Determining Body Composition Using Different Bioimpedance Technologies: Is an Agreement Possible?

Francesco Campa, A. Sampieri, G. Cerullo, L. Zoffoli, G. Coratella, Antonio Paoli

PII: S0261-5614(25)00293-6

DOI: https://doi.org/10.1016/j.clnu.2025.10.021

Reference: YCLNU 6514

To appear in: *Clinical Nutrition*

Received Date: 4 September 2025

Revised Date: 28 October 2025

Accepted Date: 29 October 2025

Please cite this article as: Campa F, Sampieri A, Cerullo G, Zoffoli L, Coratella G, Paoli A, Determining Body Composition Using Different Bioimpedance Technologies: Is an Agreement Possible?, *Clinical Nutrition*, https://doi.org/10.1016/j.clnu.2025.10.021.

Determining Body Composition Using Different Bioimpedance Technologies: Is an Agreement Possible?

Francesco Campa,[1] A. Sampieri, G[1]. Cerullo[1], L. Zoffoli[2], G. Coratella[3], Antonio Paoli[1]

[1] Department of Biomedical Sciences, University of Padua, Padua, Italy

[2] Scientific Research and Innovation Department, Technogym S.p.A., 47521 Cesena, Italy

[3] Department of Biomedical Sciences for Health, Università degli Studi di Milano, Milan, Italy

* Correspondence: giuseppe.cerullo@unipd.it

Abstract

Background and Aims:

Disagreement between bioelectrical impedance analysis (BIA) technologies in measuring resistance (R), reactance (Xc), and phase angle (PhA) is well documented and mainly due to device-specific features. Whether such a variability translates into differences in body composition estimates remains uncertain. This study evaluated agreement in fat-free mass (FFM) estimates from different BIA technologies against dual-energy X-ray absorptiometry (DXA), while accounting for the role of predictive equations. Additionally, agreement of BIA-based fat mass (FM), indirectly calculated from FFM, was assessed.

Methods:

A total of 288 adults (167 men, 37.2 ± 18.7 y, BMI 23.0 ± 3.1 kg/m²; 121 women, 33.8 ± 16.8 y, BMI 25.1 ± 3.3 kg/m²) were assessed. Whole-body foot-to-hand and direct segmental BIA at 50 kHz measured R, Xc, and PhA. DXA served as the reference. Predictive equations for FFM were developed by stepwise regression in two-thirds of the sample and validated in the remaining third. Agreement was evaluated between BIA technologies and against DXA using Bland–Altman and Lin's concordance.

Results:

Foot-to-hand BIA yielded lower R ($p < 0.001$) but higher Xc and PhA ($p < 0.001$) than direct segmental BIA. Despite these differences, no significant bias ($p > 0.05$) was observed in FFM estimation across devices. Concordance analyses indicated high agreement without systematic deviations. FM derived from FFM agreed with DXA at a group level but showed systematic trends at the individual level.

Conclusions:

Although raw bioelectrical parameters differ between technologies, FFM estimates can be comparable when equations are derived within the same population and reference method. However, FM indirectly obtained from FFM lacks accuracy at the individual level.

Keywords: BIA, DXA, fat-free mass, fat mass, phase angle

Introduction

Bioelectrical impedance analysis (BIA) is widely used to assess body composition, allowing the estimation of different body mass components through the measurement of resistance (R), reactance (Xc), and phase angle (PhA) [1,2]. Indeed, R is inversely proportional to total body water, a major constituent of fat-free mass (FFM), while Xc reflects the cell membrane integrity and body cell density [3]. The bioelectrical PhA represents the time delay, or phase shift, between the applied current and the resulting voltage, and reflects the capacitive properties of cell membranes. It is considered an indicator of the balance between intracellular and extracellular water [4,5]. When integrated into the predictive equations, these measured properties are used to estimate FFM, from which whole-body fat mass (FM) is subsequently calculated as the difference between body mass and FFM [6].

Although BIA devices operate on the same physical principles, they differ in technological aspects such as electrode placement, body position, and operating frequency, each influencing R and Xc values [2,7,8]. A lack of agreement in these parameters has been reported between commonly used technologies, particularly foot-to-hand and direct segmental systems [6]. However, discrepancies in body composition estimates cannot be attributed solely to hardware differences, as other factors,

including the reference methods and populations used to develop predictive equations, also contribute to variability [6,9]. Among the reference methods, a lack of agreement in body composition estimates has been reported, for instance, between dual-energy X-ray absorptiometry (DXA), air displacement plethysmography, and underwater weighing [10,11]. Moreover, predictive models may yield substantial errors when applied to populations whose characteristics (e.g., age, sex, or physical activity) differ from those of the original validation sample. Such methodological and population-related discrepancies can reduce comparability across devices and restrict the generalizability of literature-based reference standards for evaluating body composition in clinical, athletic, and research settings.

