Comparison of body composition measures assessed by bioelectrical impedance analysis (Tanita BC418MA) versus dual-energy X-ray absorptiometry in UK Biobank

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Abstract

Background: Bioelectrical impedance analysis (BIA) and dual-energy X-ray absorptiometry (DXA) serves as common modalities for body composition assessment. This study was aimed to evaluate the agreement between BIA and DXA measures in UK Biobank.

Methods: UK Biobank participants with body fat mass (FM) and fat-free mass (FFM) estimates obtained through BIA (Tanita BC418MA) and DXA concurrently were included. Correlation between BIA and DXA-derived estimates were assessed with Lin's concordance correlation coefficients. Bland-Altman and Passing-Boblok analyses were performed to quantify the the difference and agreement between BIA and DXA. Multivariable linear regression was used to identify predictors influencing the differences. Finally, prediction models were developed to calibrate BIA measures against DXA.

Results: The analysis included 34437 participants (female 51.4%, mean age 64.1 years at imaging assessment). BIA and DXA measurements were highly correlated (Lin's concordance correlation coefficient 0.94 for FM and 0.94 for FFM). BIA (Tanita BC418MA)-underestimates FM overall by 1.84 kg (23.77 vs. 25.61), and overestimated FFM overall by 2.56 kg (52.49 vs. 49.93). The BIA-DXA differences were associated with FM, FFM, BMI and waist circumference. The developed prediction models showed overall good performance in calibrating BIA data.

Conclusion: Our analysis exhibited strong correlation between BIA (Tanita BC418MA)- and DXA-derived body composition measures at a population level in UK Biobank. However, the BIA-DXA differences were observed at individual level and associated with individual anthropometric measures. Future studies may explore the use of prediction models to enhance the calibration of BIA measures for more accurate assessments in UK Biobank.

Keywords: body composition; fat mass; bioelectrical impedance analysis; dual-energy X-ray absorptiometry; UK Biobank

Introduction

Body composition measures, which estimate the amount of body fat mass (FM) and fat-free mass (FFM), are closely related to individual nutritional status and fitness, and have been recognised as pivotal risk factors for cardiovascular diseases and premature mortality [1–3]. Commonly used automated techniques for measuring body composition include bioelectrical impedance analysis (BIA) and dual-energy X-ray absorptiometry (DXA). BIA measures the impedance and resistance of the water component of human body to electrical currents assuming constant hydration of FFM, from which FFM is predicted based on specific equations; FM is calculated by taking the difference from total body weight [4]. During DXA assessment, the human body is scanned with X-rays of two different levels of energy and partitioned into FM, lean mass and bone mineral mass [5]. DXA is commonly considered more accurate than BIA [6]. However, BIA is more feasible to implement for large-scale studies, because BIA is easier to use, quicker, cheaper and does not involve exposure to radiation.

Previous studies have examined the concordance between BIA- and DXA-derived body composition measures using various BIA devices and in different populations, but results are inconsistent. Wan *et al.* used the Tanita MC180MA device (multi-frequency, with published equations) for BIA measurement in overweight adolescents, and observed a strong correlation between BIA- and DXA-measured FFM, although BIA seemed to slightly overestimate FFM [7]. Leahy *et al.*, using the same device (with proprietary equations), found that BIA's overestimation of FFM was similar in young males and females aged 18 to 30 years [8]. Among middle-aged patients (mean age 44.0 years), Achamrah *et al.* found that BIA (Bodystat QuadScan4000, multi-frequency, with proprietary equations) overestimated FFM and underestimated FM in those with body mass index (BMI) between 18.5 and 40 kg/m^2, whereas the opposite was observed in people with BMI < 16 kg/m^2 [9]. Sun *et al.* showed that BIA (Bodystat QuadScan4000, multi-frequency, with proprietary equations) overestimated body fat in people with lower body fat, while underestimated body fat in those with higher body fat [10]. For people aged > 60 years, the results also remained inconsistent. Steiner *et al.* found that in middle-aged individuals with respiratory disease, BIA (Bodystat 1500, multi-frequency, with proprietary equations) underestimated FFM in males while overestimated FFM in females [11]. De Silva *et al.* found that among 71 older women (mean age 71 years), BIA-measured body fat (Maltronn BioScan 916/916S,

single-frequency, with published equations) showed overall high agreement with DXA, although a wide variation existed [12]. Mally *et al*. found in a sample of 72 healthy individuals aged between 60 and 83 (mean age 69) years, that BIA (Tanita BC418MA, single frequency, with proprietary equations) overestimated FM in males and underestimated FM in females, and the difference was dependent on individual body composition [13]. Most of these studies had small sample sizes.

UK Biobank is a prospective cohort of half million individuals aged 40-69 years at recruitment [14]. During recruitment (2006-2010), 500,000 participants underwent body composition measures using BIA (Tanita BC418MA). Since 2014, up to 100 000 UK Biobank participants are undergoing both BIA (Tanita BC418MA) and DXA (Lunar iDXA Scanner) scans concurrently during an imaging assessment (more details in Methods). This provides a valuable opportunity for evaluating the accuracy of BIA-derived body composition measures against DXA in a large sample, which will help to inform the utility of using BIA body composition measures for the full cohort.

Methods

Participants

UK Biobank is a large biomedical database and research resource, comprising de-identified genetic, lifestyle and health information and biological samples from half million individuals [14]. Established to enable better understanding of the prevention, diagnosis and treatment of human diseases, UK Biobank was approved by the North West Multicenter Research Ethics Committee. The baseline assessment (2006-2010) included collection of data on socioeconomic status, anthropometry, lifestyle, health status, medication and medical history, along with a range of physical measures and biological sampling. BIA measurements for body composition were taken on all participants.

In 2014, UK Biobank initiated an multi-modal imaging assessment of up to 100 000 participants (by the end of 20204). Initial invitations for participants were sent to all living participants via email or post, followed by reminder emails sent at intervals of 2 weeks, 4 weeks, 6 months, 12 months and 24 months to non-responders. Imaging assessment visits were arranged for the individuals who consented to participate. Participants were excluded if they were unable to lie still, hold their breath voluntarily or hear instructions, or if they

had metal implants in their body [15]. The imaging visit involved concurrent DXA and BIA assessments. As of November 2023, body composition data derived from DXA and BIA during imaging visits have been made available for about 35 000 participants.

DXA

DXA assessments were carried out using Lunar iDXA Scanner (General Electric Healthcare, Wisconsin US). The scanner was calibrated daily following standard quality control protocols to maintain consistent precision. Participants were asked to lie flat on their back on the scanning couch for whole body scan. All operators had standardised central training, and all scans were performed according to standard operating procedures. Each scan acquisition was assessed in real time by the technicians for completeness, movement artefact and presence of any foreign bodies. More details on DXA assessment in UK Biobank can be found elsewhere [16].

BIA

BIA was performed using Tanita BC418MA Body Composition Analyser (Tanita, Japan). The analyser measured body impedance with a single high frequency current (50 kHz, 500 μA) and 8 metal contact electrodes. The device consists of a platform with four metallic foot pads and two hand-grips with metallic contacts. The four foot pads are made of pressure contact stainless steel and are arranged in pairs with two contacts for each foot. Each hand-grip contains one pair of contacts that are metal-plated to acrylonitrile butadiene styrene resin. The device measures body weight up to 200kg (with increment of 0.1kg) and body fat percentage between 1-75% (with increment of 0.1%). BIA assessment was carried out following the manufacturer's instruction manual. Before the assessment, participants were asked whether they had a pacemaker, and these individuals were excluded from subsequent assessment. Measurements were done in standing position with light indoor clothing. No overnight fasting was required, owing to feasibility on such a large cohort. Participants were asked to place their bare feet on the analyser platform, to keep their feet still and in good contact with the platform's metallic electrodes on platform (ensuring no obstruction by trousers), and to grip the two handles firmly with palm and thumb contacting metallic electrodes and arms hanging loosely by their sides. The device was cleaned after each participant. Body composition values were calculated automatically using undisclosed proprietary equations. The device produced segmental readings of fat percentage, FM, FFM and predicted muscle mass for trunk and four limbs, as well as impedance, FM, and FFM for

whole body. Data were centrally pre-processed by UK Biobank. More details on the device specifications and UK Biobank protocol for BIA measurement are found elsewhere [17,18].

