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Original article

Dual-energy x-ray absorptiometry derived body composition trajectories across adulthood: Reference values and associations with body roundness index and body mass index

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SUMMARY

Background: Population-specific reference values are needed to accurately contextualise age-related changes in body composition. This study aimed to a) establish age- and sex-specific reference values and cut-points for a range of dual-energy x-ray absorptiometry (DXA) derived metrics of lean mass (LM), fat mass (FM) and bone mineral density (BMD), across adulthood in a large adult cohort; and b) determine the association between DXA-derived body composition, body roundness index (BRI), and body mass index (BMI).
Methods: Cross-sectional data were collected from 10,033 men and women aged from 18 to 92 years. Whole-body DXA scans were performed, and a range of metrics were calculated for LM (total LM, arm LM, leg LM, appendicular lean mass: ALM, skeletal muscle index: SMI), FM (total FM: kg and %, FMI, android to gynoid: A/G ratio) and bone (BMD). Cut-points equivalent to Z-scores of 1.0–2.5 SDs from the mean of a young reference population were established for each body composition metric.
Results: Detailed age- and sex-specific percentile curves were generated using the LMS method. Metrics of LM, central adiposity and BMD were higher in men, compared to women, whereas metrics of general FM accumulation were higher in women, compared to men. In both sexes, all LM metrics remained broadly stable during early and middle adulthood, after which progressively lower quantities were shown, whereas progressively higher FM metrics were shown from early adulthood through to late adulthood. In men, BMD was broadly stable across adulthood, whereas in women, markedly lower BMD was observed from the fifth decade of life. Significantly higher quantities of LM were shown across BMI categories, but not across BRI categories. The BRI was better correlated with FM%, FMI, and A/G ratio, compared to the BMI.
Conclusion: The reference values presented herein may support the interpretation of body composition in public health settings and the identification of people who may benefit from intervention to improve musculoskeletal and metabolic health. The BRI better reflects DXA-derived body composition and may provide screening utility beyond that of the BMI.

1. Introduction

Lean mass (LM) is fundamental for locomotion, metabolism, and protection of the human skeleton [1]. Age-related declines in LM, and the presentation of low quantities of LM are strong risk factors for falls and fractures [2], functional dependence [3], hospitalisation, and an overall poorer quality of life among older populations [4]. Fat mass (FM), on the other hand, supports metabolism during prolonged, moderate intensity activity and/or periods of fasting [5]. Furthermore, FM is an important regulator within endocrine and thermoregulatory pathways [6,7]. Importantly however, an excessive accumulation of FM, and in particular central FM, is associated with an array of negative health outcomes, such as elevated blood pressure [8], type 2 diabetes [9], cardiovascular diseases [10], and cancer [11]. Finally, bone supports human

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locomotion and the protection of vital organs, and the presentation of low bone mineral density (BMD) is an important risk factor for fractures [12] and cardiovascular disease [13]. The assessment of body composition throughout adulthood is, therefore, an essential aspect of public health screening that may help to identify people at risk of, or with, poor musculoskeletal and metabolic health for inclusion in targeted interventions.

Indeed, changes in body composition across adulthood are important determinants of health in older adults. These changes form the diagnostic basis of several age-related diseases, such as sarcopenia [14], sarcopenic obesity [15] and osteoporosis [16], that impose a heavy burden upon older adults and healthcare systems globally. The quantity and distribution of LM, FM, and bone are important factors underpinning musculoskeletal function, and each serve an indispensable role supporting health across the human lifespan. As such, developing our understanding of typical age-related changes in body composition is needed to improve the suitability of reference data that guide screening practices, and ultimately, the delivery of interventions to enhance musculoskeletal health and lengthen health span.

Body composition can be assessed using several techniques, including dual-energy x-ray absorptiometry (DXA), magnetic resonance imaging (MRI) and computed tomography (CT) [17], with MRI and CT being perhaps the most accurate of measures. However, the widespread use of MRI and CT is hindered by high operating costs, and limited availability, particularly in primary care settings. Consequently, DXA has emerged as a suitably accurate, accessible, and cost-effective method of body composition assessment that has been widely implemented in population-based studies [17–19]. Despite this, reference values for DXA-derived metrics of body composition across adulthood remain somewhat limited for certain populations. For example, although such data have been established for North and South American [18,20–22], Australian [23–25], and Asian populations [26–29], data on European populations are more limited [30–32]. Moreover, the only existing study to provide references values across adulthood, for DXA-derived indices of LM, FM and bone in a European population is modest in size (n = 915) [33]. Importantly, it is well-established that body composition parameters should be assessed against normative data that have been generated from the population of interest [14]. As such, there remains a strong need to establish reference data across relevant indices of FM, LM, and bone from a large European cohort, to support population-specific body composition screening within Europe.

Besides detailed body composition reference data, increasing attention has been given to the appropriateness of the body mass index (BMI) for screening adiposity-related comorbidities. The BMI has long been accepted as a simple and accessible proxy for adiposity, however, it has been scrutinised for its simplistic algorithm based upon a crude measure of body mass, that often misclassifies individuals as being at risk of obesity-related comorbidities [34]. The primary weakness of the BMI, in addition to the lack of consideration of FM distribution, is its inability to delineate the composition of the body mass upon which it classifies individuals (*i.e.,* how much is FM *vs* LM). For example, two people of the same height and body mass will have the same BMI, even if one has 10 % body fat, and the other has 40 % body fat, or alternatively, if one person is more prone to central FM accumulation than the other. In light of these shortcomings, increasing efforts have been given to identifying a more appropriate, yet equally-accessible screening tool for obesity-related outcomes. Perhaps the most promising of these is the body roundness index (BRI) proposed by Thomas et al. [35] in 2013, which integrates height and waist circumference measurements to provide a proxy for adiposity and FM distribution. Indeed, accumulating data suggest that the BRI has prognostic utility for hypertension [36], diabetes [37], cancer [38], and mortality [39]. Importantly, several reports have shown that the BRI may have screening utility beyond that of the BMI for cardiometabolic abnormalities [37,40]. Although the clinical translation of the BMI and BRI is based upon the negative effects of abnormal body composition, data relating to the association between detailed DXA-derived body composition metrics, BMI and BRI are scarce. The establishment of these data may help to contextualise the differences in prognostic capacity between the BMI and BRI, and guide the extent of their use in public health settings.

