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Research Article

Direct regional comparison of whole-body dual-energy X-ray absorptiometry and whole-body CT measurements of fat mass and fat-free mass in limbs and abdomen

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Abstract

Objectives: To measure fat mass (FM) and fat-free mass (FFM) in the limbs and abdomen using whole-body dual-energy X-ray absorptiometry (DXA) and compare them with whole-body computed tomography (CT), emphasizing precise regional comparisons to demonstrate the correlation between the methods.

Methods: Fifty-eight healthy adults (aged 20-69) who underwent both whole-body DXA and whole-body CT were included in this study. The CT scans included the entire body except the head, and image segmentation was employed for body composition analysis. Total limb FM, FFM, segmental abdominal FM, and visceral adipose tissue (VAT) were measured from both DXA and CT.

Results: The DXA-derived total limb FM and segmental abdominal FM were significantly lower than the CT-derived FM, whereas the DXA-derived total limb FFM was higher than the CT-derived FFM ($P < .001$). Despite these differences, very strong positive correlations were observed between DXA and CT for total limb FM ($r = 0.951$), total limb FFM ($r = 0.992$), and segmental abdominal FM ($r = 0.984$) ($P < .001$). The correlation for VAT was also strong ($r = 0.861$) ($P < .001$).

Conclusions: Our study demonstrated very strong correlation in direct regional comparisons between whole-body DXA and CT, supporting the reliability of DXA for analysing FM and FFM in the limbs and abdomen.

Advances in knowledge: We compared FM and FFM in the limbs and abdomen between whole-body DXA and CT through a region-by-region comparison, demonstrating a more direct correlation between the 2 methods.

Keywords: body composition analysis; fat mass; fat-free mass; whole-body computed tomography; whole-body dual-energy X-ray absorptiometry.

Introduction

Early diagnosis and prevention of frailty-related diseases, such as sarcopenia, are becoming increasingly important in an aging society as they are known to be related to physical disability, hospitalization, and even death.[1,2] To date, computed tomography (CT) and magnetic resonance imaging (MRI) are known to be the most precise methods for body composition analysis, offering detailed assessments of muscle and fat compartments.[3,4] However, relatively high cost, limited availability of CT and MRI, and radiation exposure of CT scans restrict their routine use for evaluating sarcopenia and adiposity metrics in clinical practice.[5]

Therefore, the utilization of dual-energy X-ray absorptiometry (DXA) for body composition measurement is growing among healthcare professionals due to its accuracy in measuring fat mass (FM) and lean mass (LM). This has led to an expanded use of whole-body DXA scans for various applications, including identifying low LM in the potential sarcopenia cases.[6] Also, the use of DXA for diagnosing sarcopenia has prompted the development of various indices including appendicular skeletal muscle mass (ASM)—the combined lean muscle mass of arms and legs—being a key measure.[7,8] ASM is often adjusted using height squared (ASM/ht^2) to account for body size differences, and it was reported that ASM/ht^2 is highly correlated with clinical outcomes such as frailty and has been adopted in many international guidelines for diagnosing sarcopenia.[9]

Several previous studies have shown a strong correlation between measurements of FM and LM by DXA and CT.[10-12] However, most of these studies utilized CT data from specific body regions, such as the L3 vertebral level, to extrapolate whole-body composition and compared it with whole-body DXA scan results. To the best of our knowledge, no studies have directly measured the total FM and LM of the limbs using volumetric whole-body CT. With the recent advancements in CT technology, allowing for a significant reduction in radiation dose, whole-body scanning has become more feasible than before. Therefore, we hypothesize that by comparing the total FM and LM of the limbs obtained through whole-body CT with DXA measurements and confirming

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their correlation, we can further solidify the evidence supporting the use of DXA in the diagnosis of sarcopenia.

In our study, considering the methodological discrepancies in bone tissue measurement between DXA and CT scans, we analysed fat-free mass (FFM), which includes both LM and bone mass, instead of LM alone. The purpose of our study was to measure FM and FFM in the limbs and abdomen using both whole-body DXA and whole-body CT, and to demonstrate the correlation between the 2 methods through a region-by-region comparison.

Methods

The institutional review board approved this prospective study, and all the participants provided written informed consent. This study was conducted in accordance with the World Medical Association Declaration of Helsinki.