Other measurements

Height was measured using a telescopic height rod device Seca 202 (Girodmedical, UK). Waist circumference (WC) was measured using a Seca 200cm tape measure. Participants were required to stand facing directly forward with feet shoulder-width apart and arms folded across their chest, ensuring no obstruction of clothing items. Seca tape was first passed around the smallest part of the trunk (the natural indent) and secured in place using the plastic fastener on the device. If a natural indent could not be found, the circumference was measured at umbilicus level. Participants were asked to breathe normally while the tape was adjusted to a comfortable position (neither too loose nor too tight). WC was recorded in centimetres on the outbreath. Townsend Deprivation Index is a postcode-derived measure of socioeconomic deprivation status. Educational attainment was categorised into lower than university, university and above. Ethnicity included White, Black, Asian, Mixed and others. Smoking and drinking status were coded as never, previous or current users. BMI was calculated as body weight (measured by Tanita BC418MA) divided by height squared. All anthropometric measures were taken during the imaging visits, and no repeated measurement was performed.

Statistical analysis

The primary body composition measures used in this analyses were whole body FM and FFM (in kg). In this study, we included participants with available body composition data derived from BIA (Tanita BC418MA) and DXA that passed quality control checks. This involved the exclusion of participants with: missing values for BIA (Tanita BC418MA) or DXA-derived body weight, FM or FFM; a value of zero for any of those variables; implausible values for body weight, FM or FFM (e.g., weight < 20 kg); where the difference between body weight and the sum of FM and FFM was larger than 0.2 kg in DXA or BIA (Tanita BC418MA) assessment; and for which the difference between BIA- and DXA-measured body weight was larger than 5% (relative to BIA (Tanita BC418MA) measurement), regardless of its direction. The 5% cutoff was an arbitrary decision, corresponding to the 99.7% percentile of its overall distribution.

For descriptive statistics, we used mean and standard deviation (SD) for continuous variables, and frequency and percentages for categorical variables.

We calculated Lin's concordance correlation coefficient for BIA- (Tanita BC418MA) and DXA-derived body composition measures. Scatter plots of DXA-derived FM and FFM against BIA (Tanita BC418MA) were generated to visualise their relationship. The difference between BIA- and DXA-derived FM and FFM were compared using paired sample t-test. Bland-Altman analysis was performed by plotting the differences between BIA and DXA (BIA - DXA) against their average values [19], from which the mean difference and its 95% limits of agreement were obtained to show the bias and its distribution. Proportional bias was assessed via the slope estimates and their 95% confidence intervals (CIs). Passing-Bablok regression was also performed [20]. We performed subgroup analysis by sex and BMI categories (BMI < 25, 25 ≤ BMI < 30 [noted as 25-30, thereafter], and ≥ 30 kg/m^2).

To investigate potential factors that could account for the difference between BIA and DXA values, we performed multivariable linear regression, which included the following variables: age, BMI, height, waist circumference, DXA-derived FM and FFM. We performed a sensitivity analysis by excluding participants with outlier measurements based on the criteria described elsewhere [21]. Based on the identified risk factors, we developed linear models to calibrate BIA (Tanita BC418MA)-derived FFM against DXA FFM values, for each sex and BMI subgroups. Subsequently, FM can be obtained by deducting predicted FFM from body weight. Variance inflation factor (VIF) values was used to assess multicollinearity between the variables. In each subgroup, we randomly split the sample size into a training set and a testing set (80%:20%), as previously performed in methodological studies [22,23]. R^2 was estimated in the training set and the testing set to evaluate the overall goodness of fit. We fitted the predicted FFM on the actual DXA FFM measures in a linear model, to derive the calibration slope and calibration-in-the-large (i.e., regression intercept) to evaluate the model calibration in the testing set. Ideally, the calibration slope should be one and the calibration-in-the-large should be zero [24]. Bland-Altman analysis was performed to compare the predicted FFM and the DXA-derived FFM values. Additionally, we developed a prediction model for FFM values using BIA (Tanita BC418MA) derived impedance values, height, weight, age, WC and BMI; these variables were selected based on the identified risk factors and previous studies [4,25].

All analyses were performed in R software (version 4.1.1)

Results

Basic characteristics

Among the UK Biobank cohort, 34 437 participants (female 51.4%, age 55.2 [SD 7.6] years at baseline and 64.1 [SD 7.8] years at Imaging visit) were included in analysis (Figure 1). The baseline characteristics are shown in Table 1 and Supplementary table 1. Mean height and weight were 169.22 (9.28) cm and 76.25 (15.22) kg, respectively. The majority of participants were of White ancestry (96.3%), 45.6% attended higher education, 95.2% were current drinkers, and 6.4% were current smokers. Males were more likely to be older, more highly educated, and current drinkers and smokers. Compared to the whole UK Biobank cohort, participants included in this analysis (i.e. who attended the imaging assessment) were more likely to be younger, White, more affluent, better educated, current drinker, but less likely to be smokers; however, height, body weight, WC and BMI were similar.

Correlations between BIA (Tanita BC418MA) and DXA

BIA (Tanita BC418MA) and DXA body composition measures were highly correlated overall, with Lin's concordance correlation coefficient of 0.94 for FM and 0.94 for FFM; however, the correlation varied across sex and BMI subgroups (Table 2). Females showed higher correlation than males in BIA (Tanita BC418MA)- and DXA- derived FM (0.97 vs. 0.90) and FFM (0.87 vs. 0.82). For FM, the lowest correlation was observed in males with BMI between 25-30 kg/m^2 (0.67), while the highest in females with BMI ≥ 30 kg/m^2 (0.95). For FFM, the lowest correlation was observed in males with BMI ≥ 30 kg/m^2 (0.71), while the highest in females with BMI < 25 kg/m^2 (0.84). Scatter plots showed agreement between the two measures, with R^2 ranging from 69% to 94% across sex and BMI subgroups, but suggested that BIA overestimated FFM in males and females, but underestimated FM, especially in males (Figure 2). Sensitivity analysis excluding outliers showed similar results (Supplementary figure 1).

Differences between BIA (Tanita BC418MA) and DXA

The overall BIA (Tanita BC418MA)-derived FM was lower than DXA (23.77 vs. 25.61, difference -1.84 kg), while BIA-derived FFM was higher than DXA (52.49 vs. 49.93, difference 2.56 kg), which was consistent in all sex and BMI subgroups. BIA-DXA differences were larger in males than in females for both FM and FFM (-2.81 kg vs. -0.92 kg for FM, 3.54 kg vs. 1.64 kg for FFM, respectively). Looking at differences in percentage, BIA underestimated FM

by 11.4% in males and 3.5% in females, which was consistent across BMI subgroups. In contrast, BIA overestimated FFM by 6.1% and 3.9% in males and females, respectively, with smaller difference in participants with lower BMI levels (Table 3).

Bland-Altman plots showed similar patterns, but there was wide variation in the BIA-DXA difference at an individual level, demonstrated by the wide 95% limits of agreement, suggesting proportional bias. For FM, BIA-DXA difference was associated with individual FM in males across all BMI categories, but the association was much weaker in females. For FFM, the association between BIA-DXA difference and individual FFM was positive in males, but negative in females. However, the association strengths varied across BMI subgroups. (Figure 3)

Figure 4 shows the results of Passing-Bablok regression for each sex and BMI subgroup. The slope estimates were significantly different from 1 for most subgroups, indicating systematic bias between the two methods, except for FM in females with BMI < 25 or ≥ 30 kg/m^2.