The primary aim of the current study was to generate age- and sex-specific reference values and cut-points for DXA-derived metrics of LM (total LM, arm LM, leg LM, ALM, SMI), FM (total FM [kg and %], FMI, android to gynoid [A/G] ratio) and BMD from over 10,000 men and women aged from 18 to 92 years. These data may support the interpretation of body composition in public health settings assessed using widely available DXA systems, and support the identification of people who may benefit from interventions to improve musculoskeletal and metabolic health. The secondary aim was to assess the association between DXA-derived metrics of body composition and the BMI and BRI.

2. Methods

2.1. Study sample

Participants were recruited via the ‘GenoFit’ study, a large cross-sectional analysis of the relationship between genetics, fitness, and health within the Irish population, between September 2017 and October 2020 [41,42]. GenoFit involved random sampling from the general population of Ireland, with purposely broad inclusion criteria of being aged ≥18 years and able to provide written informed consent. The broadness of inclusion criteria allowed for the GenoFit cohort to be representative of the wider population of Ireland, as indicated by governmental central statistics data [41,43]. In total, 10,546 people took part, involving a single assessment visit where blood samples were collected, and a suite of physiological assessments were performed. The sample for the present study was refined to include all participants with complete DXA data (n = 10,033), with specific exclusion criteria including being pregnant, potentially pregnant, currently breastfeeding or weighing over 159 kg. No participants had any severe musculoskeletal or neurological disease, or cancer that would affect typical age-related changes in body composition. Medication intake was recorded, but not included as an exclusion criterion, given that the purpose of this study was to establish reference body composition values for the general population, where medication intake is prevalent. In total, 2277 participants were using some form of medication (males: n = 821; females: n = 1456), with the most common reasons being contraception (n = 288), hypertension (n = 257), asthma (n = 179), hypothyroidism (n = 158), anxiety (n = 155), and hypercholesterolemia (n = 133). Ethical approval was obtained from University College Dublin's Research Ethics Committee (approval no. LS-17-07) and all participants provided written informed consent.

2.2. Anthropometry and body composition assessment

Height and body mass were obtained using a SECA stadiometer and weight scales (SECA, Hamburg, Germany), and a BMI was calculated (kg/m^2). Classification categories for BMI were <25 kg/m^2, 25–29.9 kg/m^2, and ≥30 kg/m^2. Numbers were not sufficient to create a standalone BMI <18.5 kg/m^2 category (n = 4 males and n = 14 females). A BRI was calculated using the following formula: $364.2 - 365.5 \times \sqrt{(1 - [\text{waist circumference in centimetres}/2\pi]^2/[0.5 \times \text{height in centimetres}]^2)}$, as initially proposed by Thomas et al. [35]. Due to the lack of reference cut-points for BRI, we opted to generate BRI tertiles to facilitate a comparison with BMI (men: T1 <2.74, T2 2.74–3.66, T3 ≥3.67; and women: T1 <2.32, T2 2.32–3.26, T3 ≥3.27). Body composition was assessed by trained research professionals using whole-body DXA (DXA; Lunar Prodigy, GE-Healthcare Technologies, Chicago, IL, USA), according to manufacturer's guidelines. Daily quality assurance and calibration measures were performed according to GE-Healthcare recommendations. Participants were dressed lightly, without shoes, and without any metal on their clothing or body. In consideration of the array of clinical assessments as part of the GenoFit study, participants were not asked to fast, limit fluid intake, or void their bladders prior to body composition testing, an approach adopted by other large-scale population studies [44]. Participants were positioned supine within the DXA imaging field as illustrated by measurement lines on the scanner bed. A gap was maintained between each leg, and between each arm and the torso. The hands were positioned flat on the scanner bed, where possible. and where there was insufficient space to do so, they were placed with palms facing the hips, while maintaining a slight gap. Default automatic scan and analysis settings were used for every participant. The following variables were extracted from the scans: total lean mass (LM) (DXA-derived LM does not include bone), arm LM, leg LM, total fat mass (FM), android FM, gynoid FM, and total bone mineral density (BMD). In addition, the following indices were calculated: appendicular lean mass (ALM: sum of arm LM and leg LM), skeletal muscle index (SMI: ALM divided by height squared), fat mass index (FMI: FM dived by height squared), android/gynoid FM ratio (A/G).

2.3. Statistical analyses

Data are presented as mean ± standard deviation or standard error of mean, unless stated otherwise. Spearman's correlation coefficient was used to determine the relationship between each body composition variable and age, given the non-linear relationships between these parameters. Student's t-tests were used to assess differences in body composition parameters between men and women, according to age group. For this, the dataset was stratified by sex and split into the following age categories: 18–29 years, 30–39 years, 40–49 years, 50–59 years, 60–69 years, 70–79 years, and ≥80 years. Analyses of variance (ANOVA) with Tukey's Honest Significant Difference post-hoc tests were used to assess differences in body composition parameters between age groups overall and according to defined BMI and BRI categories. Age- and sex-specific percentile curves were generated using the lambda-mu-sigma (LMS) method described by Cole and Green [45]. The threshold for statistical significance was set at $p < 0.05$ and all statistical analyses were performed using SPSS (Version 29, IBM SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Participant characteristics

A total of 10,033 people aged from 18 to 92 years were included in the analysis (males: n = 4326, mean age 43.1 ± 13.6 years; females: n = 5707, mean age 47.0 ± 13.3 years). The characteristics of the study sample are presented in Supplementary Table 1.

