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Jonathan C Wells, Jane E Williams, Sirinuch Chomtho, Tegan Darch, Carlos Grijalva-Eternod, Kathy Kennedy, Dalia Haroun, Catherine Wilson, Tim J Cole, and Mary S Fewtrell

Body composition reference data for simple and reference techniques and a four-component model: a new UK reference child

Jonathan CK Wells [1], Jane E Williams [1], Sirinuch Chomtho [4], Tegan Darch [1], Carlos Grijalva-Eternod [2], Kathy Kennedy [1], Dalia Haroun [5], Catherine Wilson [6], Tim J Cole [3], Mary S Fewtrell [1]

[1] Childhood Nutrition Research Centre, [2] Centre for International Health and Development, and [3] MRC Centre of Epidemiology for Child Health, UCL Institute of Child Health, 30 Guilford St, London WC1N 1EH;

[4] Pediatric Department, Faculty of Medicine, Chulalongkorn University, Bangkok 10330

[5] Department of Nutrition, Zayed University, United Arab Emirates

[6] Radiology Department, Great Ormond Street Hospital for Sick Children, Great Ormond Street, London WC1N 3JH

Telephone: + 44 207 905 2389

Fax: + 44 207 831 9903

Address for correspondence and reprints: J. Wells (email: Jonathan.Wells@ucl.ac.uk)

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Author last-name list: Wells, Williams, Chomtho, Darch, Grijalva-Eternod, Kennedy, Haroun, Wilson, Cole, Fewtrell

Running head: Reference data for children’s body composition

Abbreviations

4C – 4-component

BIA - bioelectrical impedance analysis

BMC – bone mineral content

BMI – body mass index

BV – body volume

DXA – dual energy X-ray absorptiometry

FFM – fat-free mass

FM – fat mass

LMS - lambda sigma mu

SDS – standard deviation score

SEE – standard error of the estimate

TBW – total body water

WT – body weight

Abstract

Background: Routine pediatric clinical assessment of body composition is increasingly recommended, but has long been hampered by two factors: a lack of appropriate techniques, and a lack of reference data with which to interpret individual measurements. Several techniques have become available, but reference data are needed.

Design: We aimed to measure body composition using a gold standard four-component model, along with various widely used reference and bedside methods, in a large representative sample of British children aged 4-20+ years, to provide body composition reference data for use in clinical practice and research.

Methods: Measurements were made of anthropometry (weight, height, four skinfold thicknesses, waist girth), dual-energy X-ray absorptiometry (Lunar Prodigy), body density (Bodpod \), bioelectrical impedance (Tanita BC418MA) and total body water, and four-component fat and fat-free masses were calculated. Reference charts and standard deviation scores (SDS) were constructed for each outcome using the LMS method. The same outcomes were generated for fat-free mass index and fat mass index.

Results: Body composition growth charts and SDS for 5-20 years were based on a final sample of 533 individuals. Correlations between SDS by different techniques were ≥0.68 for adiposity outcomes and ≥0.80 for fat-free mass outcomes.

Conclusions: These comprehensive reference data for pediatric body composition can be used across a variety of techniques. Together with advances in measurement technologies, they should greatly enhance the ability of clinicians to assess and monitor body composition in routine clinical practice, and should facilitate the use of body composition measurements in research studies.

Introduction

Growth charts for weight and height have been the backbone of pediatric clinical assessment of nutritional status for decades (1-4). However, efforts to obtain more detailed information on body composition have long been hampered by two challenges. First, methods for the measurement of pediatric body composition have taken time to develop. Only within the past decade have techniques such as DXA, air displacement plethysmography, bioelectrical impedance analysis and isotope dilution become widely applied in the pediatric population (5). Second, even where such techniques are available, interpretation is severely hindered by the lack of appropriate reference data.

Clinical practice has thus been strongly influenced by the nature of the available data. Reference data for British children's skinfold thickness measurements were provided in the 1970s (1). More recently, reference data for UK children's BMI were published in the 1990s (6), using Cole's LMS method to take into account age changes in the variability and skewness of the data (7). These BMI charts have become the primary UK reference for interpreting nutritional status in the clinic, and have been replicated in many other populations (8-11). To aid convergence between these approaches, the skinfold data were also converted to LMS format (12).

International BMI cut-offs for categorising overweight/obesity and underweight have also been published (13, 14). Such BMI data have been widely adopted in part because of their value in predicting clinical outcome. Nevertheless, they suffer from limitations when more detailed information about fat mass or fat-free mass is required. Historically, fat-free tissue has been considered the functional and dynamic component of weight, with fat mass conceptualised as a relatively inert energy store. Recent studies identifying numerous hormonal products of adipose tissue challenge this view, and adipose tissue is now understood to play a complex regulatory role, exerting many of its effects on fat-free tissue (15). There is

therefore increasing interest in the ability to categorise fat-free mass and fat mass, and monitor their changes over time.

Recently, we summarised a number of contexts in which information about body composition could be of value to the pediatrician (16), and also described the methodologies available (5). However, until reference data for children's body composition are available, measurements of individual patients will remain difficult to interpret (17). Reference data for individual techniques (eg skinfold thicknesses, BIA, DXA), have been reported in the literature (18-25), but no study has yet provided comprehensive reference data on a range of techniques in any single population. Here, we describe reference data for a number of different measures of body composition, allowing our reference dataset to be used across a variety of techniques.

