-part II: utilization in clinical practice. *Clin Nutr* **23**, 1430–1453.
33. Tinsley GM, Stratton MT, Harty PS, *et al.* (2022) Influence of acute water ingestion and prolonged standing on raw bioimpedance and subsequent body fluid and composition estimates. *J Electr Bioimpedance* **13**, 10–20.
34. Hicks CS, McLester CN, Esmat TA, *et al.* (2017) A comparison of body composition across two phases of the menstrual cycle utilizing dual-energy X-ray absorptiometry, air displacement plethysmography, and bioelectrical impedance analysis. *Int J Exerc Sci* **10**, 1235–1249.

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