3.2. Sex-specific differences in body composition across adulthood

Significant sex-specific differences across all body composition parameters were observed in every age-group (all $p < 0.01$), except for FM (kg) in groups ≥60 years. All indices of LM (*i.e.,* total LM, ALM, SMI, leg LM, arm LM) were higher in men compared to women, across all age groups. Indices of general FM accumulation (*i.e.,* FM kg, FM %, FMI) were higher in women compared to men, across all age groups (except FM kg in age groups ≥60 years), whereas the indicator of central FM accumulation, the A/G ratio, was higher in men than women, throughout adulthood. BMD was higher in men than in women, in all age groups.

3.3. Lean mass indices across adulthood

Age- and sex-specific percentile curves for each LM parameter are presented in Fig. 1. Overall, significant negative correlations were observed between age and each LM parameter in both sexes (men: LM r = −0.235, ALM r = −0.275, SMI r = −0.200, leg LM r = −0.241, arm LM r = −0.305, and women: LM r = −0.230, ALM r = −0.283, SMI r = −0.180, leg LM r = −0.302, arm LM r = −0.178, all $p < 0.001$).

In both sexes, all indices of LM were broadly stable during early and middle adulthood, after which a progressive decline was observed. In men, significantly lower quantities were observed, per decade, in LM and SMI between the 30–39 year age group and the 60–69 year age group (differences: 30–39 to 40–49 years, LM −1.16 kg, p = 0.003, SMI −0.19 kg/m^2, $p < 0.001$; 40–49 to 50–59 years, LM −1.30 kg, p = 0.003, SMI −0.17 kg/m^2, $p < 0.001$; 50–59 to 60–69 years, LM −2.27 kg, SMI −0.26 kg/m^2, both $p < 0.001$), and in ALM, leg LM and arm LM between the age groups of 30–39 years and 70–79 years (differences: 30–39 to 40–49 years, ALM −0.78 kg, $p < 0.001$, leg LM −0.44 kg, p = 0.004, arm LM −0.33 kg, $p < 0.001$; 40–49 to 50–59 years, ALM −0.89 kg, leg LM −0.62 kg, arm LM −0.27 kg, all $p < 0.001$; 50–59 to 60–69 years, ALM −1.47 kg, leg LM −1.08 kg, arm LM −0.39 kg, all $p < 0.001$; 60–69 to 70–79 years, ALM −1.31 kg, p = 0.008, leg LM −0.93 kg, p = 0.001, arm LM −0.38 kg, p = 0.031). In women, significantly lower quantities were observed, per decade, in ALM and leg LM between the age groups of 30–39 years and 70–79 years (differences: 30–39 to 40–49 years, ALM −0.38 kg, p = 0.004, leg LM −0.34 kg, $p < 0.001$; 40–49 to 50–59 years, ALM −0.72 kg, leg LM −0.58 kg, both $p < 0.001$; 50–59 to 60–69 years, ALM −0.86 kg, leg LM −0.70 kg, both $p < 0.001$; 60–69 to 70–79 years, ALM −0.80 kg, p = 0.001, leg LM −0.65 kg, $p < 0.001$), in LM and SMI between the age groups of 40–49 years and 60–69 years (differences: 40–49 to 50–59 years, LM −1.19 kg, SMI −0.18 kg/m^2, both $p < 0.001$; 50–59 to 60–69 years, LM −1.76 kg, SMI −0.18 kg/m^2, both $p < 0.001$), and in arm LM between the age groups of 40–49 years and 70–79 years (differences: 40–49 to 50–59 years −0.14 kg, $p < 0.001$; 50–59 to 60–69 years −0.17 kg, $p < 0.001$; 60–69 to 70–79 years −0.16 kg, p = 0.035). Sex-specific Z-score cut-points of 1.0, 1.5, 2.0 and 2.5 standard deviations below the mean of a young adult population (18–39 years) for each LM index are presented in Table 1, and detailed age- and sex-specific reference values for each LM parameter are presented in Supplementary Tables 2-6.

3.4. Fat mass indices across adulthood

Age- and sex-specific percentile curves for each FM parameter are presented in Fig. 2. Overall, significant positive correlations were observed between age and each FM parameter in both sexes (men: A/G ratio r = 0.599, FM (kg) r = 0.387, FM (%) r = 0.438, FMI r = 0.424, and women: A/G ratio r = −0.433, FM (kg) r = 0.275, FM (%) r = 0.348, FMI r = 0.322, all $p < 0.001$).

In both sexes, significantly higher quantities were observed, per decade, in A/G ratio, FM (%) and FMI between the youngest age group and the 60–69 year age group (Men, differences: 18–29 to 30–39 years, A/G ratio +0.10, FM +4.01 %, FMI +1.40 kg/m^2, all $p < 0.001$; 30–39 to 40–49 years, A/G ratio +0.11, FM +2.50 %,