However, a recent study has shown that agreement in body composition estimates between different methods (i.e., DXA, anthropometry, and BIA) could still be possible when reference-specific and population-specific predictive equations are used [12]. Thus, it is reasonable that the same agreement can derive from different BIA technologies. For these reasons, the present study assessed the agreement in R, Xc, and PhA and FFM obtained using predictive equations developed on the same population and reference method (i.e., DXA) between the foot-to-hand and the direct segmental technology. Additionally, agreement in BIA-derived FM, calculated as the difference between the body mass and the FFM, was assessed. We hypothesized that comparable FFM and FM values may derive from different BIA technologies when standardizing estimation procedures.

Material and methods

Participants

A total of 291 adults expressed interest in participating in the study following recruitment through public advertisements, digital announcements, and local outreach. A convenience sampling approach

was applied, recruiting volunteers from the general adult population. Participants were required to be healthy adult, free of any injury or impairment in the upper and lower limbs. Exclusion criteria were the presence of acute or chronic diseases (such as metabolic or endocrine disorders) recent hospitalization, or recent musculoskeletal injuries, or other conditions known to alter body fluid distribution and body composition assessments.

Eligibility screening was conducted before enrollment to ensure that only individuals meeting all predefined inclusion and exclusion criteria were invited to participate.

Of the 293 eligible individuals, 291 were scheduled for assessment. Three participants later declined to undergo the DXA scan for personal reasons and were therefore excluded from the final analysis. The remaining 288 participants successfully completed all BIA assessments and were included in the analytical sample. Within this final sample, a random allocation procedure was subsequently applied to divide participants into development and validation groups for the construction and testing of predictive equations.

To facilitate demographic characterization, participants were categorized into three age groups: young adults (18–39 years), adults (40–64 years), and older adults (≥65 years). All participants were fully informed about the study procedures and provided written informed consent before testing. The study protocol was approved by the local Ethics Committee (HEC-DSB-022023) and conducted in accordance with the principles of the Declaration of Helsinki. A flow diagram summarizing recruitment and exclusion is presented in Supplementary Figure 1.

Procedures

Body mass and stature were measured to the nearest 0.1 kg and 0.1 cm, respectively, using a scale with stadiometer (Seca, Hamburg, Germany).

BIA was performed using two phase-sensitive bioelectrical impedance analyzers operating at 50 kHz: a foot-to-hand device (BIA 101 BIVA® PRO, Akern Ltd, Pisa, Italy) and a direct segmental device

(Checkup 9000 - Technogym Spa, Cesena Italy). Both instruments directly measure resistance R, Xc, and PhA. Participants fasted for at least 2 hours and avoided alcohol, caffeine, and diuretics for 24 hours prior to testing. They also refrained from intense physical activity the day before, rested for five minutes prior to the measurement, wore light clothing, and removed all metal accessories.

For the foot-to-hand BIA, participants were instructed to lie in a supine position, isolated from the ground and electrical conductors, with legs abducted at 45°, shoulders abducted at 30° relative to the body midline, and hands pronated. Four adhesive electrodes (Biatrodes Akern Srl, Firenze, Italy) were applied following standard procedures: two on the dorsal surface of the right hand and two on the dorsal surface right foot. According to the bioelectrical impedance vector analysis (BIVA), R and Xc, standardized for height in meters, were plotted on the R–Xc Z-score graph including reference ellipses for the general population [13] in order to assess participants' hydration and fluid distribution. BIVA plots standardized R and Xc on tolerance ellipses. The major axis reflects total body water, with vectors positioned higher indicating lower hydration and vectors lower indicating greater hydration. The minor axis reflects body cell mass and the intracellular-to-extracellular fluid ratio, with leftward vectors indicating higher cell mass and intracellular-to-extracellular fluid ratio, and rightward vectors indicating lower cell mass and intracellular-to-extracellular fluid ratio [13].

For the direct segmental BIA, participants were instructed to stand upright with their upper limbs held away from the trunk and hands resting on the integrated hand electrodes. The lower limbs were positioned apart, with feet placed on the corresponding foot electrodes integrated into the device platform.

Calibration and precision of the bioelectrical devices were assessed before each test session. The test–retest coefficient of variation (CV = [standard deviation / mean] × 100%) for duplicate measurements of R and Xc was 0.3% and 0.9%, respectively, for the foot-to-hand device, and 0.4% and 0.7%, respectively, for the direct segmental device. R and Xc indices were calculated by dividing height squared (cm^2) by R and Xc values, respectively. Based on bioelectrical measurements, FM was

calculated by subtracting the estimated FFM obtained through the newly developed models from body mass.

A whole-body DXA scanner (QDR 4500A, Hologic, Marlborough, Massachusetts) that operated with software version V8.26a:3.19 was used to estimate FM and FFM. System calibrations were conducted on a regular basis as specified by the manufacturer using a standard calibration block (Hologic DXA Quality Control Phantom Lumbar Spine). Participants were first weighed and had their height measured, followed by BIA assessments using the direct segmental device and then the foot-to-hand device. Finally, DXA scan was performed. All measurements were conducted on the same day under standardized environmental conditions (temperature 22–24 °C).