Participants

The sample size was calculated based on a previous study comparing DXA and CT measurements of thigh composition.[13] That study reported correlation coefficients of 0.967 and 0.981 for FM and LM, respectively. Based on these values, our study was designed with a null hypothesis of correlation coefficients less than 0.8 and an alternative hypothesis of 0.92. In setting the alternative hypothesis at a correlation coefficient of 0.92, we considered the increased anatomical complexity of measuring both arms and legs compared to the previous study, which focused solely on the thigh. Under these assumptions, we determined that 57 participants would be required to detect a statistically significant difference with 95% power at a 5% significance level. Anticipating a 10% dropout rate, the total enrolment was adjusted to 63 participants. Sample size calculations were performed using "G*Power 3.1.9.7."

This study was designed to prospectively recruit healthy adults aged 20-69 from January to February 2024, applying the following exclusion criteria: (1) women who were pregnant or potentially pregnant; (2) individuals with metal implants from previous surgeries; and (3) those with a body size that makes full-body imaging with CT scans difficult. A total of 63 healthy adults who voluntarily agreed to participate were successfully recruited. During the analysis, 2 participants with unexpected metal implants and 3 participants whose limbs were not fully included in the CT scan range were excluded. Consequently, the final study group consisted of 58 participants [42 females and 16 male patients; mean age ± standard deviation (SD), 43.57 ± 11.32 years].

DXA acquisition

A whole-body DXA scan (iNSiGHT C510, Osteosys, Korea) was conducted by a trained radiologic technologist to measure the total body composition. The scans were automatically analysed based on predefined regions of interest, with manual adjustments made as necessary. This procedure allows for the detailed measurement of tissue mass with a particular focus on the limbs and the abdomen. Measurements of FM, LM, and bone mineral content (BMC) were recorded for the arms, legs, and other regions (Figure 1A). For comparison with FFM measured by CT, FFM in DXA was defined as the sum of LM and BMC. Modifying the method from a previous study,[14] the region for measuring segmental abdominal FM and visceral adipose tissue (VAT) was defined as the rectangular area within 1.1-6.5 cm upward from the line connecting the tops of the bilateral iliac crests (Figure 1B).

CT acquisition

All CT examinations were performed using a third-generation dual-source scanner (Somatom Force, Siemens Healthineers, Germany), equipped with 2 distinct tubes and detectors. The entire body, except for the head, was scanned with both arms placed alongside the body in a supine position. The protocol included the application of low-dose (LD) CT with tube voltages of 100 kVp and a reference tube current-time product of 60 mAs, employing a tube voltage ratio (A tube: B tube = 3:1) to optimize the balance between image quality and radiation dose.

The other CT image acquisition parameters were as follows: a gantry rotation time, 0.5 s; a pitch, 0.6; matrix, 512 × 512; and slice thickness, 1 mm. Reconstructions were performed with 500 × 500 mm field of view using the iterative reconstruction algorithm (ADMIRE level III, Siemens Healthineers). The mean effective dose for the LD CT scans was 4.55 ± 1.05 mSv (range, 2.97-8.76 mSv).

CT segmentation and mass conversion for body composition analysis

The CT image segmentation was performed by a research assistant under the supervision of a musculoskeletal radiologist (J.O., with 9 years of experience) using 3D software (AView Research, Coreline Soft, Korea), including the detailed segmentation of fat and lean soft tissues in the limbs and the abdomen (Figure 2). The 3-dimensional segmentation function of the 3D software was used to segment the entire body's fat tissue and fat-free tissue in a single process. After segmentation, the target measurement regions in the limbs and abdomen were extracted, and the corresponding tissue volumes were measured. Fat tissues, including subcutaneous and visceral fat, were identified within a Hounsfield Unit (HU) range of −190 to −30, while lean soft tissues were distinguished by an HU range of −29 to 150. In the context of CT, FFM was defined as the total tissue mass excluding FM, which corresponded to the combination of lean soft tissues and bone tissues. In addition, the amount of segmental abdominal FM and VAT was measured in the same region as the DXA analysis (Figure 2E). If any areas had ambiguous boundaries between the 2 tissue types, the original images were examined, and the boundaries were manually adjusted using the free-hand drawing tool in the 3D software.