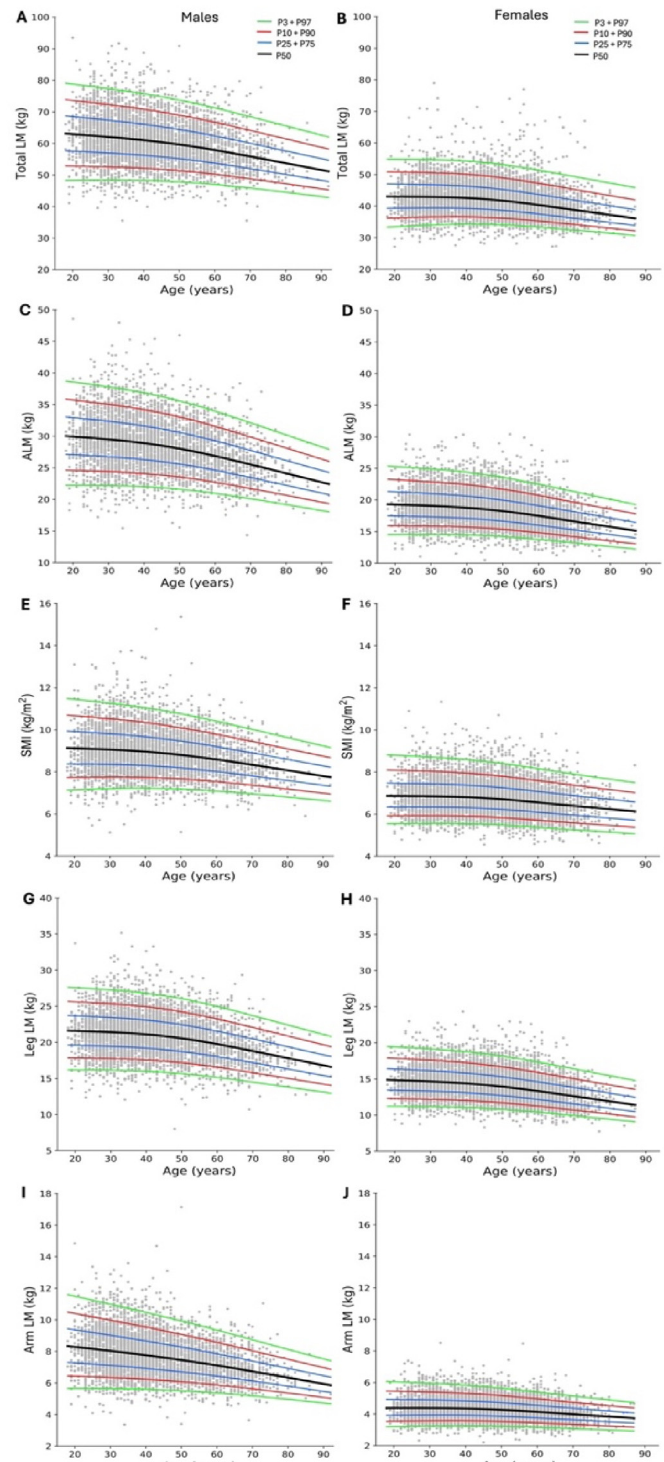

Fig. 1. Age- and sex-specific percentile curves for total lean mass (LM) (panels A–B), appendicular lean mass (ALM) (panels C–D), skeletal muscle index (SMI: ALM divided by height squared) (panels E–F), leg LM (panels G–H) and arm LM (panels I–J).

FMI +0.82 kg/m^2, all p < 0.001; 40–49 to 50–59 years, A/G ratio +0.09, FM +1.85 %, FMI +0.60 kg/m^2, all p < 0.001; 50–59 to 60–69 years, A/G ratio +0.06, p < 0.001, FM +1.64 %, p = 0.002, FMI +0.52 kg/m^2, p = 0.015; Women, differences: 18–29 to 30–39 years, A/G ratio +0.03, p < 0.001, FM +1.31 %, p = 0.006, FMI +0.63 kg/m^2, p < 0.001; 30–39 to 40–49 years, A/G ratio +0.05, FM +1.83 %, FMI +0.75 kg/m^2, all p < 0.001; 40–49 to 50–59 years, A/G ratio +0.06, FM +2.66 %, FMI +0.83 kg/m^2, all p < 0.001; 50–59 to 60–69 years, A/G ratio +0.03, p < 0.001, FM +1.50 %, p < 0.001, FMI +0.41 kg/m^2, p = 0.037), and in FM (kg) between the age groups of 18–19 years and 50–59 years (Men, differences: 18–29 to 30–39 years + 4.33 kg; 30–39 to 40–49 years + 2.54 kg; 40–49 to 50–59 years + 1.62 kg, all p < 0.001; Women, differences: 18–29 to 30–39 years + 1.74 kg; 30–39 to 40–49 years + 1.76 kg; 40–49 to 50–59 years + 1.96 kg, all p < 0.001). Sex-specific Z-score cut-points of 1.0, 1.5, 2.0 and 2.5 standard deviations above the mean of a young adult population (18–39 years) for each FM index are presented in Table 2, and detailed age- and sex-specific reference values for each FM parameter are presented in Supplementary Tables 7-10.

3.5. *Bone mineral density across adulthood*

Age- and sex-specific percentile curves for BMD are presented in Fig. 2 (panels I–J). Overall, significant negative correlations were observed between age and BMD in both sexes (men: r = −0.140 and women: r = −0.337, both p < 0.001). In men, no statistically significant differences were observed in BMD between age-groups, although they were highest in the 18–29 and 30–39 year age groups and lowest in the ≥80 year age group. In women, significantly lower quantities were observed, per decade, in BMD between the age groups of 30–39 years and 70–79 years (differences: 30–39 to 40–49 years −0.02 g/cm^3, p = 0.002; 40–49 to 50–59 years −0.04 g/cm^3, p < 0.001; 50–59 to 60–69 years −0.09 g/cm^3, p < 0.001; 60–69 to 70–79 years −0.05 g/cm^3, p < 0.001). Sex-specific Z-score cut-points of 1.0, 1.5, 2.0 and 2.5 standard deviations below the mean of a young adult population (18–39 years) for BMD are presented in Table 1 and detailed age- and sex-specific reference values for BMD are presented in Supplementary Table 11.