All assessments, including both BIA and DXA scans, were performed and analyzed by the same trained researcher to ensure methodological consistency. Inter-observer variability was therefore not applicable by design. To document measurement precision, intra-operator test–retest repeatability was assessed in a subsample of 10 participants (5 men and 5 women). For raw bioelectrical parameters, CV values were 0.3% (R), 0.7% (Xc), and 0.1% (PhA) for the foot-to-hand BIA, and 0.4% (R), 0.7% (Xc), and 0.1% (PhA) for the direct segmental BIA. For body-composition estimates, CV values were 1.7% (FM) and 0.8% (FFM) for DXA, 1.6% (FM) and 0.9% (FFM) for the foot-to-hand BIA, and 1.7% (FM) and 0.8% (FFM) for the direct segmental BIA.

Statistical analysis

Statistical analyses were performed using RStudio (version 2024.x; RStudio Team, 2024). All variables were checked for normality, using Kolmogorov-Smirnov test. Sex group distribution was compared using the Chi-square test. Paired t-tests and repeated-measures analysis of variance (ANOVA) were used to assess within-subject differences between conditions. Two-thirds of the participants were randomly assigned (using random.org) to the development group, while the

remaining participants (1/3) to the validation group. Descriptive characteristics for the development and validation groups are presented as means ± standard deviation. The ability of the following variables (age, sex, R index, Xc index, and PhA) to predict FFM in the development group was assessed using backward stepwise linear regression analysis, with equations developed separately for each technology. To assess multicollinearity, the variance inflation factor was calculated. Using Lin's approach [14] the concordance correlation coefficient (CCC) was calculated and interpreted as suggested by McBride [15] (almost perfect >0.99; substantial >0.95 to 0.99; moderate =0.90 – 0.95; and poor <0.90). Agreement between BIA models and DXA was also determined using linear regression analysis, Bland-Altman method [16], and non-parametric Passing–Bablok regression. Intercept and slope were reported with their 95% confidence intervals, and agreement was inferred when the confidence interval for the intercept included zero and the confidence interval for the slope included one. The smallest detectable change (SDC) was calculated to determine the minimum difference interpretable as a true change beyond measurement error. This value was estimated from the standard error of measurement derived from the test–retest reliability data collected under identical conditions. Statistical significance was set at $p < 0.05$ for all analyses.

Results

The final analytical sample included 288 participants (167 men, 121 women). The sex distribution did not differ significantly ($\chi^2 = 1.85$, $p = 0.17$). The age distribution was as follows: young adults (18–39 years, n = 112, 38.9%), adults (40–64 years, n = 109, 37.8%), and older adults (≥65 years, n = 67, 23.3%). BIVA results, obtained with the foot-to-hand device, are shown in Supplementary Figure 2. Most participants exhibited bioelectrical vectors falling within the 95% tolerance ellipses of the Italian adult reference population [13], indicating hydration patterns consistent with normal physiological ranges.

Figure 1 shows the comparison of raw parameters between the two technologies. The foot-to-hand technology showed lower values of R ($t = -17.7$, $p < 0.001$), and higher values of Xc ($t = 17.3$, $p < 0.001$) and PhA ($t = 32.5$, $p < 0.001$) compared to the direct segmental technology.

*** Figure 1 here ***

Figure 1. Boxplots show the distribution across conditions. The solid horizontal line in each box is the median, while the dashed line shows the mean. Whiskers indicate the data range within 1.5× the interquartile range. Individual values are shown as dots (black = men, white = women), slightly spread to reflect density. Gray lines connect measures from the same subject.

The descriptive characteristics of the participants, grouped by development and validation groups, are presented in Table 1.

*** Table 1 here ***

Table 2 presents the new BIA-based predictive equations. Only variables that contributed to the FFM estimates, as identified through a backward stepwise approach, were included in the models.

*** Table 2 here ***

FFM estimated using the new equations did not differ between foot-to-hand and direct segmental BIA technologies and DXA ($F = 2.816$, $p = 0.062$), as shown in Figure 2. FM calculated from FFM data did not differ between foot-to-hand and direct segmental BIA technologies and DXA ($F = 2.204$, $p = 0.113$) (Figure 2).

*** Figure 2 here ***

Figure 2. Boxplots show the distribution in fat and fat-free mass within methods. The solid horizontal line in each box is the median, while the dashed line shows the mean. Whiskers indicate the data range within 1.5× the interquartile range. Individual values are shown as dots (black = men, white = women), slightly spread to reflect density. Gray lines connect measures from the same subject. DXA, dual energy X-ray absorptiometry.

Table 3 presents the results of the validation for the estimated FFM and the calculated FM.

*** Table 3 here ***

The outcomes of the linear regression and Bland–Altman analyses are also shown graphically in Figure 3 and 4, for FFM and FM, respectively.