The determined volumes of FM and FFM were then converted to mass using predefined formulas, allowing for a direct and comprehensive comparison with the DXA scan results. To convert the measured volumes into mass, we applied specific density factors to each tissue type, using the following formulas: the fat volume was multiplied by 0.92 kg/L to calculate FM and fat-free volume was multiplied by 1.04 kg/L for FFM.[15,16]

Statistical analysis

The Kolmogorov-Smirnov test was used to check the data for normality. DXA and CT data were presented as means and SDs and compared using paired-sample t-tests. Variables were compared between men and women using

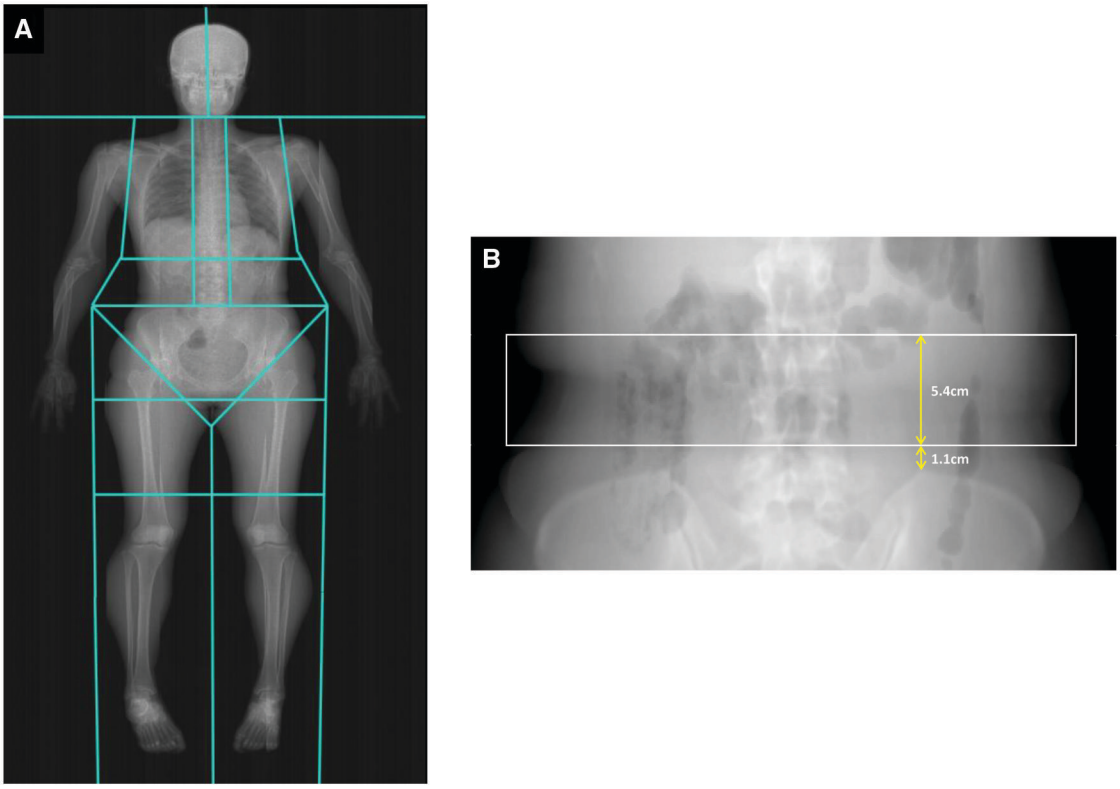

Figure 1. Example of post-processed whole-body DXA scan. (A) FM and FFM measurements were recorded for the arms, legs, and other regions. (B) The abdominal region for measuring segmental FM and VAT was defined.