3.6. *Body mass index and body roundness index across adulthood and their association with lean mass and fat mass indices*

In both sexes, BMI and BRI were positively correlated with age (men: r = 0.226, r = 0.519; and women: r = 0.224, and r = 0.416, respectively, all p < 0.001). In both sexes, significant decade-specific differences were shown in BRI between the youngest age group and the 70–79 year age group (ranged in men from 7.0 to 22.0 % per decade, and in women from 7.2 to 17.1 % per decade), whereas decade-specific differences in BMI were smaller and plateaued from 50 to 59 years of age (ranged in men from 1.8 to 6.0 % per decade, and in women from 1.9 to 3.8 % per decade) (Fig. 3). Higher BMI was associated with greater quantities of LM, ALM and SMI in men and women (men: r = 0.383, r = 0.442, r = 0.603; and women: r = 0.320, r = 0.396, r = 0.607, respectively, all p < 0.001), whereas, notably weaker associations were shown between BRI and ALM and SMI (men: r = 0.066, r = 0.244; and women: r = 0.113, r = 0.345, respectively, all p < 0.001), and no associations were shown between BRI and LM (p > 0.05 in both sexes) (Supplementary Table 12). Strong positive associations were observed between BRI and a range of FM metrics in men and women (r ranged from 0.75 to 0.84 in men, and 0.77–0.82 in women), while slightly weaker associations were shown between the BMI and the same FM metrics (r ranged from 0.56 to 0.79 in men, and 0.64–0.77 in women) (Supplementary Table 12). When stratified according to BMI, significantly higher quantities across categories were shown for LM, ALM and SMI in both sexes, whereas following classification by BRI tertile, significant, yet notably smaller differences across tertiles was shown for SMI, and no associations were shown for LM or ALM (Fig. 4). BMI and BRI somewhat modified the strength of the relationship between age and LM indices, such that stronger associations were

Table 1
Sex-specific reference cut-points derived from a young adult population (18–39 years) for lean mass indices and bone mineral density.

Z-score (SD)[a]	LM (kg)	ALM (kg)	SMI (kg/m^2)	Leg LM (kg)	Arm LM (kg)	BMD (g/cm^3)
Men (n = 1925)						
Mean	62.13	29.52	9.10	21.44	8.09	1.36
−1.0	54.35	25.36	8.02	18.47	6.67	1.24
−1.5	50.46	23.28	7.48	16.99	5.96	1.18
−2.0	46.57	21.20	6.94	15.50	5.25	1.11
−2.5	42.68	19.11	6.40	14.02	4.55	1.05
Women (n = 1750)						
Mean	43.15	19.16	6.91	14.73	4.43	1.20
−1.0	37.53	16.42	6.06	12.62	3.70	1.11
−1.5	34.72	15.05	5.64	11.56	3.33	1.06
−2.0	31.90	13.68	5.21	10.50	2.97	1.01
−2.5	29.09	12.31	4.79	9.44	2.61	0.96

LM = lean mass; ALM = appendicular lean mass; SMI = skeletal muscle index; BMD = bone mineral density.
[a] Z-scores calculated as mean of young adults minus 1.0, 1.5, 2.0, 2.5 standard deviations (SD).

shown in people in the highest BMI and BRI categories (Supplementary Table 13). Percentile curves detailing the association between age and LM, ALM and SMI, within defined BMI and BRI categories in men and women are available in Supplementary Figs. 1–4.

4. Discussion

We have established age- and sex-specific reference values and cut-points for a range of body composition parameters that may guide the clinical interpretation of body composition throughout adulthood in European populations. Our primary findings show that: 1) in both sexes, total and regional indices of LM are broadly stable during early and middle adulthood, while lower quantities are observed, per decade, from approximately 40 years of age; 2) in both sexes, general and central indicators of FM are lowest in early adulthood and highest in older adulthood, and women typically have higher FM metrics, except for central adiposity; 3) in men, BMD remains broadly stable in across adulthood, whereas in women, significantly lower BMD is shown, per decade, from 40 years of age; 4) the BRI better reflects DXA-derived body composition metrics than the BMI, and as such, may provide additional screening utility in public health settings.

To date, our ability to interpret, and act-upon DXA-based body composition assessments has been hampered by a lack of high-quality population- and country-specific normative data from European populations. The present study builds upon the single existing study in a European population that reports DXA-derived normative data on muscle, fat, and bone from the same cohort [33], by generating detailed reference values across these components from a ten-fold larger cohort, and providing insight into the relationship between these body composition metrics, BMI and BRI. These data may be helpful for interpreting DXA-derived body composition metrics at different stages of adulthood, identifying people at risk of, or with, poor metrics, and ultimately, facilitating timely implementation of interventions to enhance musculoskeletal tissue and metabolic health.

4.1. Fat mass indices across adulthood

In men and women, significantly higher relative FM metrics (*i.e.,* total FM % and FMI) were shown, per decade, between the ages of 18–29 years and 60–69 years, after which somewhat of a plateau was observed. These findings align with existing reports that relative FM indices increase throughout early, middle, and early stages of late adulthood, but then typically plateau, or even decrease, in later stages of late adulthood [31,33]. Although whole-body FM indices (*i.e.,* total FM %, total FM kg, and FMI) were higher in women than in men throughout adulthood in the present study, a finding also shown in several previous reports [24,30], central adiposity, as determined by the A/G ratio, was substantially higher in men throughout adulthood. The establishment of A/G ratio normative data is a notable strength of the present study, given the current paucity of reference data for European populations, and the proposed clinical importance of central FM accumulation, beyond that of general FM accumulation [46]. Importantly, these data may help to screen people with excessive central FM accumulation, who consequently, may be at an increased risk of cardiometabolic health disorders, including cardiovascular disease [47] and type 2 diabetes [48]. It is worth noting, that although in the present study, adiposity cut-points were established using the classical Z-score approach as adopted elsewhere [24], determining cut-points based upon specific health risks, such as cardiometabolic conditions, may provide further utility in identifying vulnerable people for inclusion in primary care interventions. These data may complement existing reference ranges and provide more support to public health screening.