*** Figure 3 here ***

Figure 3. On the left side the outputs of the linear regression analysis. The black line shows the linear regression fit. The shaded area represents the 95% confidence interval of the regression. On the right side, the Bland-Altman outputs. The dashed line shows the mean difference. Dotted lines indicate the 95% limits of agreement. The solid line shows the trend across the measurement range. FFM, fat-free mass; DXA, dual energy X-ray absorptiometry.

*** Figure 4 here ***

Figure 4. On the left side the outputs of the linear regression analysis. The black line shows the linear regression fit. The shaded area represents the 95% confidence interval of the regression. On the right side, the Bland-Altman outputs. The dashed line shows the mean difference. Dotted lines indicate the 95% limits of agreement. The solid line shows the trend across the measurement range. FM, fat mass; DXA, dual energy X-ray absorptiometry.

Regarding FFM estimations, agreement at the group level showed a Lin's CCC of 0.971, with a coefficient of determination (r^2) of 0.98 and a standard error of estimation of 1.79 kg. At the individual level, 95% limits of agreement ranged from −3.81 to 3.17 kg, with no significant trend ($r = 0.144$, $p = 0.160$). When FM was calculated from FFM, agreement at the group level showed a Lin's CCC of 0.969, with a coefficient of determination (r^2) of 0.95 and a standard error of estimation of 1.64 kg. At the individual level, 95% limits of agreement ranged from −3.64 to 2.82 kg, with significant trend ($r = 0.262$, $p = 0.011$). The results of the linear regression and Bland–Altman analyses are presented graphically in Figure 5.

*** Figure 5 here ***

Figure 5. On the left side the outputs of the linear regression analysis. The black line shows the linear regression fit. The shaded area represents the 95% confidence interval of the regression. On the right side, the Bland-Altman outputs. The dashed line shows the mean difference. Dotted lines indicate the 95% limits of agreement. The solid line shows the trend across the measurement range. FFM, fat-free mass; FM, fat mass.

Passing–Bablok regression analyses comparing BIA devices with DXA are presented in Supplementary Figure 3. For FFM, the foot-to-hand device showed an intercept of 2.15 (95% CI −1.01 to 5.41) and a slope of 0.96 (95% CI 0.89 to 1.02), while the direct segmental device showed

an intercept of 1.24 (95% CI −1.10 to 3.89) and a slope of 0.96 (95% CI 0.91 to 1.01). In both cases, the confidence intervals for the intercept included zero and those for the slope included one, indicating no constant or proportional bias compared with DXA. For FM, the foot-to-hand device yielded an intercept of 4.71 (95% CI 2.93 to 6.24) and a slope of 0.75 (95% CI 0.66 to 0.83), whereas the direct segmental device showed an intercept of 3.77 (95% CI 2.40 to 5.08) and a slope of 0.83 (95% CI 0.75 to 0.90). These results indicate a systematic underestimation of DXA-derived FM by both BIA methods, reflected by a non-zero intercept and a slope below unity. The direct comparison between the two BIA devices demonstrated an intercept of −0.23 (95% CI −1.73 to 1.29) and a slope of 0.99 (95% CI 0.96 to 1.03), confirming strong agreement between them for FFM estimation.

The SDC ranged from 1.1 to 1.3 kg for FFM and from 0.8 to 0.9 kg for FM and across methods, representing the threshold beyond which differences can be interpreted as true changes rather than measurement noise.

Discussion

The current study assessed the agreement in R, Xc, and PhA and FFM obtained using predictive equations developed on the same population and reference method (i.e., DXA) between the foot-to-hand and the direct segmental technology. Additionally, agreement in BIA-derived FM, calculated as the difference between the body mass and the FFM, was determined. The initial hypothesis was confirmed, showing that although a lack of agreement in bioelectrical properties between the foot-to-hand and the direct segmental technology, comparable body composition estimates could be achieved when predictive models were developed using the same reference method and population. Specifically, R values were lower with foot-to-hand devices, while Xc and PhA were higher compared to the direct segmental devices. Nonetheless, the FFM estimates generated by their respective

predictive models did not differ, nor were different from those obtained via DXA. However, FM calculated as the difference between body mass and FFM showed no bias at the group level, but was less accurate at the individual level. The present results suggest the possibility of using population- and technology-specific predictive equations to estimate FFM even when the bioelectrical properties may differ.

The present lack of agreement in bioelectrical properties across different BIA technologies is consistent with previous literature. It can be attributed to key methodological differences, including body position during the measurement, i.e., supine vs. standing, affecting fluid distribution [7,8], and the type of electrodes used, i.e., adhesive vs. integrated, that lead to variability in bioelectrical properties depending on their material, placement, and the inter-electrode distance, particularly when applied on the hands and feet [17]. As a further consequence, R, Xc, and PhA differed between the foot-to-hand and the segmental technology, particularly PhA values are higher in the foot-to-hand than the segmental technology. As for R and Xc, these can be primarily integrated in the bioelectrical BIVA, which classifies individuals based on total body water and cellular mass relative to population-specific reference ellipses [13]. Given the device-dependent nature of these standards, they are not interchangeable across technologies due to the observed lack of agreement. Moreover, PhA is associated with muscle mass, increased frailty risk, and extracellular fluid accumulation [18], and reference values for PhA exist for both foot-to-hand and direct segmental devices [13]. Thus, awareness of device-related discrepancies is essential when interpreting BIA-measured body composition metrics, and raw parameters obtained from different devices should not be directly compared, as this is now widely recognized and established in the field.