Table 4 shows the results of multivariable regressions on BIA (Tanita BC418MA)-DXA differences. These variables together explained 34.8-46.2% of the variation, with a higher proportion explained in males than in females. After adjusting for age, we found BMI, waist circumference, height, individual FM and FFM were associated with BIA-DXA differences. More specifically, FM was negatively associated with the difference in FM in both males (beta [95% confidence interval]: -0.37 [-0.40, -0.34]) and females (-0.25 [-0.27, -0.23]), while FFM was positively associated with it (0.06 [0.03, 0.09] for males and 0.13 [0.11, 0.15] for females). For the differences in FFM, individual FFM showed a negative association in males (-0.37 [-0.39, -0.34]) and females (-0.36 [-0.38, -0.34]), but FM showed a positive association (0.11 [0.08, 0.14] for males and 0.06 [0.04, 0.08] for females). BIA (Tanita BC418MA)'s underestimation of FM was smaller in people with low FM, but the overestimation of FFM was smaller in people with high FFM. BMI showed consistent positive associations with differences in FM and in FFM, for both males and females. Waist circumference was positively associated with FM and FFM, consistent in both sexes.

Using the identified risk factors for BIA-DXA differences as the predictors, we developed prediction models to calibrate BIA (Tanita BC418MA) FFM against DXA values for each sex and BMI subgroup (Table 5). VIF values showed no evidence for multicollinearity between these predictors (Supplementary table 2). Overall, the prediction models yielded high R^2 (> 80%) for FFM prediction, which was similar in the training and testing sets. The highest R^2

was observed in females with BMI ≥ 30 kg/m^2 (85.6% and 87.5% for training and testing data, respectively) and the lowest in females with BMI < 25 kg/m^2 (81.4% and 80.5% for training and testing data, respectively). Most models demonstrated good calibration in the testing sets, as we observed no evidence for calibration slopes deviating from one and for calibration-in-the-large deviating from zero. Bland-Altman analysis for comparing the predicted and DXA-derived FFM showed very small bias, although proportional bias may still exist (supplementary figure 2).

Compared to the prediction equations using BIA derived FM and FFM, prediction equations using BIA (Tanita BC418MA) impedance data showed similar R^2 for males, but lower R^2 for females, especially for those with BMI < 25 kg/m^2; for example, the R^2 were 69.2% vs. 81.4% in the training set, and 72.4% vs. 80.5% in the testing set. (Supplementary table 3)

Discussion

The present study demonstrated overall strong correlation between BIA (Tanita BC418MA) and DXA in measuring body FM and FFM within UK Biobank, although small differences existed at the individual level. Compared with DXA, the BIA (Tanita BC418MA) exhibited trends of underestimating FM by an average of 1.84 kg, and overestimating FFM by 2.56 kg. The differences between BIA and DXA were more pronounced in males than in females, and were additionally linked with individual body composition and other anthropometric measures.

The observed high correlation between BIA and DXA was consistent with previous research in people of various age groups [7–10,26,27]. However, differences between the two methods exist at individual level, as suggested by the wide limits of agreements, with patterns that BIA underestimated FM and overestimated FFM. Alves *et al.* found that single frequency BIA (BioStat 1500) underestimated FM by 2.2 kg, and overestimated FFM by 3.7 kg in 55 individuals with heart failure (mean age 56 years), which were larger than our estimates [28]. Using the same BIA device (with proprietary equations) as in UK Biobank, Mally *et al.* [13] found that BIA overestimated FM by 5.8kg but underestimated FFM by 1.0kg in 40 males (mean age 69), while BIA underestimated FM by 0.8kg and overestimated FFM by 3.9kg in 32 females, which was inconsistent with our findings; this could be due to its small sample size. Volgyi et al. [29] used the same device in a larger sample size of 168 healthy adults (mean age 55 years) and showed that BIA overestimates FFM by 2.4 kg, very close to our estimates.

Although the observed patterns remained qualitatively consistent across all sex and BMI subgroups, quantitative variation was present. Existing research presented mixed evidence regarding this matter. In terms of sex, the BIA-DXA differences were more pronounced in males compared to females, aligning with the findings of Liao *et al*. in a cohort of 239 healthy Chinese participants [26]. Conversely, Leahy *et al*. reported larger BIA-DXA differences in females than in males in a younger sample of 400 individuals aged 18-29 years [8]. Concerning BMI categories, our investigation revealed that individuals with higher BMI levels demonstrated a notable amplification of BIA's overestimation in FFM, in both absolute kilogram and percentage metrics; however, a larger extend of underestimation in FM in people with higher BMI levels was observed only when measured in kilogram, but not in percentage. Achamrah *et al*. similarly found that BIA-DXA difference in FM and FFM varied by BMI levels, but did not recognise a clear pattern, probably due to inclusion of both sexes in their investigation [9]. Sun *et al*. found the BIA-DXA difference in body fat percentage was positively associated with individual BMI [10], similar to our findings. Shafer *et al*. also found larger BIA-DXA differences in obese individuals compared to those with overweight or normal weight among males, and they also suggested the potential influences of other obesity measures, such as waist circumferences [30]. As suggested by a previous study [31], this variation across obesity level was possible due to hydration levels. Obesity and specifically increased amounts of adipose tissue directly affect the validity of bioimpedance to estimate FFM, since adipose tissue contains water in the extracellular space, but that is measured as body water and reported as impedance. Therefore, it is important to distinguish extracellular and intracellular water, and to more accurately estimate extracellular-to-intracellular water ratio in BIA body composition assessment.

Our analysis revealed that the BIA-DXA differences in UK Biobank exhibited associations with various factors, including sex, BMI, waist circumference, as well as body composition measures. With adjustment of covariates, BIA's underestimation of FM was smaller in people with lower FM, but the overestimation of FFM was smaller in those with higher FFM. This was consistent with the findings of Sun *et al*. that BIA-DXA difference in FM percentage was negatively associated with DXA-derived FM percentage, after adjusted for BMI, sex and age [10]. We also observed negative associations between FM differences with BMI and waist circumference. Therefore, the BIA-DXA difference in FM was smaller in males who had

higher BMI, higher waist circumference and lower FM, and in females who additionally had higher FFM and height.

The presence of individual BIA-DXA difference indicated the potential for bias in body composition assessment using BIA for personal health monitoring and clinical practice. In light of this, the development of prediction models that calibrated BIA values against DXA was important.

To address individual-level discrepancies between BIA and DXA, we derived two sets of prediction models based on the risk factors identified in the regression analyses, one using BIA device output FM and FFM, while the other using impedance data. The models were stratified by sex and BMI levels, to reflect the potential effect modification of sex and BMI. Fundamentally the two sets of models were both functions of BIA-impedance, together with other anthropometric measures. Notably, our models demonstrated good overall performance in both training and testing sets, such as high R^2, lower bias and narrower LOA. It turned out that the models using BIA-FM and -FFM slightly outperformed the models using BIA-impedance, especially in females with lower BMI levels, although they had similar performance in males. We recommend future UK Biobank studies use the prediction models using BIA-FM and -FFM (or at least as a sensitivity analysis) if they aim to calibrate BIA body composition data, while the prediction models using BIA-impedance are more generalizable to other studies using the same device when the BIA-FM and -FFM data are not available.

BIA devices measure body impedance, and employ regression equations to predict FFM, subsequently obtaining FM from deducting FFM from body weight [32]. Although the in-built equation of the BIA analyser used in UK Biobank (Tanita BC418) is undisclosed, which also contribute the inconsistency of previous evidence comparing BIA and DXA, according to the device manual, the equation was derived from a case-mix of western and Asian populations. The same device has been used and compared against DXA in other studies, which similarly demonstrated strong correlation with DXA with individual-level variation in various western and Asian populations [29,33,34]. Although UK Biobank consists of multiple ethnicities, the dominating ethnicity in UK biobank was British White (approximately 95%), which enhances the reliability of BIA-derived body composition estimates, as previous research has shown that BIA performs better in a population of single ethnicity, than in a complex multi-ethnic population [32].