4.2. Lean mass indices across adulthood

In contrast to how higher quantities of FM were shown, per decade, from early adulthood, LM remained stable up until approximately the fifth decade of life. Indeed, our findings complement existing reports showing that LM, regardless of the specific index, is broadly stable during early and middle adulthood in men and women, and that progressively lower quantities are shown thereafter [24,33]. Of particular functional relevance are the indices of ALM, SMI and leg LM, which we observed to peak between the ages of 30–39 years, for both men and women. While similar trajectories in ALM and SMI across adulthood have been reported [24], there is a dearth of reference values for leg LM across adulthood, despite lower extremity LM being an important aspect underpinning physical function and independence in older adults [49]. As such, the limb-specific reference values presented herein may allow for a more comprehensive assessment of LM changes at different stages of adulthood. Notably, the cut-points derived from a young reference population in this study, may be particularly useful for the clinical interpretation of LM decline in vulnerable groups, such as older adults. Although originally implemented within the context of osteoporosis, a Z-score approach has since been adopted by several working groups for the diagnosis and management of sarcopenia, an age-related disease characterised by

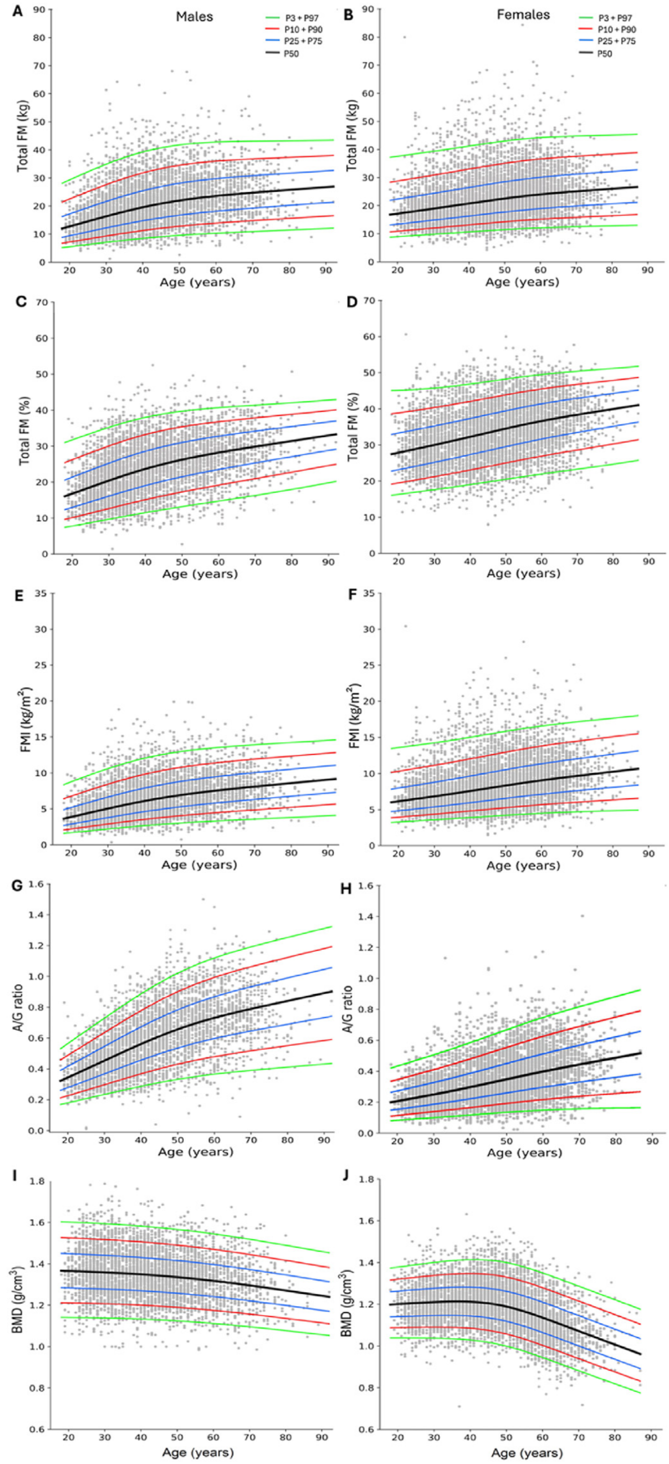

Fig. 2. Age- and sex-specific percentile curves for total fat mass (FM) (kg: panels A–B, %: panels C–D), fat mass index (FMI: FM divided by height squared) (panels E–F), android to gynoid (A/G) ratio (panels G–H) and bone mineral density (BMD) (panels I–J).

low muscle mass and function [14,50]. As such, the Z-scores that we have generated for specific LM metrics, including ALM and SMI, may aid in the identification and diagnosis of people with low LM, for inclusion in primary care interventions to improve skeletal muscle health. Our cut-points for SMI, the most widely used sarcopenia metric for LM, are broadly similar to those included in the current EWGSOP guidelines (males: 6.94 kg/m^2 *vs* 7.0 kg/m^2; females: 5.5 kg/m^2 *vs* 5.21 kg/m^2) [14], although ours are derived from a young cohort which firstly, is from a European rather than Australian reference population, and secondly, is of a 6-fold larger scale [23]. The similarity of our cut-points with those of the EWGSOP reinforces the clinical relevance of our data, which may help to facilitate a more targeted, population-specific interpretation of age-related changes in LM within Europe.

Table 2
Sex-specific reference cut-points derived from a young adult population (18–39 years) for fat mass indices.

Z-score (SD)[a]	A/G ratio	FM (kg)	FM (%)	FMI (kg/m^2)
Men (n = 1925)				
Mean	0.47	17.91	21.20	5.53
+1.0	0.61	25.96	28.45	7.98
+1.5	0.69	29.99	32.07	9.21
+2.0	0.76	34.01	35.70	10.44
+2.5	0.83	38.04	39.32	11.67
Women (n = 1750)				
Mean	0.30	20.55	30.69	7.43
+1.0	0.41	28.61	38.11	10.36
+1.5	0.47	32.64	41.82	11.83
+2.0	0.53	36.67	45.54	13.30
+2.5	0.58	40.70	49.25	14.77

A/G = android to gynoid fat mass; FM = fat mass; FMI = fat mass index.
[a] Z-scores calculated as mean of young adults plus 1.0, 1.5, 2.0, 2.5 standard deviations (SD).