To date, the use of BIA for estimating body composition has not always taken into account several critical aspects, leading to a lack of agreement among technologies not only in measurements but also in estimates [19–21]. In particular, insufficient attention has been paid to the characteristics of the

prediction equations (such as the population and the reference method) [19], and in several cases the applied formulas have not even been reported [21,22]. Body composition components such as FFM and FM are typically quantified by BIA through two main methodological approaches: property-based type-I methods and combined methods [23]. Specifically, property-based type-I methods estimate body composition from a directly measurable parameter, applying mathematical functions calibrated against a reference technique (FFM in the present study), while combined methods integrate both a measurable property and an estimated component, i.e., FM [23]. Building on the bioelectrical properties measured with each technology, we have developed two predictive models for FFM using DXA as a reference in the general population (age 18–83, both sexes). Additionally, sex and age were also included, accounting for the higher FFM in males and its age-related decline [24]. This suggests that when BIA is applied as a property-based type-I method and mathematical procedures are rigorously followed, comparable estimates across technologies can be achieved. Consequently, obtaining consistent estimates of body composition across different technologies mainly depends on the appropriate use of prediction equations, which allows the universal application of reference values reported in the literature [25,26]. In light of this, such reference values should be used only in comparison with estimates derived from prediction equations developed in the same population and, even more importantly, validated against the same reference method (such as DXA, magnetic resonance imaging, or other multicomponent approaches).

The novel insights from the present study, combined with existing evidence, contribute to a comprehensive understanding of the agreement between BIA technologies in both the measurement and the estimation of body composition. This conceptual framework is illustrated in Figure 6. Looking ahead, greater accuracy in BIA-combined approaches could be achieved by developing regression models that also incorporate anthropometric characteristics such as circumferences, which are increasingly accessible through digital optical systems. Indeed, combining dimensional

parameters such as circumferences with bioelectrical variables allows for a more accurate representation of body geometry and volume, and has shown high predictive power for FM assessment [27].

***** Figure 6 here *****

Figure 6. The agreement paradigm in bioelectrical impedance analysis (BIA) for bioelectrical properties and estimates. The top of the funnel represents the device characteristics that lead to variations in the raw parameters (i.e., resistance (R), reactance (Xc), and phase angle (PhA)) as well as in the amount of fluid assessed when different. The neck of the funnel represents the predictive equation, that should be based on similar features (e.g., the reference method used for development and the target population), resulting in similar final amount of fluid in the glass. The liquid in the glass represents the body composition estimates (e.g., fat-free mass).

Given the following limitation, the present results should not be generalized without caution. First, although the participants followed standardized fasting protocols before undergoing BIA assessments and were strictly instructed about the timing to ingest food and liquids, no marker of hydration status, such as the urine specific gravity, was assessed to confirm euhydration. However, BIVA revealed that all participants were located within the 95% tolerance ellipse, with the exception of four cases. One underweight female (body mass = 42.5 kg) was positioned at the upper end of the major axis, likely reflecting lower absolute body water relative to body size rather than true dehydration. In addition, three older adults (two females aged 80 and 81 years and one male aged 83 years) were located beyond the right side of the ellipse along the minor axis, which predominantly reflects PhA and cellular mass. These latter positions are consistent with patterns typically observed in advanced age and correspond to the reference ellipses for the Italian elderly population [28]. Second, while DXA is a widely accepted criterion method to estimate FFM and FM, the four-component model could be considered a methodological improvement [29]. Therefore, although the new predictive equations presented here

may be used for estimating FFM, models developed and validated vs. the four-component model should be preferred when available. Finally, the applicability of predictive equations strongly depends on the population in which they were developed and validated. Generic equations may have limited accuracy in specific groups, such as children, individuals with obesity, or those with altered hydration status, highlighting the need for population-tailored models that consider age, body composition, and fluid distribution. In our study, agreement between BIA devices was observed in apparently healthy adults with normal hydration, but in clinical populations with fluid imbalance, such as patients with renal, hepatic, or cardiac conditions, or those experiencing dehydration or edema, small device differences could become clinically meaningful. Bioelectrical impedance measurements are sensitive to tissue conductivity and extracellular water, so even modest discrepancies may be amplified in these settings. Therefore, while our findings support strong concordance in healthy individuals, caution is warranted when extrapolating to populations with altered fluid balance. Future studies should aim to develop and validate both population-specific prediction equations and device-specific adjustment criteria to enhance the clinical and epidemiological relevance of bioimpedance assessments.