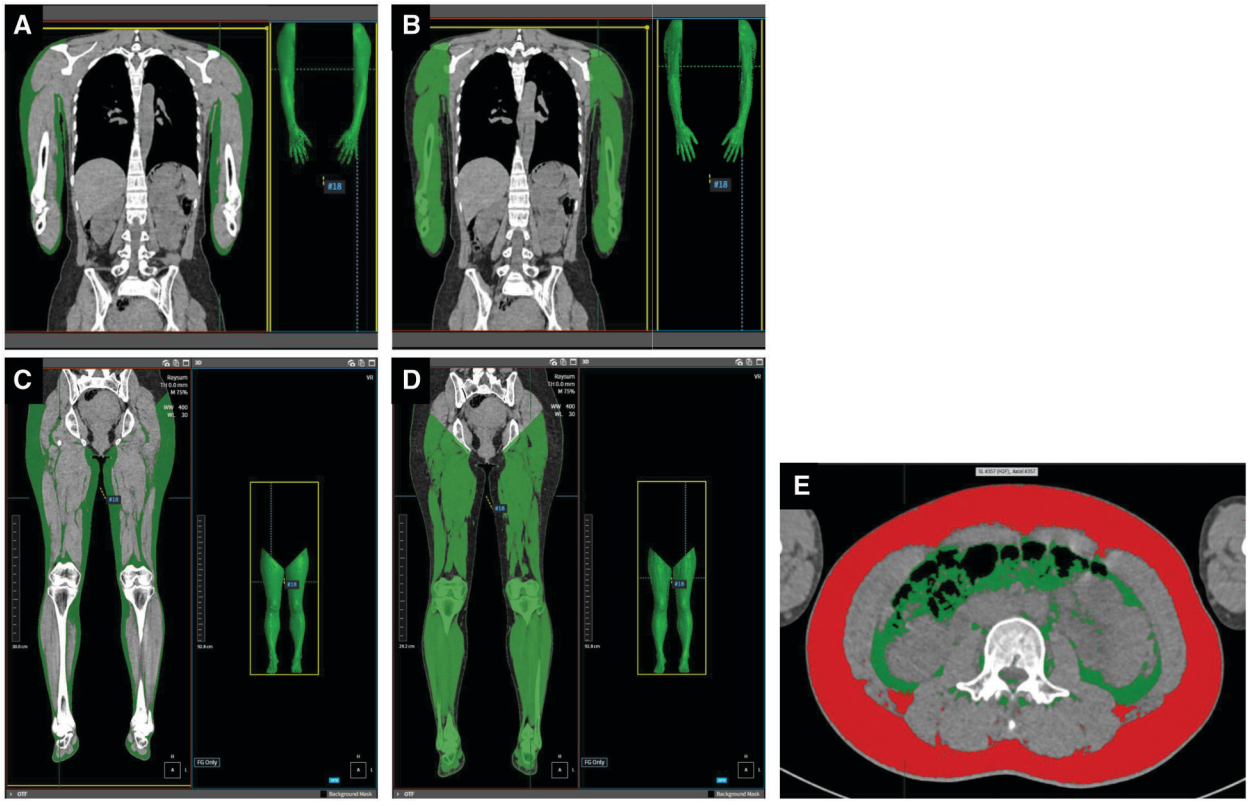

Figure 2. Example of body composition analysis using low-dose whole-body CT. (A-D) CT image segmentation was performed using 3D software to analyse fat tissues (A, C) and fat-free tissues (B, D) in both the upper and lower extremities. (E) In axial abdominal CT images, adipose tissue was manually segmented into subcutaneous fat (red) and VAT (green), and their respective amounts were measured. The sum of these 2 was defined as the segmental abdominal FM.

independent-sample t-tests. The correlation between variables measured by DXA and CT was determined using Pearson's correlation analysis. Based on the correlation coefficient, the relationships were classified as very weak correlation ($r = 0.00$-0.19), weak correlation ($r = 0.20$-0.39), moderate correlation ($r = 0.40$-0.69), strong correlation ($r = 0.70$-0.89), and very strong correlation ($r = 0.90$-1.00).[17] Bland-Altman analysis was used to assess the agreement between the 2 methods, and the 95% limits of agreement (LOA) between the 2 methods were obtained.

A P value of less than .05 was considered to indicate a significant difference. All statistical analyses were performed by using commercially dedicated software (MedCalc for Windows, version 22.023; MedCalc, Mariakerke, Belgium and SPSS 27 software for Windows; IBM Corp., Armonk, NY, United States).

Results

Body composition analysis

The FM, FFM in the limbs, segmental abdominal FM, and VAT mass derived from DXA and CT are summarized in Table 1. The DXA-derived total limb FM and segmental abdominal FM were significantly less than the CT-derived FM, whereas the DXA-derived total limb FFM was higher than the CT-derived FFM ($P < .001$).