4.3. Bone mineral density across adulthood

The BMD percentile curves presented herein illustrate the marked sex-specific difference in BMD that occurs from middle adulthood. Indeed, we show that, similar to reports in American populations [18], whole body BMD is largely stable in men across adulthood, but progressively lower BMD is observed from approximately 40 years of age in women. This reflects the substantial negative effects of the menopause on the structural integrity of bone tissue in women [51], and highlights the need for appropriate screening and therapeutic measures to combat the degradation. Importantly, we are not promoting the BMD reference data presented in this study as a means of diagnosing osteopenia or osteoporosis, as that necessitates region-specific assessments of the femur neck and lumbar spine [16]. Where we do see the utility of these data, however, is in facilitating initial bone health screening for those who have had a whole-body DXA body composition assessment. Indeed, these data may help identify those with poor whole-body BMD, who may benefit from engaging in specific bone health assessments.

4.4. Appropriateness of the body mass index and body roundness index for public health screening

It is well established that the BMI is a useful tool for assessing adiposity amongst the general population. However, it is prone to misclassification, particularly of men, with high LM misinterpreted as either overweight or obese, even if accompanied by a healthy body fat % [34]. In accordance with this phenomenon, we observed significantly higher quantities of LM, ALM and SMI across BMI categories in men and women, which were largely absent across BRI categories. Importantly, the BRI was also better correlated with clinically relative FM metrics, including the FM%, FMI and A/G ratio, when compared to the BMI. As such, the BRI may provide screening utility beyond that of the BMI, in identifying people with an

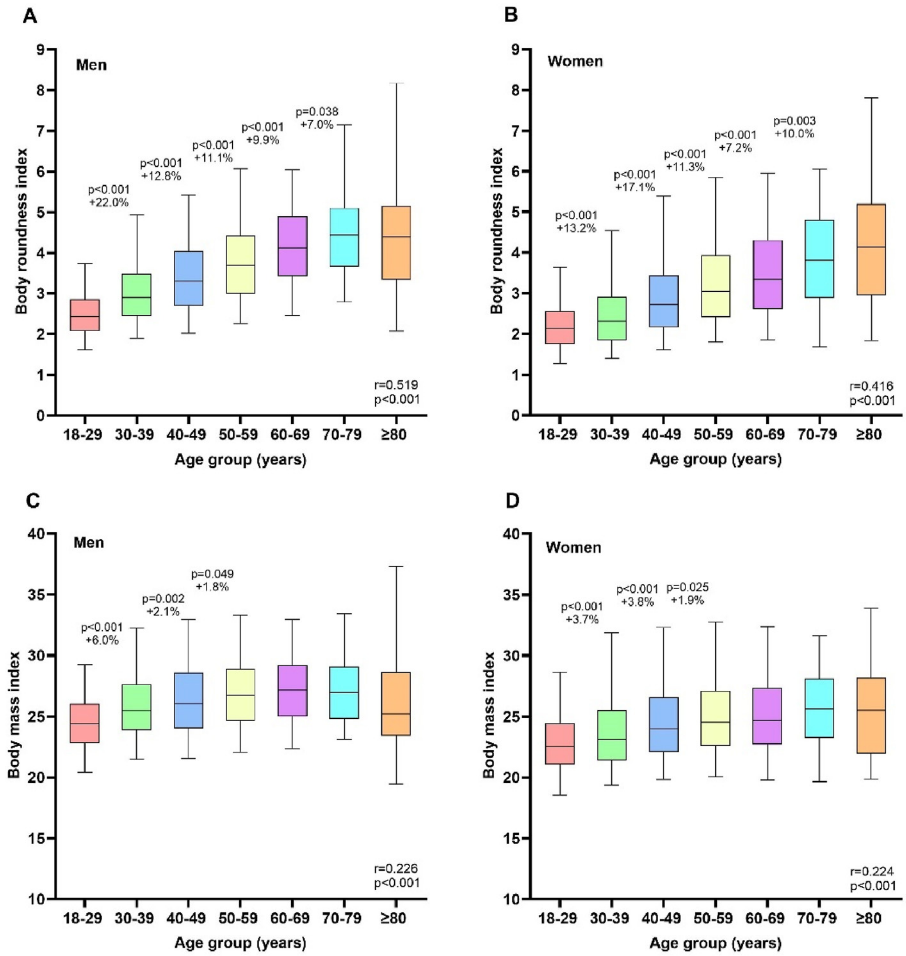

Fig. 3. Changes in body mass index (BMI) and body roundness index (BRI) across adulthood in men (panels A + C) and women (panels B + D). Spearman's correlation coefficients (r) established using age, BMI, and BRI as continuous variables. Error bars reflect 5th to 95th percentile.

unhealthy body composition for inclusion in targeted therapeutic interventions. Moreover, a wider implementation of the BRI within public health settings may help reduce the misclassification of people with high quantities of LM. For example, in the present study nearly 40 % of men who were classified as overweight by the BMI (n = 2121) had a DXA-derived body fat of 25 % or less, while 10 % of men who were classified as obese by the BMI (n = 549), had a body fat of 25 % or less. Evidently, these men would be misclassified if screened using the BMI, highlighting the shortcomings of the index and the need for a more appropriate, widely implementable screening tool. Although the absence of established BRI categories prevents a 'like-for-like' comparison between the BMI and BRI, as a crude example, using the top BRI decile as the cut-off threshold (>4.92), which captures a comparable proportion of men to that of the obese BMI category (10 % *vs* 12 %), only 1.4 % of men had a body fat % of 25 or less, rather than 10 % within the obese BMI category. Although, we fully acknowledge that this threshold is somewhat arbitrary, the findings do support the potential improvement in sensitivity that the BRI may provide. Nevertheless, it should be stressed that before the BRI can be integrated within public health settings, clinically informative cut-off thresholds need to be established and validated in a range of representative cohorts across the globe.