Prior studies have validated and compared multiple BIA equations for estimating body composition using DXA as reference in various populations, for example, people with obesity [35], in cancer patients [36], in hospitalised elderly patients [37], in healthy elderly people [38], and in obese adolescents [39], and in Chinses dialysis patients [40], but the findings remain inconclusive regarding their performance. Those equations commonly incorporate variables like resistance and reactance, weight, height, BMI, and sex [25]. All these models showed differed performance in external populations, and use of correction factor was recommended when applying them to new populations [38]. We did not validate these equations in this study, because first, it was out of the scope of this study, and second, BIA resistance and reactance data were unavailable in UK Biobank. Nevertheless, our study developed its own prediction models using DXA as reference and similar predictors, the BIA variables (FM and FFM) in our models are inherently linked to resistance and reactance, aligning with the essence of previously published models.

The high correlation between the two methods indicates that BIA (Tanita BC418MA) serves as a reliable surrogate for DXA at population level in UK Biobank, although the derived prediction models are required to calibrate the BIA-DXA differences observed at individual level. In future epidemiological studies of associations of body composition with health outcomes, researchers could consider using either baseline BIA-measured FM and FFM or calibrated values based on the prediction models. Compared to using only DXA-derived FM and FFM data obtained during imaging visits, this would substantially increase sample size (500 000 vs. 35 000 [as undertaken in this analysis, or 100 000 when the imaging study is completed]) and would maximise the follow up period (starting from 2006/2010 vs. 2014/2024), thus increasing statistical power while maintaining high accuracy of measurement. Moreover, BIA has logistic advantages of low cost, rapidity, high accessibility, convenience and free of radiation. It is important to note that when using BIA for body composition assessment, various factors may influence the results, including changes in quantity and distribution of body water (e.g., diet, exercise), body skin temperature and ambient temperature. [32].

This study has several limitations. First, the analysis was based on data from 35000 in UK Biobank, because the recruitment in the imaging study is still in progress. Although the current sample size has sufficiently powered to detect a correlation coefficient > 0.8 (power > 99.9%), it is essential to acknowledge that our sample is slightly younger compared to the

whole UK Biobank cohort, but the body size and body composition measures are comparable. Second, the comparison did not include lean mass. Because BIA is a two-component model, in which human body is partitioned into FM and FFM. By contrast, DXA is a three-component model, in which FFM is further partitioned into lean mass and bone mineral mass. Therefore, BIA FFM is not directly comparable to DXA lean mass. Third, we did not compare segmental body composition, such as trunk, limbs and visceral parts. In UK Biobank, BIA provided segmental FFM for various body regions, whereas DXA only had lean mass for different body regions. Fourth, this study did not evaluate the agreement between BIA and DXA in longitudinally monitoring changes in body composition, due to the cross-sectional design, although prior studies have shown that BIA can assess FM changes longitudinally as well as DXA [27]. Fifthly, while DXA measurements was used as the reference, the gold standard for measuring body composition is four-component model (which was not available), to which DXA may have some systematic bias [41]. Lastly, the accuracy of BIA is highly dependent on the device and the measurement protocol. In this study, we used Tanita BC418MA with undisclosed proprietary equations, and some quality control procedures, such as overnight fasting and urinating before assessment were not possible to adhere to. All these factors could potentially contribute to the discrepancy between BIA and DXA measurement.

Conclusions

This study of 35000 UK Biobank participants revealed high correlation between BIA (Tanita BC418MA)- and DXA-derived body composition measures at population level. Individual level differences were observed and linked to individual anthropometric measures; to address this, we developed prediction models for calibrating BIA (Tanita BC418MA)-data against DXA, affirming the overall efficacy of BIA (Tanita BC418MA) as a good surrogate for DXA. We recommend that future studies utilizing UK Biobank data consider employing either original or calibrated BIA (Tanita BC418MA)-derived body composition measures to enhance statistical power for investigating associations between body composition and health outcomes.

Ethics approval

The Research Tissue Bank approval from its governing Research Ethics Committee was obtained for the UK Biobank, as recommended by the National Research Ethics Service. Permission to use the UK Biobank Resource was approved by the access subcommittee of the UK Biobank Board. Written informed consent was obtained for all participants.

The UK Biobank has ethical approval from the North West Multi-centre Research Ethics Committee (MREC reference 21/NW0157) as a Research Tissue Bank and therefore no separate ethical approval was required to analyse UK Biobank data. UK Biobank data for this study was accessed in April 2023.

Data sharing statement

The data that support the findings of this study are available from the UK Biobank but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. The UK Biobank resources are however available and can be accessed through applications on their website (https://www.ukbiobank.ac.uk/). Analytic codes are available upon reasonable request.

Conflict of interest

There is no conflict of interest.

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Author contribution

QF and NA contributed to the study conception and design. Material preparation, data collection and analysis were performed by QF. The first draft of the manuscript was written by QF and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

None .

Figure legend

Figure 1: Flowchart of participant selection

Figure 2: Scatter plots of BIA (Tanita BC418MA)- and DXA-measured fat mass (kg) and fat free mass (kg).
The colored solid lines are the linearly fitted lines. The gray dashed lines are reference lines (y = x), indicating perfect agreement between BIA and DXA. BIA: bioelectrical impedance analysis assessed using Tanita BC418MA device. DXA: dual-energy X-ray absorptiometry.

Figure 3: Bland-Altman plots for BIA (Tanita BC418MA)- and DXA-measured fat mass (kg) and fat free mass (kg) stratified by sex and BMI groups.
Showing the average bias and its 95% limits of agreement. Shaded band: 95% confidence interval. BIA: bioelectrical impedance analysis assessed by Tanita BC418MA. DXA: dual-energy X-ray absorptiometry.

Figure 4: Passing-Bablok plots for BIA (Tanita BC418MA)- and DXA-measured fat mass (kg) and fat free mass (kg) stratified by sex and BMI groups.
Solid black line: line of identity (y = x). Red line: Passing-Bablok regression line and its 95% confidence band. BIA: bioelectrical impedance analysis assessed by Tanita BC418MA. DXA: dual-energy X-ray absorptiometry. BMI: body mass index, kg/m^2.

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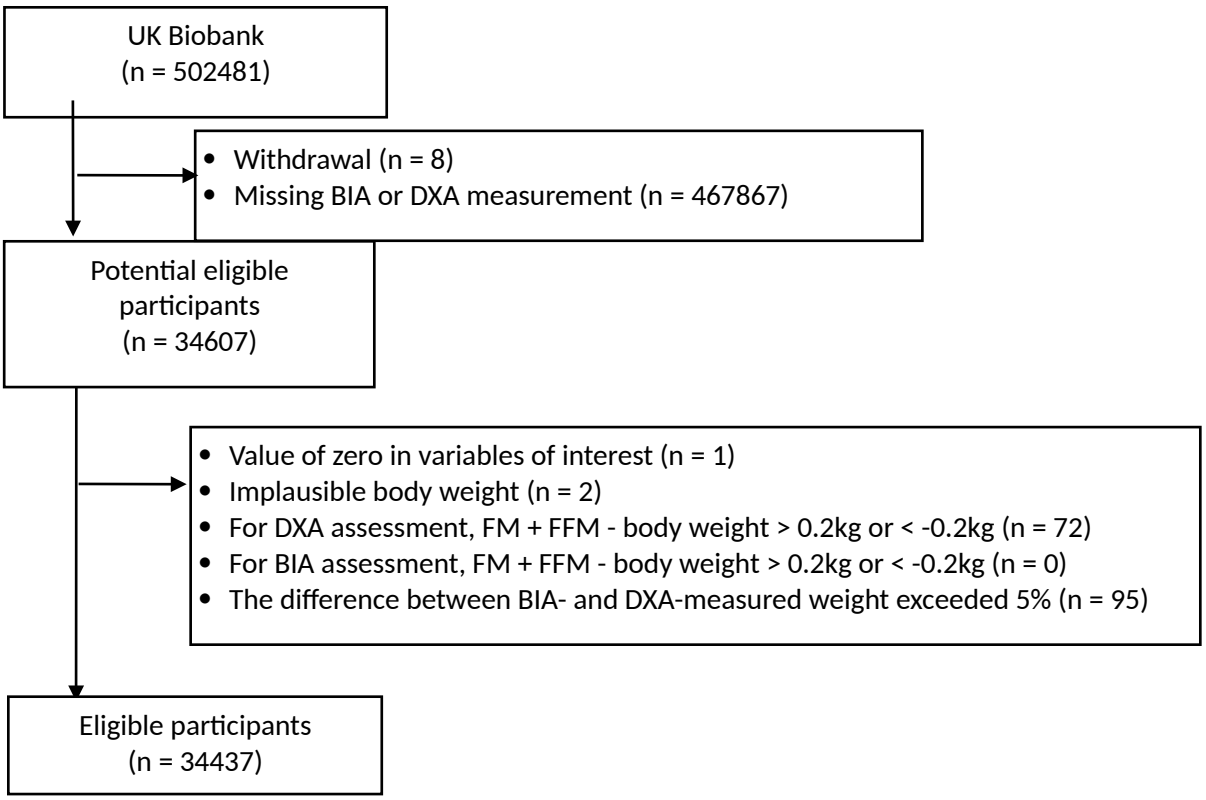
Figure 1: Flowchart of participant selection