The mean body mass index (BMI) ± SD of 58 patients was $22.79 \pm 3.01\ kg/m^2$ (range, 17.22-29.41 kg/m^2). There was no significant difference in total limb FM between men and women, with values of 6655.63 ± 2279.36 g vs 7902.07 ± 2205.49 g on DXA and 8142.81 ± 2368.08 g vs 9719.28 ± 2856.09 g on CT ($P > .05$). Similarly, segmental abdominal FM showed no significant difference by sex, with measurements of 973.56 ± 345.26 g vs 856.88 ± 390.44 g on DXA and 1332.1 ± 427.64 g vs 1176.5 ± 501.79 g on CT ($P > .05$). In contrast, total limb FFM was significantly higher in men than in women, with values of 24333.13 ± 2454.56 g vs 15717.38 ± 2164.37 g on DXA and 24445.56 ± 2324.37 g vs 15468.67 ± 2143.49 g on CT ($P < .001$).

Correlation and agreement between DXA and CT measurements

There were very strong positive correlations between DXA and CT measurements for total limb FM ($r = 0.951$), total limb FFM ($r = 0.992$), and segmental abdominal FM ($r = 0.984$) ($P < .001$). Additionally, VAT showed a strong positive correlation ($r = 0.861$) ($P < .001$) (Table 1 and Figure 3).

The Bland-Altman analysis revealed systematic differences between DXA and CT measurements across various parameters (DXA—CT). Total limb FM and segmental abdominal FM showed negative biases, while total limb FFM and VAT exhibited positive biases. Full numerical details, including mean differences, standard deviations, and confidence intervals, are presented in Figure 4. On average, DXA-measured total limb FM was 18% lower than CT measurements (95% LOA: −38% to 2%), while total limb FFM was 7% higher (95% LOA: 0%-13%). Additionally, DXA-derived abdominal FM was 27% lower (95% LOA: −48% to −6%), and VAT mass was 8% higher (95% LOA: −56% to 72%) than CT-derived values.

Discussion

Our study demonstrated very strong positive correlations between DXA and CT measurements for total limb FM, FFM, segmental abdominal FM, and a strong positive correlation for VAT. Although previous studies[10-12] have reported similar findings, they utilized partial CT data obtained from specific body regions, such as the L3 vertebra or 28 selected levels of the whole body, rather than direct measurements from the limbs. In contrast, our study is distinctive for its direct 1:1 anatomical comparison between DXA and whole-body CT, encompassing both the upper and lower extremities as well as the abdomen. As CT is considered as a standard tool for body composition analysis due to its high accuracy and reproducibility, our results further substantiate the usefulness of DXA as a technique for assessing whole body composition. This is crucial in clinical practice, where frequent assessments of muscle mass or visceral fat are needed for monitoring treatment progress in conditions like physical disability or metabolic disease.[1,2,18-20]

Recent studies suggest that measuring FM and FFM offers a more detailed insight into an individual's health status. Elevated FM, particularly visceral fat, is associated with increased risks of cardiovascular diseases, type 2 diabetes, and metabolic syndrome.[21,22] FM and FFM have opposing associations with mortality, with excess FM increasing mortality risk, while FFM provides a protective effect.[23] We analysed FFM, which includes both LM and bone mass, instead of LM to ensure that bone tissue was consistently reflected in both DXA and CT measurements. FFM includes all components of the body except fat, such as muscle mass, bone, non-adipose parts of internal organs, and extracellular fluid.[24] Previous studies have shown that fat-free mass index (FFMI) correlates strongly with ASM indices, and individuals with higher FFMI exhibit significantly greater muscle mass.[25,26] Therefore, FFM measured by DXA or CT can be considered an indirect indicator for assessing muscle mass.

Despite the high correlation between DXA and CT measurement, our results showed that DXA-derived total limb FM and segmental abdominal FM were significantly lower than those measured by CT. This finding aligns with previous studies comparing body composition measurements between DXA and CT, where discrepancies in FM and LM have been reported.[11-13,27] This discrepancy is probably due to the different principles of the 2 methods. FM measurements in DXA are based on the "chemical compartment" of triglycerides, while adipose tissue measurements in CT are based on "anatomical compartments" that contain not only adipocytes but also surrounding constituents such as collagen and elastic fibres, fibroblasts, and capillaries.[28] Consequently, FM measured by DXA tends to be lower than CT-derived FM due to the chemical vs anatomical distinction. Similarly, DXA-derived LM is somewhat higher than CT-derived LM because DXA includes body proteins, body water, non-fat lipids, carbohydrates, and soft tissue minerals in its measurements.[29] This inclusion of additional components in LM measurements of DXA contributes to the observed differences.