Conclusions

The foot-to-hand and the direct segmental BIA technology present differences in raw parameters such as R, Xc, and PhA. However, when predictive equations are rigorously applied and derived from the same reference method and population, comparable estimates of body composition can be obtained across technologies. Agreement in body mass components is therefore achievable, although accuracy may be reduced when additional processing is required, for example, deriving FM as body mass minus FFM, since this increases the distance from the original reference standard. Overall, reliable and clinically meaningful BIA assessments depend on the proper use of prediction equations and careful consideration of both methodological and technological factors.

Acknowledgements

The authors are grateful to all people who took part in this study.

Declarations

Conflict of interest

The author L.Z. is currently employed by Technogym S.p.A. The authors F.C., A.S., G.C. A.P., and G.C. have no conflict of interest to declare.

Funding disclosure

The authors received no funding for the present investigation.

Authors' contributions

Francesco Campa: Conceptualization, Data curation, Formal analysis, Validation, Writing - original draft, Writing - review & editing. **Alessandro Sampieri**: Data collection. **Giuseppe Cerullo**: Data curation, Writing - review & editing. **Luca Zoffoli**: Writing - review & editing. **Giuseppe Coratella**: Writing - review & editing. **Antonio Paoli**: Methodology, Resources, Supervision, Writing - review & editing.

All authors meet all conditions to comply with International Committee of Medical Journal Editors (ICMJE) recommendations and no one eligible for authorship has been excluded from the list of authors.

Data available on request from the authors.

The study protocol was approved by the local Ethics Committee (HEC-DSB-022023) and conducted in accordance with the principles of the Declaration of Helsinki.

No AI-based technologies were used in the writing process.

References

[1] Silva AM, Campa F, Stagi S, Gobbo LA, Buffa R, Toselli S, et al. The bioelectrical impedance analysis (BIA) international database: aims, scope, and call for data. Eur J Clin Nutr 2023. https://doi.org/10.1038/s41430-023-01310-x.

[2] Campa F, Toselli S, Mazzilli M, Gobbo LA, Coratella G. Assessment of body composition in athletes: a narrative review of available methods with special reference to quantitative and qualitative bioimpedance analysis. Nutrients 2021;13:1620. https://doi.org/10.3390/nu13051620.

[3] Lukaski HC. Evolution of bioimpedance: a circuitous journey from estimation of physiological function to assessment of body composition and a return to clinical research. Eur J Clin Nutr 2013;67 Suppl 1:S2-9. https://doi.org/10.1038/ejcn.2012.149.

[4] Francisco R, Matias CN, Santos DA, Campa F, Minderico CS, Rocha P, et al. The Predictive Role of Raw Bioelectrical Impedance Parameters in Water Compartments and Fluid Distribution Assessed by Dilution Techniques in Athletes. Int J Environ Res Public Health 2020;17. https://doi.org/10.3390/ijerph17030759.

[5] Lukaski H, Raymond-Pope CJ. New Frontiers of Body Composition in Sport. Int J Sports Med 2021. https://doi.org/10.1055/a-1373-5881.

[6] Campa F, Gobbo LA, Stagi S, Cyrino LT, Toselli S, Marini E, et al. Bioelectrical impedance analysis versus reference methods in the assessment of body composition in athletes. Eur J Appl Physiol 2022. https://doi.org/10.1007/s00421-021-04879-y.

[7] Stratton MT, Smith RW, Harty PS, Rodriguez C, Johnson BA, Dellinger JR, et al. Longitudinal agreement of four bioimpedance analyzers for detecting changes in raw bioimpedance during purposeful weight gain with resistance training. Eur J Clin Nutr

2021;75:1060–8. https://doi.org/10.1038/s41430-020-00811-3.

[8] Dellinger JR, Johnson BA, Benavides ML, Moore ML, Stratton MT, Harty PS, et al. Agreement of bioelectrical resistance, reactance, and phase angle values from supine and standing bioimpedance analyzers. Physiol Meas 2021.

[9] Coratella G, Campa F, Matias C, Toselli S, Koury J, Andreoli A, et al. Generalized bioelectric impedance-based equations underestimate body fluids in athletes. Scand J Med Sci Sport 2021;31:2123–32. https://doi.org/10.1111/SMS.14033.

[10] Tinsley GM, Harty PS, Stratton MT, Smith RW, Rodriguez C, Siedler MR. Tracking changes in body composition: comparison of methods and influence of pre-assessment standardisation. Br J Nutr 2022;127:1656–74. https://doi.org/10.1017/S0007114521002579.

[11] Deemer SE, Kolb DE, Cipriano NL, Smith DL, King GA. Comparison of Body Composition Estimates in Hispanic Women by Dual-Energy X-ray Absorptiometry and Hydrostatic Densitometry. J Clin Densitom Off J Int Soc Clin Densitom 2025;28:101595. https://doi.org/10.1016/j.jocd.2025.101595.