Eligible participants
(n = 34437)

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636 *Table 1: Basic characteristics of eligible participants and the whole UK Biobank cohort*

	Females (n = 17686)	Males (n=16751)	All (n = 34437)	Whole UK Biobank (n = 502481)	P value for difference females vs. males
Age [at baseline], years	54.53 (7.44)	55.96 (7.68)	55.22 (7.59)	56.53 (8.09)	< 0.01
Age [at Imaging visit], years	63.42 (7.61)	64.85 (7.85)	64.12 (7.76)	NA	< 0.01
Townsend Deprivation Index	-1.83 (2.74)	-1.94 (2.74)	-1.89 (2.74)	-1.23 (3.09)	< 0.01
Height, cm	162.74 (6.27)	176.06 (6.65)	169.22 (9.28)	169.11 (9.26)	< 0.01
BIA-derived body weight, kg	69.10 (13.12)	83.80 (13.54)	76.25 (15.22)	76.31 (15.29)	< 0.01
DXA-derived body weight, kg	68.39 (12.91)	83.09 (13.31)	75.54 (15.02)	NA	< 0.01
Waist circumference, cm	82.10 (11.72)	93.81 (10.71)	87.80 (12.67)	88.55 (12.82)	< 0.01
Body mass index, kg/m^2	26.09 (4.74)	27.01 (3.94)	26.54 (4.39)	26.59 (4.46)	< 0.01
Ethnicity, White	17046 (96.38)	16116 (96.21)	33162 (96.3)	472673 (94.07)	0.07
Education, higher education	7744 (43.79)	7975 (47.61)	15719 (45.65)	161153 (32.07)	0.03
Drinking, current user	16698 (94.41)	16089 (96.05)	32787 (95.21)	460342 (91.61)	< 0.01
Smoking, current user	938 (5.30)	1275 (7.61)	2213 (6.43)	52975 (10.54)	< 0.01

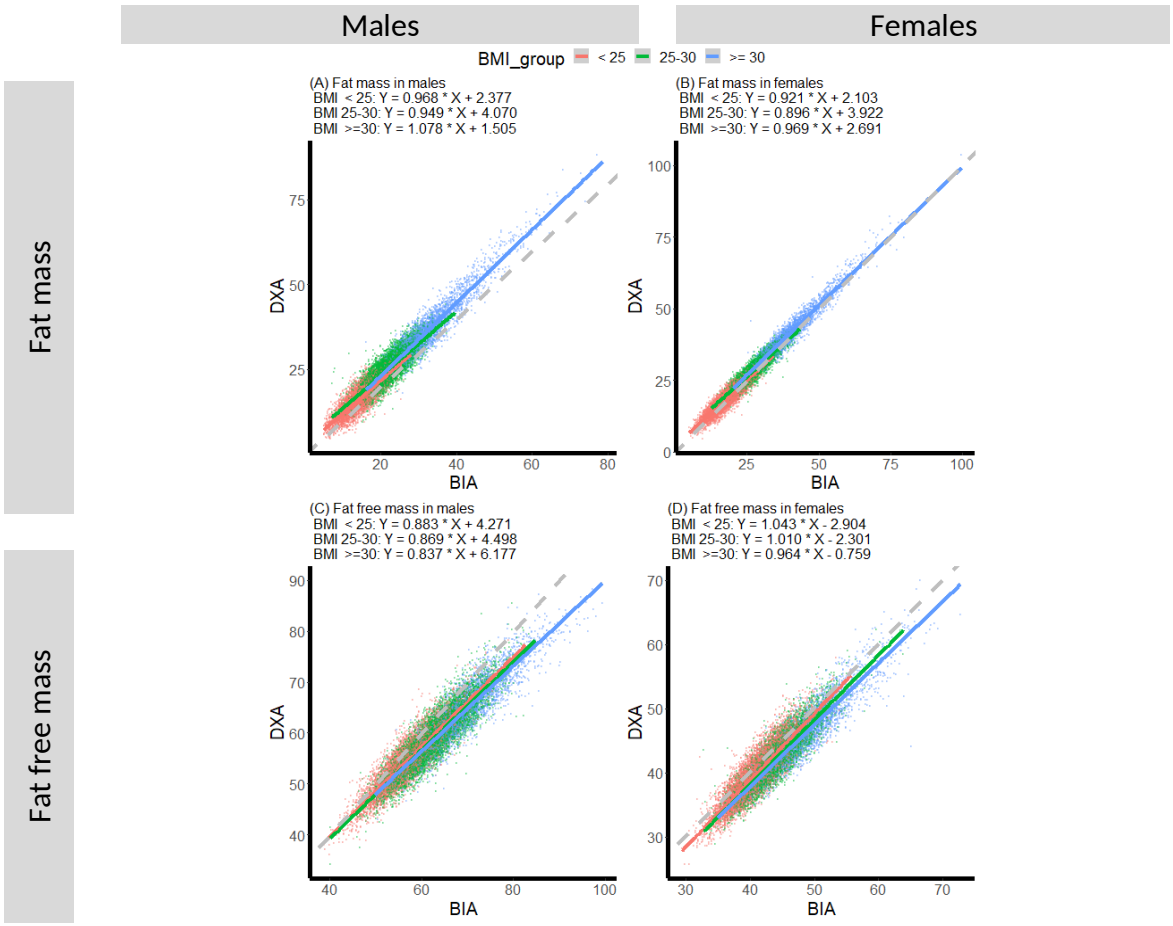
637 The table shows mean(standard deviation) for continuous variables, and frequency
638 (percent) for categorical variables. P values for difference between females and males were
639 obtained from t test for continuous variables and chi-square test for categorical variables.
640 Anthropometric variables (height, body weights, body mass index) were measured at
641 imaging visit, while other variables were measured at baseline, unless specifically
642 mentioned.
643

644

645 *Table 2: Pearson correlation coefficients and Lin concordance coefficients between BIA (Tanita*
646 *BC418MA)-measured and DXA-measured fat mass and fat-free mass*

		Lin's concordance coefficient	
	n	Fat mass	Fat free mass
All	34437	0.94 (0.94, 0.94)	0.94 (0.94, 0.94)
Males	16751	0.90 (0.89, 0.90)	0.82 (0.81, 0.82)
BMI < 25 kg/m^2	5467	0.74 (0.73, 0.75)	0.82 (0.81, 0.83)
BMI 25-30 kg/m^2	8107	0.67 (0.66, 0.68)	0.75 (0.74, 0.75)
BMI ≥ 30 kg/m^2	3177	0.82 (0.81, 0.83)	0.71 (0.70, 0.72)
Females	17686	0.97 (0.97, 0.97)	0.87 (0.87, 0.87)
BMI < 25 kg/m^2	8405	0.91 (0.90, 0.91)	0.84 (0.83, 0.84)
BMI 25-30 kg/m^2	6118	0.88 (0.87, 0.88)	0.80 (0.78, 0.80)
BMI ≥ 30 kg/m^2	3163	0.95 (0.95, 0.96)	0.82 (0.81, 0.82)

647 BIA: bioelectrical impedance analysis assessed with Tanita BC418MA. DXA: dual-energy X-
648 ray absorptiometry. BMI: body mass index