Our study demonstrated a trade-off in FM and FFM measurements between DXA and CT. Table 1 showed that DXA-derived total limb FM (7558.22 ± 2276.36 g) was significantly lower than the value measured by CT (9284.40 ± 2801.50 g). In contrast, DXA-derived total limb FFM

Table 1. Comparison of whole-body DXA and CT measurements for body composition.

	Limb fat mass (g)					Limb FFM (g)					Abdominal FM[a] (g)	
	Right UE	Left UE	Right LE	Left LE	Total limbs	Right UE	Left UE	Right LE	Left LE	Total limbs	Segmental	VAT
DXA	827.52 ± 299.45	721.97 ± 345.02	3085.29 ± 887.12	2923.55 ± 899.45	7558.22 ± 2276.36	2276.53 ± 738.57	2373.72 ± 779.58	7193.83 ± 1585.13	7311.92 ± 1608.48	19156.0 ± 4646.56	889.07 ± 379.19	465.82 ± 268.87
CT	1012.34 ± 369.49	1008.90 ± 378.60	3654.47 ± 1094.19	3608.72 ± 1105.32	9284.40 ± 2801.50	2193.64 ± 715.11	2101.31 ± 705.44	6854.59 ± 1624.13	6795.48 ± 1609.36	17945.05 ± 4594.21	1219.42 ± 483.91	431.94 ± 267.07
P-values (paired t-test)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	.073
Pearson's coefficients (*R*)	0.931	0.911	0.943	0.93	0.951	0.978	0.972	0.989	0.984	0.992	0.984	0.861
P-values (Pearson's correlation)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001

Data were reported as the mean ± SD.
Abbreviations: LE = lower extremity; VAT = visceral adipose tissue; UE = upper extremity.
[a]Segmental abdominal FM and VAT were measured in the rectangular area within 1.1-6.5 cm upward from the line connecting the tops of the bilateral iliac crests.