[12] Campa F, Matias CN, Moro T, Cerullo G, Casolo A, Teixeira FJ, et al. Methods over Materials: The Need for Sport-Specific Equations to Accurately Predict Fat Mass Using Bioimpedance Analysis or Anthropometry. Nutrients 2023;15. https://doi.org/10.3390/nu15020278.

[13] Campa F, Coratella G, Cerullo G, Stagi S, Paoli S, Marini S, et al. New bioelectrical impedance vector references and phase angle centile curves in 4,367 adults: The need for an urgent update after 30 years. Clin Nutr 2023;42:1749–58. https://doi.org/10.1016/j.clnu.2023.07.025.

[14] Lin LI. A concordance correlation coefficient to evaluate reproducibility. Biometrics 1989;45:255–68.

[15] McBride GB. Statistical Calculators; Lin's Concordance 2007.

[16] Bland JM, Altman DG, Warner DS. Agreed Statistics: Measurement Method Comparison. Anesthesiology 2012;116:182–5. https://doi.org/10.1097/ALN.0b013e31823d7784.

[17] Dupertuis YM, Pereira AG, Karsegard VL, Hemmer A, Biolley E, Collet T-H, et al. Influence of the type of electrodes in the assessment of body composition by bioelectrical impedance analysis in the supine position. Clin Nutr 2022;41:2455–63. https://doi.org/10.1016/j.clnu.2022.09.008.

[18] Bellido D, García-García C, Talluri A, Lukaski HC, García-Almeida JM. Future lines of research on phase angle: Strengths and limitations. Rev Endocr Metab Disord 2023;24:563–83. https://doi.org/10.1007/s11154-023-09803-7.

[19] Bennett JP, Cataldi D, Liu YE, Kelly NN, Quon BK, Gonzalez MC, et al. Variations in bioelectrical impedance devices impact raw measures comparisons and subsequent prediction of body composition using recommended estimation equations. Clin Nutr ESPEN 2024;63:540–50. https://doi.org/https://doi.org/10.1016/j.clnesp.2024.07.009.

[20] Rudnev S, Burns JS, Williams PL, Lee MM, Korrick SA, Denisova T, et al. Comparison of bioimpedance body composition in young adults in the Russian Children's Study. Clin Nutr ESPEN 2020;35:153–61. https://doi.org/10.1016/j.clnesp.2019.10.007.

[21] Siedler MR, Rodriguez C, Stratton MT, Harty PS, Keith DS, Green JJ, et al. Assessing the reliability and cross-sectional and longitudinal validity of fifteen bioelectrical impedance analysis devices. Br J Nutr 2023;130:827–40. https://doi.org/10.1017/S0007114522003749.

[22] Paoli A, Campa F. Problems and Opportunities in the use of Bioelectrical Impedance Analysis for Assessing Body Composition During Ketogenic Diets: A Scoping Review. Curr Obes Rep 2024. https://doi.org/10.1007/s13679-024-00573-0.

[23] Wang ZM, Heshka S, Pierson RNJ, Heymsfield SB. Systematic organization of body-

composition methodology: an overview with emphasis on component-based methods. Am J Clin Nutr 1995;61:457–65. https://doi.org/10.1093/ajcn/61.3.457.

[24] Lauretani F, Russo CR, Bandinelli S, Bartali B, Cavazzini C, Di Iorio A, et al. Age-associated changes in skeletal muscles and their effect on mobility: an operational diagnosis of sarcopenia. J Appl Physiol 2003;95:1851–60. https://doi.org/10.1152/japplphysiol.00246.2003.

[25] Pratt J, Narici M, Boreham C, De Vito G. Dual-energy x-ray absorptiometry derived body composition trajectories across adulthood: Reference values and associations with body roundness index and body mass index. Clin Nutr 2025;46:137–46. https://doi.org/https://doi.org/10.1016/j.clnu.2025.02.001.

[26] Santos DA, Dawson JA, Matias CN, Rocha PM, Minderico CS, Allison DB, et al. Reference values for body composition and anthropometric measurements in athletes. PLoS One 2014;9. https://doi.org/10.1371/journal.pone.0097846.

[27] Marini E, Campa F, Buffa R, Stagi S, Matias CN, Toselli S, et al. Phase angle and bioelectrical impedance vector analysis in the evaluation of body composition in athletes. Clin Nutr 2020;39:447–54. https://doi.org/10.1016/j.clnu.2019.02.016.

[28] Campa F, Annunziata G, Barrea L, Sampieri A, Ceolin C, De Rui M, et al. Bioelectrical impedance vector analysis in older adults: reference standards from a cross-sectional study. Front Nutr 2025;12:1640407. https://doi.org/10.3389/fnut.2025.1640407.

[29] Wang Z, Pi-Sunyer FX, Kotler DP, Wielopolski L, Withers RT, Pierson RNJ, et al. Multicomponent methods: evaluation of new and traditional soft tissue mineral models by in vivo neutron activation analysis. Am J Clin Nutr 2002;76:968–74. https://doi.org/10.1093/ajcn/76.5.968.