4.5. Strengths and limitations

The main strength of this study is the large sample size with an equal representation of men and women across a wide, adult age-range. In addition, we present a comprehensive set of reference values across an array of important body composition metrics that may be helpful in public health settings, and provide insight into the relevance of the BMI and BRI as screening tools. There are also several limitations to acknowledge, the first of which is the cross-sectional study design which ultimately does not allow for longitudinal assessment of individual changes in body composition. Secondly, the normative data presented herein were established from people who volunteered to partake in a general health assessment as part of the GenoFit study [52] and as such could be prone to selection bias. However, the normative ranges established in this study are similar to those reported in other population-based studies used to establish reference data [18,23], implying the suitability of our study sample. Finally, although this study included a wide adult age-range (18–92 years), the proportion of people in the 70–79 year age group, and particularly the ≥80 year age group, was somewhat limited, and so there remains a need for future studies integrating larger cohorts of older people to contextualise our normative data for these age-groups.

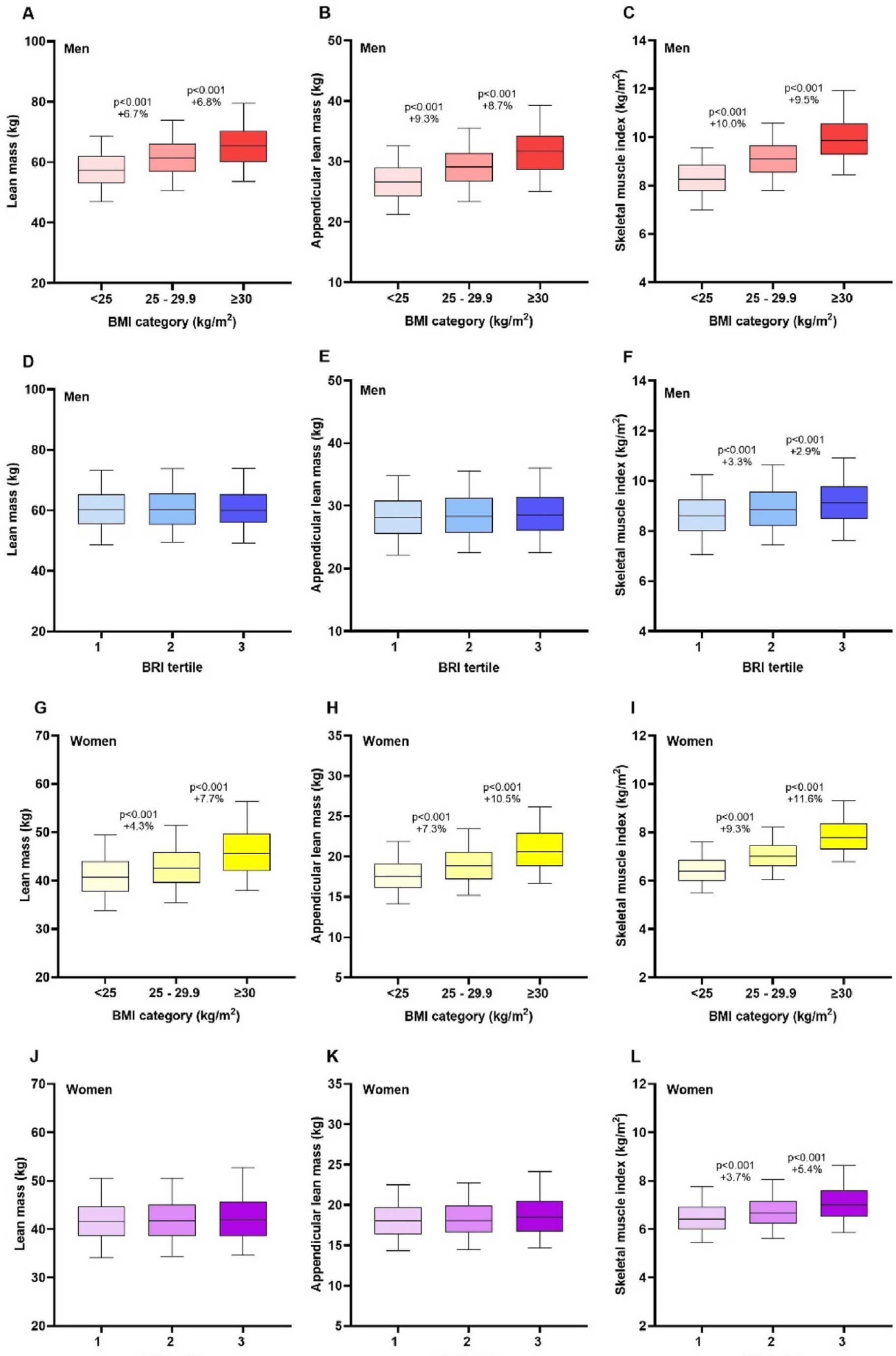

Fig. 4. Differences in lean mass, appendicular lean mass, and skeletal muscle index, according to defined categories of body mass index (BMI) and body roundness index (BRI) in men (panels A–F) and women (panels G–L). BRI tertiles = men: T1 <2.74, T2 2.74–3.66, T3 ≥3.67; women: T1 <2.32, T2 2.32–3.26, T3 ≥3.27. Error bars reflect 5th to 95th percentile.

5. Conclusion

In conclusion, we have generated detailed age- and sex-specific reference values and cut-points across a range of clinically relevant body composition metrics across adulthood. These data may be used to interpret body composition assessments at different stages of adulthood, and guide the delivery of targeted interventions to promote musculoskeletal and metabolic health.

Author contributions

Jedd Pratt: conceptualization, methodology, data curation, data analysis, writing – original draft, writing – review and editing;

Colin Boreham, Marco Narici and Giuseppe De Vito: supervision, writing – review and editing.

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None to declare.

Conflict of interest

None to declare.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clnu.2025.02.001.

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