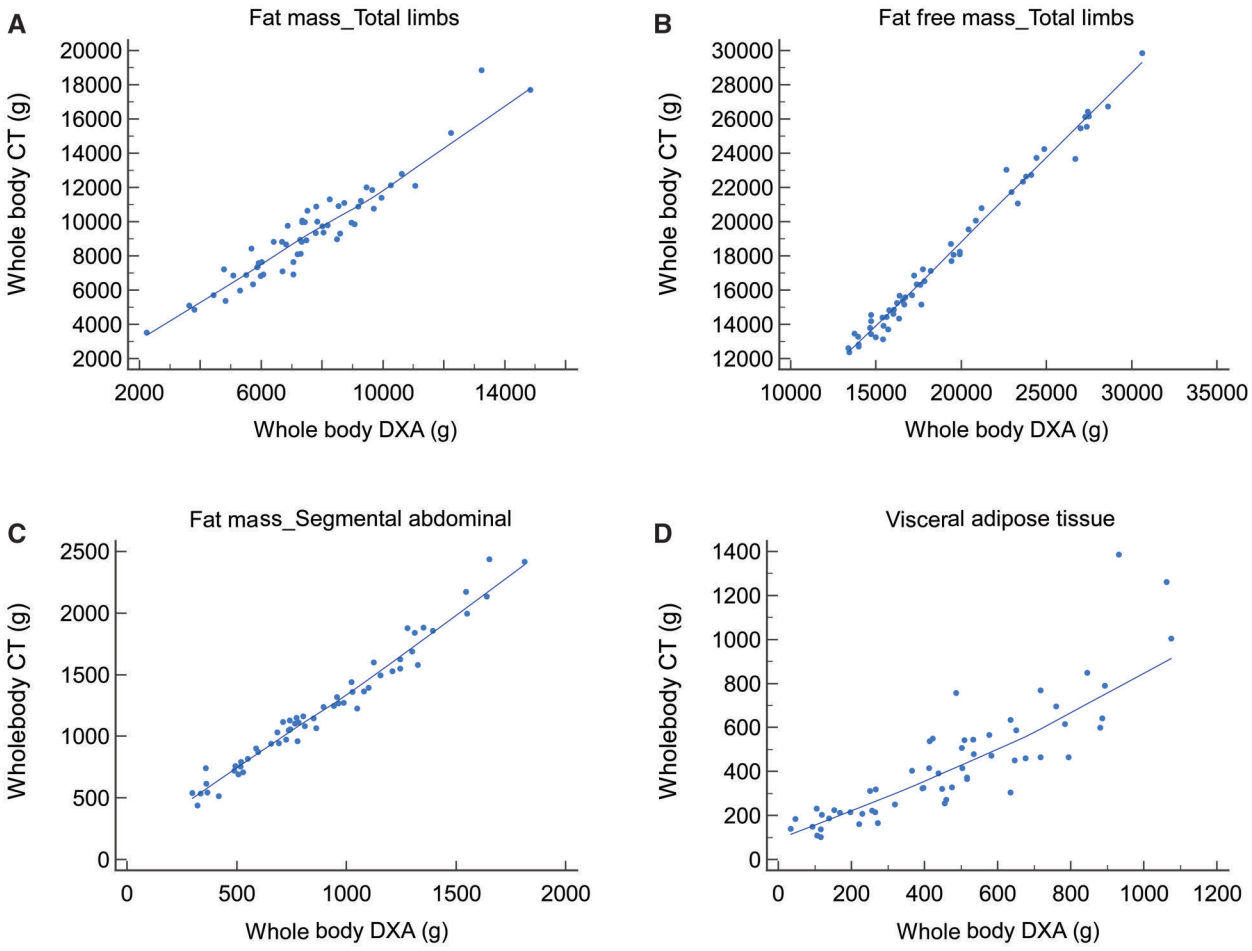

Figure 3. Scatter plots showing the correlations between DXA and CT measurements. (A) Fat mass of total limbs ($r = 0.951$, $P < .001$). (B) FFM of total limbs ($r = 0.992$, $P < .001$). (C) Segmental abdominal FM ($r = 0.984$, $P < .001$). (D) VAT ($r = 0.861$, $P < .001$).

(19156.0 ± 4646.56 g) was significantly higher than the corresponding CT measurement (17945.05 ± 4594.21 g). This relatively distinct difference is likely attributed not only to the previously mentioned trade-off principle between FM and LM measurements but also to certain methodological characteristics of our study, which may have contributed to the observed discrepancies between DXA and CT measurements. First, the regions analysed by DXA and CT may not have been perfectly aligned. CT may have captured more tissue than DXA, possibly due to differences in patient positioning or segmentation techniques. Second, the conversion of volume to mass in CT may have been influenced by the specific conversion factors used for FM and FFM calculations. The density factors for converting CT scan volumes to mass are not constant, typically around 0.90-0.92 g/cm^3 for fat, 1.04-1.1 g/cm^3 for lean tissue or fat-free tissue, but may vary depending on the study or population.[15,16,30]

In our study, segmental abdominal FM showed a very strong correlation between DXA and CT measurements, while VAT demonstrated a strong correlation, similar to findings in previous studies.[31,32] Despite the strong correlation, the relatively lower correlation for VAT compared to segmental abdominal fat could be related to the method DXA uses to estimate VAT. Specifically, VAT is calculated by subtracting subcutaneous fat from segmental abdominal fat. In this process, the lateral abdominal subcutaneous fat visualized in the DXA image is used to estimate both the anterior and posterior subcutaneous fat, with the remainder being classified as VAT.[14] This estimation method may contribute to the slightly lower correlation observed for VAT in DXA compared to segmental abdominal fat.

There are some limitations in our study. First, it was a single-centre study, which may introduce potential bias. Second, due to the inherent characteristics of imaging modalities, there were differences in the approach to body composition analysis between DXA and CT. As a result, the focus of our analysis should be on the strength of the correlation between the 2 methods, rather than on the degree of agreement between the measurements. Accordingly, although a high correlation was observed between the measurements from the 2 methods, there were limitations in using them interchangeably.

In conclusion, there was a very strong correlation between FM and FFM measurements from whole-body DXA and CT. Our study has the advantage of directly comparing the same regions, with both DXA and CT assessing the entire limbs and abdomen. Future research will be necessary for the conversion of measurements between the 2 methods.