Figure captions for supplementary materials

Supplementary Figure 1. Consort flow chart of patients screened.

Supplementary Figure 2. Standardized R–Xc vectors (Z-scores) plotted on the 50%, 75%, and 95% tolerance ellipses of the Italian adult reference population (Campa et al., 2023).

Supplementary Figure 3. Passing–Bablok regression analyses comparing fat-free mass (FFM) and fat mass (FM) estimates among DXA, foot-to-hand BIA, and direct segmental BIA.

Panels A–C display regression analyses for FFM (A: DXA vs. foot-to-hand; B: DXA vs. direct segmental; C: foot-to-hand vs. direct segmental), and panels D–F for FM (D: DXA vs. foot-to-hand; E: DXA vs. direct segmental; F: foot-to-hand vs. direct segmental).

Table 1. Descriptive characteristics for the development and validation groups.

	Development group (N=192)	Validation group (N=96)
Number of men	114	53
Age (years)	35.6 ± 17.6	32.7 ± 16.2
Range (years)	18-81	18-83
Body mass (kg)	73.9 ± 14.7	67.9 ± 11.4
Stature (cm)	173.1 ± 9.7	169.9 ± 10.3
BMI (kg/m^2)	24.5 ± 3.7	23.4 ± 2.3
FFM $_{DXA}$ (kg)	53.9 ± 12.9	50.0 ± 11.0
FM $_{DXA}$ (kg)	19.9 ± 7.5	18.0 ± 5.9
R $_{Foot\text{-}to\text{-}hand}$ (Ohm)	519.3 ± 91.5	547.2 ± 96.4
Xc $_{Foot\text{-}to\text{-}hand}$ (Ohm)	57.4 ± 8.5	60.9 ± 8.6
PhA $_{Foot\text{-}to\text{-}hand}$ (degrees)	6.4 ± 0.9	6.5 ± 0.8
R $_{Direct\ segmental}$ (Ohm)	549.2 ± 98.1	570.4 ± 91.6
Xc $_{Direct\ segmental}$ (Ohm)	53.9 ± 7.6	56.1 ± 7.2
PhA $_{Direct\ segmental}$ (degrees)	5.7 ± 0.9	5.7 ± 0.9

Note: Data are reported as mean ± standard deviation. BMI, Body mass index; DXA, dual energy X-ray absorptiometry; FFM, Fat-free mass; FM, Fat mass; PhA, Phase angle; R, Resistance; Xc, Reactance.

Table 2. Developed bioelectrical models for fat-free mass prediction.

	Coefficient	R^2	SEE (kg)	VIF
Foot-to-hand				
Model 1		0.90	3.98	
Intercept	4.952			
H^2/R (cm^2/ohm)	0.813			1.00
Model 2		0.92	3.70	
Intercept	9.541			
H^2/R (cm^2/ohm)	0.688			2.59
Sex[§]	4.850			2.59
Model 3		0.93	3.05	
Intercept	12.670			
H^2/R (cm^2/ohm)	0.675			2.62
Sex[§]	5.142			2.60
Age (years)	-0.070			1.01
Direct segmental				
Model 1		0.91	3.78	
Intercept	5.106			
H^2/R (cm^2/ohm)	0.856			1.00
Model 2		0.92	3.59	
Intercept	8.970			
H^2/R (cm^2/ohm)	0.746			2.72
Sex[§]	4.050			2.72
Model 3		0.93	3.36	
Intercept	12.197			
H^2/R (cm^2/ohm)	0.732			2.74
Sex[§]	4.323			2.73
Age (years)	-0.073			1.01

Abbreviations: H^2/R, resistance index; R^2, coefficient of determination; SEE, standard error of the estimate; VIF, variation inflation factor.
[§] 1 if men; 0 if women.

Table 3. Validation of the developed predictive equations.

		Group level agreement				Individual level agreement
	Mean ± SD	r^2 (SEE)	CCC	Bias	95% LoA	Trend
FFM_{DXA} (kg)	50.0 ± 11.0	-	-	-	-	-
$FFM_{Foot\text{-}to\text{-}hand}$ (kg)	50.3 ± 11.4	0.89 (3.5)	0.947	0.37	-6.7; 7.5	r= 0.101; p=0.328
$FFM_{Direct\ segmental}$ (kg)	50.7 ± 11.1	0.93 (2.8)	0.965	0.69	-4.9; 6.3	r= 0.037; p=0.723
FM_{DXA} (kg)	18.0 ± 5.9	-	-	-	-	-
$FM_{Foot\text{-}to\text{-}hand}$ (kg)	17.9 ± 7.0	0.78 (2.8)	0.873	-0.14	-6.6; 6.6	r= 0.341; p=0.001
$FM_{Direct\ segmental}$ (kg)	17.5 ± 6.6	0.83 (2.5)	0.903	-0.55	-5.9; 4.8	r= 0.247; p=0.007

Note: r^2, coefficient of correlation; SEE, standard error of estimation; CCC, concordance correlation coefficient; LoA, limits of agreement.