	Males		Females	
BMI subgroups	Slope and intercept	R^2	slope	R^2
Fat mass				
BMI < 25 kg/m^2	Slope: 0.968 (0.951, 0.985) Intercept: 2.377 (2.112, 2.641)	69	Slope: 0.921 (0.913, 0.930) Intercept: 2.103 (1.938, 2.267)	84
BMI 25-30 kg/m^2	Slope: 0.949 (0.935, 0.963) Intercept: 4.070 (3.765, 4.375)	70	Slope: 0.896 (0.885, 0.906) Intercept: 3.922 (3.635, 4.209)	83
BMI ≥ 30 kg/m^2	Slope: 1.078 (1.064, 1.091) Intercept: 1.505 (1.046, 1.965)	88	Slope: 0.969 (0.960, 0.977) Intercept: 2.691 (2.331, 3.051)	94
Fat free mass				
BMI < 25 kg/m^2	Slope: 0.883 (0.872, 0.894) Intercept: 4.271 (3.616, 4.926)	81	Slope: 1.043 (1.031, 1.054) Intercept: -2.904 (-3.378, -2.431)	79
BMI 25-30 kg/m^2	Slope: 0.869 (0.860, 0.878) Intercept: 4.498 (3.919, 5.077)	81	Slope: 1.010 (0.998, 1.023) Intercept: -2.301 (-2.866, -1.737)	80
BMI ≥ 30 kg/m^2	Slope: 0.837 (0.823, 0.851) Intercept: 6.177 (5.216, 7.138)	82	Slope: 0.964 (0.950, 0.979) Intercept: -0.759 (-1.479, -0.040)	84

Figure 2: Scatter plots of BIA (Tanita BC418MA)- and DXA-measured fat mass (kg) and fat free mass (kg).

The colored solid lines are the linearly fitted lines. The gray dashed lines are lines of identity ($y = x$), indicating perfect agreement between BIA and DXA. BIA: bioelectrical impedance analysis assessed using Tanita BC418MA device. DXA: dual-energy X-ray absorptiometry.

Table 3: Comparison of fat mass (kg) and fat free mass (kg) obtained by BIA (Tanita BC418MA) versus by DXA.

	n	BIA	DXA	Difference (95%CI)	Difference %	p	95% LOA
Fat mass							
All	34437	23.77 (8.81)	25.61 (9.25)	-1.84 (-1.87, -1.81)	7.18	<0.01	-6.70, 3.02
Males	16751	21.85 (7.80)	24.67 (8.82)	-2.81 (-2.86, -2.77)	11.39	<0.01	-8.04, 2.41
BMI < 25 kg/m^2	5467	15.04 (3.68)	16.95 (4.28)	-1.90 (-1.96, -1.84)	11.21	<0.01	-6.55, 2.75
BMI 25-30 kg/m^2	8107	22.11 (4.04)	25.05 (4.58)	-2.94 (-3.00, -2.89)	11.74	<0.01	-7.89, 2.00
BMI ≥ 30 kg/m^2	3177	32.91 (7.32)	36.97 (8.39)	-4.06 (-4.16, -3.96)	10.98	<0.01	-9.79, 1.67
Females	17686	25.59 (9.31)	26.50 (9.56)	-0.92 (-0.95, -0.89)	3.47	<0.01	-4.58, 2.75
BMI < 25 kg/m^2	8405	18.79 (4.36)	19.41 (4.38)	-0.63 (-0.66, -0.59)	3.25	<0.01	-4.11, 2.86
BMI 25-30 kg/m^2	6118	27.55 (4.29)	28.60 (4.23)	-1.05 (-1.10, -1.00)	3.67	<0.01	-4.61, 2.51
BMI ≥ 30 kg/m^2	3163	39.84 (8.04)	41.28 (8.05)	-1.44 (-1.51, -1.37)	3.49	<0.01	-5.48, 2.60
Fat free mass							
All	34437	52.49 (11.13)	49.93 (10.14)	2.56 (2.53, 2.59)	5.13	<0.01	-2.56, 7.69
Males	16751	61.96 (7.47)	58.42 (6.75)	3.54 (3.50, 3.58)	6.06	<0.01	-2.05, 9.13
BMI < 25 kg/m^2	5467	57.00 (5.62)	54.61 (5.52)	2.40 (2.33, 2.46)	4.39	<0.01	-2.52, 7.32
BMI 25-30 kg/m^2	8107	62.38 (5.89)	58.70 (5.70)	3.68 (3.63, 3.74)	6.27	<0.01	-1.44, 8.81
BMI ≥ 30 kg/m^2	3177	69.43 (7.28)	64.29 (6.74)	5.14 (5.04, 5.25)	8.00	<0.01	-0.96, 11.25
Females	17686	43.52 (4.81)	41.89 (4.92)	1.64 (1.61, 1.66)	3.92	<0.01	-2.21, 5.49
BMI < 25 kg/m^2	8405	41.07 (3.43)	39.92 (4.02)	1.15 (1.11, 1.19)	2.88	<0.01	-2.47, 4.78
BMI 25-30 kg/m^2	6118	44.00 (3.64)	42.15 (4.12)	1.84 (1.80, 1.89)	4.37	<0.01	-1.80, 5.48
BMI ≥ 30 kg/m^2	3163	49.12 (4.95)	46.60 (5.20)	2.52 (2.45, 2.59)	5.41	<0.01	-1.55, 6.59

Difference = BIA – DXA. P: p value for paired sample t test. Difference % = difference / DXA measurement. LOA: limits of agreement based on Bland-Altman analysis. BIA: bioelectrical impedance analysis assessed by Tanita BC418MA. DXA: dual-energy X-ray absorptiometry. BMI: body mass index, kg/m^2.