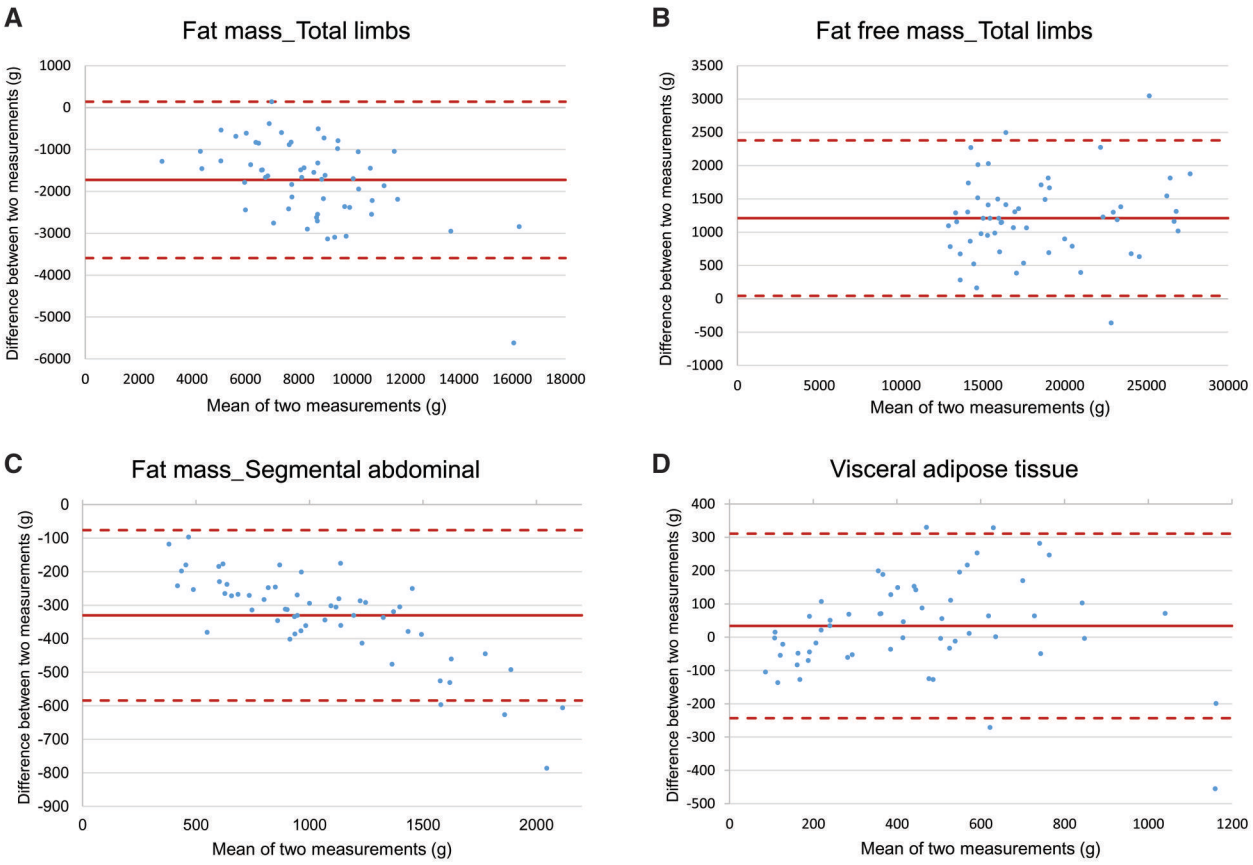

Figure 4. Bland-Altman plots comparing DXA and CT measurements (difference = DXA measurement – CT measurement). (A) Fat mass of total limbs: Mean difference = −1726.14 g (SD 952.37; 95% CI, −3592.78 to 140.51). (B) FFM of total limbs: Mean difference = 1211.01 g (SD 595.60; 95% CI, 43.63-2378.39). (C) Segmental abdominal FM: Mean difference = −330.36 g (SD 129.61; 95% CI, −584.40 to −76.32). (D) VAT: Mean difference = 33.89 g (SD 141.36; 95% CI, −243.18 to 310.96).

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Conflicts of interest

None declared.

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