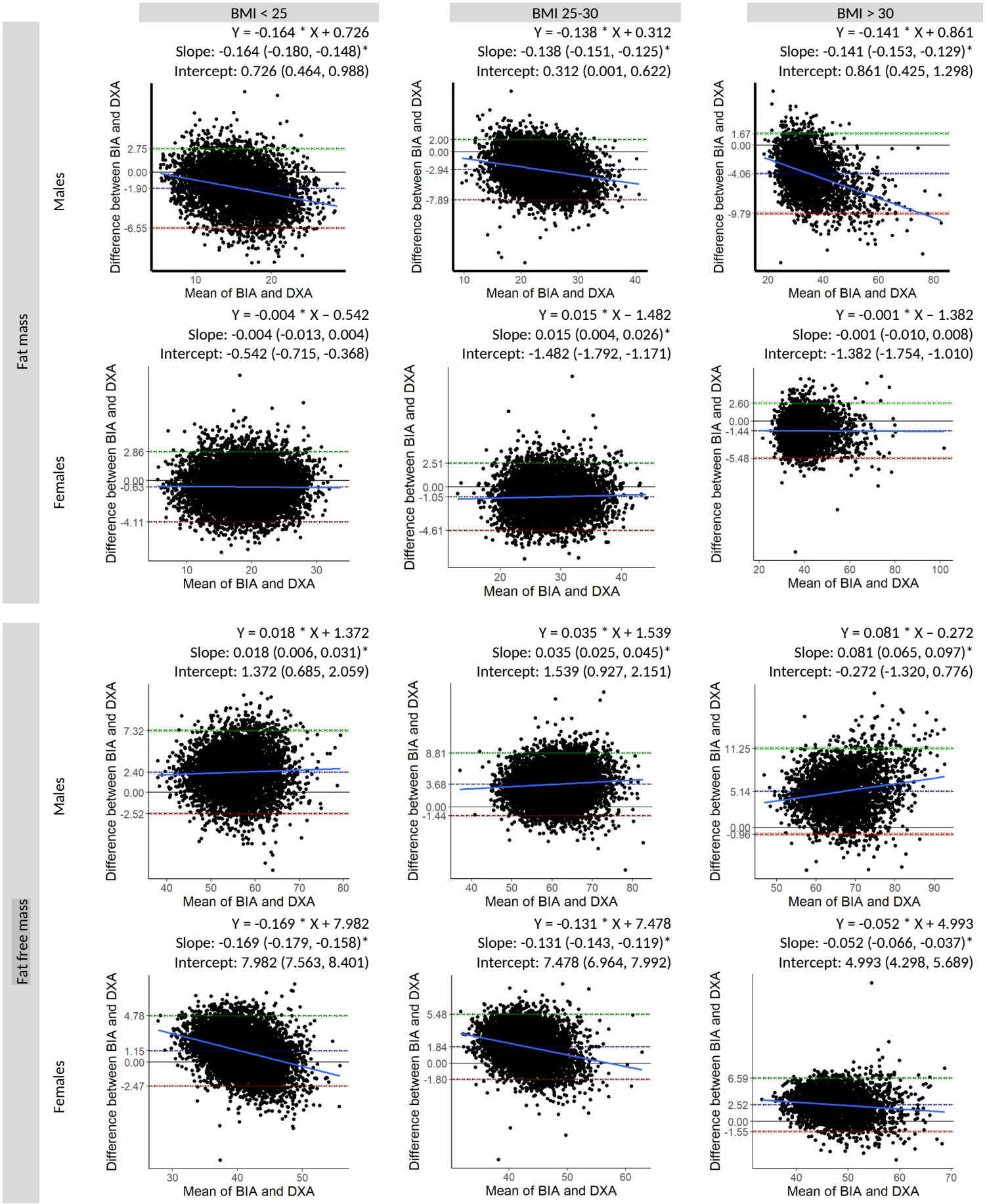

BMI < 25
BMI 25-30
BMI > 30
Fat mass
Fat free mass
Males
Females
Y = -0.164 * X + 0.726
Slope: -0.164 (-0.180, -0.148)*
Intercept: 0.726 (0.464, 0.988)
Y = -0.138 * X + 0.312
Slope: -0.138 (-0.151, -0.125)*
Intercept: 0.312 (0.001, 0.622)
Y = -0.141 * X + 0.861
Slope: -0.141 (-0.153, -0.129)*
Intercept: 0.861 (0.425, 1.298)
Y = -0.004 * X – 0.542
Slope: -0.004 (-0.013, 0.004)
Intercept: -0.542 (-0.715, -0.368)
Y = 0.015 * X – 1.482
Slope: 0.015 (0.004, 0.026)*
Intercept: -1.482 (-1.792, -1.171)
Y = -0.001 * X – 1.382
Slope: -0.001 (-0.010, 0.008)
Intercept: -1.382 (-1.754, -1.010)
Y = 0.018 * X + 1.372
Slope: 0.018 (0.006, 0.031)*
Intercept: 1.372 (0.685, 2.059)
Y = 0.035 * X + 1.539
Slope: 0.035 (0.025, 0.045)*
Intercept: 1.539 (0.927, 2.151)
Y = 0.081 * X – 0.272
Slope: 0.081 (0.065, 0.097)*
Intercept: -0.272 (-1.320, 0.776)
Y = -0.169 * X + 7.982
Slope: -0.169 (-0.179, -0.158)*
Intercept: 7.982 (7.563, 8.401)
Y = -0.131 * X + 7.478
Slope: -0.131 (-0.143, -0.119)*
Intercept: 7.478 (6.964, 7.992)
Y = -0.052 * X + 4.993
Slope: -0.052 (-0.066, -0.037)*
Intercept: 4.993 (4.298, 5.689)
Difference between BIA and DXA
Mean of BIA and DXA

Figure 3: Bland-Altman plots for BIA (Tanita BC418MA)- and DXA-measured fat mass (kg) and fat free mass (kg) stratified by sex and BMI groups.

Showing the average bias and its 95% limits of agreement. Shaded band: 95% confidence interval. BIA: bioelectrical impedance analysis assessed by Tanita BC418MA. DXA: dual-energy X-ray absorptiometry. BMI: body mass index, kg/m^2.

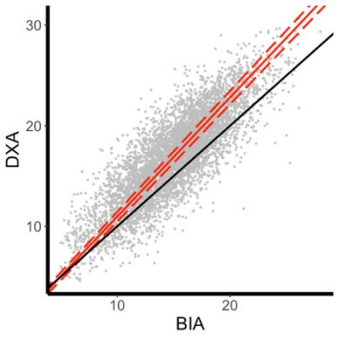
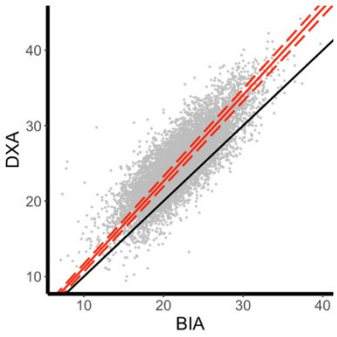
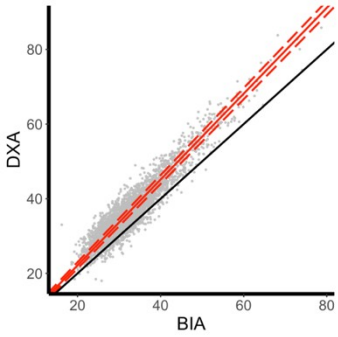
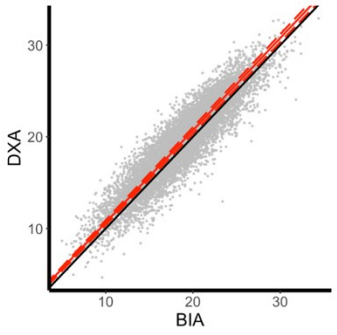
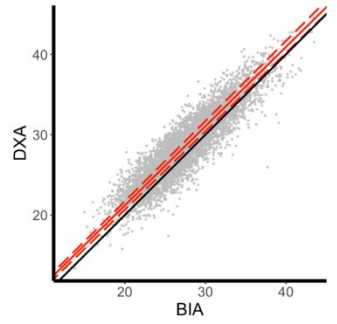
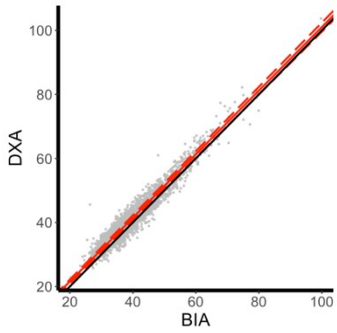
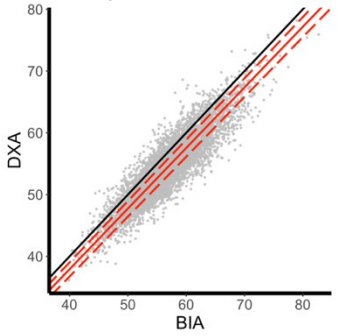
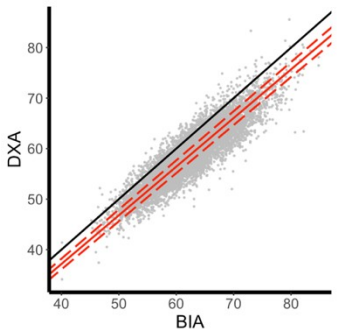
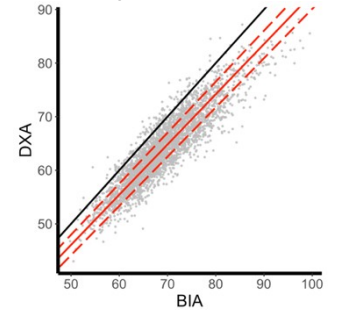
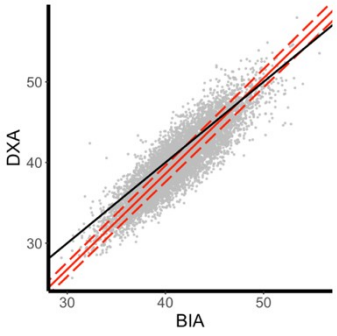
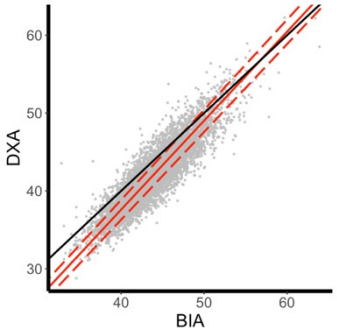
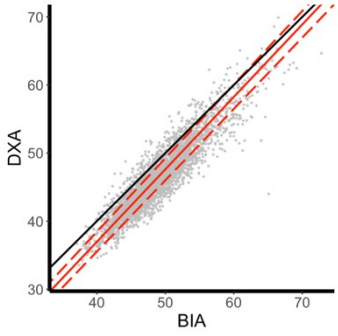
		BMI < 25	BMI 25-30	BMI > 30
Fat mass	Males	Y = *1.185* * X *-0.886* Slope: *1.185 (1.166, 1.203)* Intercept: *-0.886 (-1.183, -0.595)*	Y = 1.145 * X -0.289 Slope: *1.145 (1.129, 1.160)* Intercept: *-0.289 (-0.647, 0.066)*	Y = 1.150 * X -0.848 Slope: *1.150 (1.134, 1.166)* Intercept: *-0.848 (-1.380, -0.308)*
				
	Females	Y = 1.006 * X +0.585 Slope: *1.006 (0.997, 1.014)* Intercept: *0.585 (0.403, 0.759)*	Y = 0.987 * X +1.455 Slope: *0.987 (0.976, 0.998)* Intercept: *1.455 (1.145, 1.760)*	Y = 0.993 * X +1.716 Slope: *0.993 (0.983, 1.003)* Intercept: *1.716 (1.303, 2.100)*
				
Fat free mass	Males	Y = 0.981 * X -1.308 Slope: *0.981 (0.969, 0.993)* Intercept: *-1.308 (-2.015, -0.690)*	Y = 0.963 * X -1.351 Slope: *0.963 (0.952, 0.973)* Intercept: *-1.351 (-1.973, -0.704)*	Y = 0.937 * X -0.776 Slope: *0.937 (0.919, 0.952)* Intercept: *-0.776 (-1.792, 0.364)*
				
	Females	Y = 1.185 * X -8.795 Slope: *1.185 (1.172, 1.197)* Intercept: *-8.795 (-9.293, -8.268)*	Y = 1.143 * X -8.123 Slope: *1.143 (1.128, 1.158)* Intercept: *-8.123 (-8.817, -7.473)*	Y = 1.064 * X -5.594 Slope: *1.064 (1.048, 1.081)* Intercept: *-5.594 (-6.396, -4.804)*
				

Figure 4: Passing-Bablok plots for BIA (Tanita BC418MA)- and DXA-measured fat mass (kg) and fat free mass (kg) stratified by sex and BMI groups.

Solid black line: line of identity (y = x). Red line: Passing-Bablok regression line and its 95% confidence band. BIA: bioelectrical impedance analysis assessed by Tanita BC418MA. DXA: dual-energy X-ray absorptiometry. BMI: body mass index, kg/m^2.

Table 4: Results of multivariable linear regression of the BIA (Tanita BC418MA)-DXA differences.

	BIA-DXA difference in fat mass			BIA-DXA difference in fat free mass		
	Coefficient (95%CI)	P value	R^{2*}	Coefficient (95%CI)	P value	R^{2*}
Male						
DXA-derived fat mass	-0.37 (-0.40, -0.34)	<0.01	39.4%	0.11 (0.08, 0.14)	<0.01	46.2%
DXA-derived fat free mass	0.06 (0.03, 0.09)	<0.01		-0.37 (-0.39, -0.34)	<0.01	
BMI	0.36 (0.27, 0.45)	<0.01		0.54 (0.45, 0.63)	0.01	
Waist circumference	0.05 (0.04, 0.05)	<0.01		-0.05 (-0.05, -0.04)	<0.01	
Height	-0.01 (-0.03, 0.03)	0.64		0.29 (0.26, 0.31)	<0.01	
Female						
DXA-derived fat mass	-0.25 (-0.27, -0.23)	<0.01	34.8%	0.06 (0.04, 0.08)	<0.01	40.7%
DXA-derived fat free mass	0.13 (0.11, 0.15)	<0.01		-0.36 (-0.38, -0.34)	<0.01	
BMI	0.28 (0.22, 0.34)	<0.01		0.29 (0.23, 0.34)	<0.01	
Waist circumference	0.03 (0.03, 0.04)	<0.01		-0.03 (-0.03, -0.03)	<0.01	
Height	0.09 (0.07, 0.11)	<0.01		0.09 (0.08, 0.11)	<0.01	

All variables were fitted as continuous variables. Models were adjusted for age. BIA: bioelectrical impedance analysis assessed using Tanita BC418MA. DXA: dual-energy X-ray absorptiometry. CI: confidence interval. BMI: body mass index. *: R^2 of the fitted model.

Table 5: Sex and BMI stratified prediction equations for DXA-calibrated fat-free mass using BIA-measured fat mass and fat-free mass

Sex	BMI	Prediction equations
Male	< 25	FFM_DXA = 3.807 + 0.114 * FM_BIA + 0.857 * FFM_BIA + -0.120 * WC + 0.059 * height
Male	25 - 30	FFM_DXA = 6.152 + 0.141 * FM_BIA + 0.842 * FFM_BIA + -0.129 * WC + 0.052 * height
Male	≥ 30	FFM_DXA = 7.017 + 0.051 * FM_BIA + 0.839 * FFM_BIA + -0.118 * WC + 0.057 * height
Female	< 25	FFM_DXA = -16.697 + 0.021 * FM_BIA + 0.88 * FFM_BIA + -0.015 * WC + 0.13 * height
Female	25 - 30	FFM_DXA = -17.133 + 0.02 * FM_BIA + 0.814 * FFM_BIA + -0.012 * WC + 0.148 * height
Female	≥ 30	FFM_DXA = -18.25 + 0.023 * FM_BIA + 0.798 * FFM_BIA + 0.02 * WC + 0.141 * height

		Performance of the prediction equation					
		Training set	Testing set				
		R^2 (%)	R^2 (%)	Calibration slope	Calibration-in-the-large	Bias (95% LOA)	Proportional bias
Male	< 25	81.61	83.23	1.03 (1.00, 1.05)	-1.38 (-2.88, 0.12)	0.01 (-4.55, 4.56)	-0.12 (-0.15, -0.10)
Male	25 - 30	82.07	82.26	1.01 (0.99, 1.03)	-0.64 (-1.98, 0.70)	0.01 (-4.69, 4.71)	-0.11 (-0.13, -0.09)
Male	≥ 30	82.86	83.53	1.02 (0.99, 1.06)	-1.15 (-3.40, 1.11)	-0.15 (-5.45, 5.15)	-0.11 (-0.15, -0.08)
Female	< 25	81.42	80.46	0.98 (0.96, 1.01)	0.50 (-0.42, 1.43)	0.11 (-3.36, 3.58)	-0.10 (-0.12, -0.07)
Female	25 - 30	81.72	83.37	1.00 (0.98, 1.03)	-0.08 (-1.13, 0.98)	0.03 (-3.29, 3.36)	-0.10 (-0.12, -0.07)
Female	≥ 30	85.58	87.49	1.03 (1.00, 1.06)	-1.30 (-2.71, 0.13)	0.05 (-3.71, 3.81)	-0.10 (-0.12, -0.07)

BMI: body mass index, kg/m^2. FM: fat mass. FFM: fat free mass. DXA: dual-energy X-ray absorptiometry. BIA: bioimpedance analysis assessed by Tanita BC418MA. WC: waist circumference. In each sex and BMI subgroup, individuals were randomly assigned to a training set and a testing set (80%:20%). Prediction equations were derived from the training sets, and validated in the testing sets. Calibration slope and calibration-in-the-large: observed values were fitted on predicted values in a linear regression model, from which the slope is the calibration slope, and the intercept is the calibration-in-the-large. Bias (95% LOA): bias (the average difference between predicted and observed values), and 95% limits of agreement. Proportional bias: Bland-Altman slope estimate. Ideally, calibration slope should be 1, calibration-in-the -large should be 0, bias should be 0, and proportional bias should be 0.