Methods

A total of 565 normal healthy children and adolescents aged 4 to 23 years were recruited using flyers and newspaper adverts in London and the south-east of England, starting in 2001. There were no exclusion criteria for BMI, hence some individuals were categorised as overweight or obese, but they were not recruited directly from obesity weight-loss clinics, and had no disease that might have adversely affected growth and development. The lower age limit of 4 years was chosen based on our previous work, in that younger children are unlikely to satisfy the protocol for air displacement plethysmography. Data collection was extended to young adults in order to cover the entire pediatric age range. Ethical approval was granted by the Ethical Committee of UCL Institute of Child Health and Great Ormond Street Hospital. All individuals attended our body composition investigation suite located at Great Ormond Street Hospital for a 2-h measurement session.

Weight and height were measured using standard protocols. WT was measured in duplicate as part of the air displacement plethysmography protocol (see below). Height was measured using a wall-mounted stadiometer (Holtain, Dyfed, UK). BMI was calculated as weight (kg) divided by the square of height (m). Data on weight, height and BMI were converted to SDS format using UK reference data (6, 26). Obesity was defined as BMI >95th centile (SDS >1.64), and overweight as BMI >85th centile (SDS >1.04) (6). Pubertal development was assessed by Tanner staging, using self-assessment based on line drawings.

Skinfold thickness measurements were performed in triplicate at the biceps, triceps, subscapular and supra-iliac sites, and the mean of the three values used. Waist girth was measured using a non-stretchable fibreglass tape. BIA was conducted using Tanita BC418MA instrumentation (Tanita Corporation, Tokyo, Japan), however this instrument was only available from 2004 onwards, hence the sample size was 451 (83% of the total) for this outcome. Using whole-body values for impedance (Z, in ohms) at 50 kHz, the impedance index height^2/Z (cm^2/ohms) was calculated. Numerous pediatric equations have been published for BIA, leaving users uncertain as to which equation to select for any given population. The BIA output was therefore analysed in raw cm^2/ohm units, avoiding influencing this outcome by the choice of one or another equation. This approach prevents use of BIA data as an index of adiposity, hence skinfolds were the primary bedside approach tested for adiposity. Given that absolute body composition values obtained from using predictive equations in combination with such bedside techniques have high SEE, our combined 'skinfolds + BIA' bedside approach has the added advantage that fat-free and fat tissues are assessed with independent techniques, and error on the adiposity index should be independent from error on the fat-free mass index.

Measurements of TBW (litres) by deuterium dilution, BMC (kg) by DXA (Lunar Prodigy, software version 6.7; GE Medical Systems, Madison, WI) and BV (litres) in

duplicate by air displacement plethysmography (Bodpod ; Life Measurements, Concord, CA) were obtained as described previously, with post-dose saliva collected after 4-5 hours (27). The deuterium dilution space was converted to TBW assuming the degree of over-estimation attributable to proton exchange to be 1.044 (28). Lung volume was predicted rather than measured in the plethysmography measurements, because we have found a large proportion of children are unable to complete the lung volume measurement protocol satisfactorily. Values for fat-free mass from DXA were the sum of lean soft tissue and bone mineral mass.

The 4C model is considered the most accurate *in vivo* approach for the differentiation of fat and fat-free masses, and is particularly valuable in patients in whom assumptions of constant fat-free tissue composition are not valid (29, 30). The 4C model used here to calculate LM and FM has been described previously (31, 32), and uses the following equations:

$$FM = (2.747 * BV) – (0.710* TBW) + (1.460 * BMC) – (2.050 * WT) \quad \text{(Equation 1)}$$

$$LM = WT – FM \quad \text{(Equation 2)}$$

The proportion of fat in weight (%fat) was calculated as (FM/WT)*100. In our laboratory, precision is 1% for TBW (32) and 0.24 l for BV (33). Precision of BMC is 1.1% (34).

Statistics

Analyses were conducted for a range of adiposity and fat-free mass outcomes. For adiposity, the outcomes were (a) each of the four skinfolds, (b) waist girth, (c) whole-body, arm, leg and trunk fat mass from DXA, (d) body density by air-displacement plethysmography, and (e) 4C fat mass. For fat-free mass, the outcomes were (a) TBW, (b)

height^2/Z, (c) whole body, arm, leg and trunk fat-free mass by DXA, and (d) 4C fat-free mass. For the 4C data, the fat-free mass index (fat-free mass/height^2) and fat mass index (fat mass/height^2) were also calculated, as described and recommended previously (17, 35). Each of these variables was converted to standard deviation scores as described below.

Sex-specific values by month of age were obtained for all body composition outcomes using the LMS method (LMS Chart Maker, Medical Research Council, UK) (7). This statistical approach, widely used to construct reference data for traits which incorporate the effects of growth, provides three outputs: (a) a smoothed median (M or mu) curve which represents how the outcome varies in relation to age; (b) the coefficient of variation (S or sigma), which models the scatter of values around the mean and adjusts for any non-uniform dispersion; and (c) the skewness (L or lambda) which is addressed using age-specific Box-Cox transformation to achieve a normal distribution. Adiposity indices were fitted using original age, and fat-free mass outcomes using re-scaled age, which improves the goodness of fit for monotonic data by fitting the M curve twice. Goodness-of-fit was assessed with the Bayesian Information Criterion, adding an extra unit of complexity to the model only if it reduced the deviance by more than $\log_e(N)$ units, where N is the sample size. As the precision of the M curve at any age depends on data points at younger and older ages, precision is lower at the extremes of the age range. We therefore fitted the data for all ages (4-23 years) and derived LMS values for the age range 5-20 years.

These data represent new body composition growth charts, available for both the 4C model and individual techniques such as DXA, TBW, body density, BIA and skinfolds. Such charts will allow the monitoring of adiposity and fat-free mass over time, to improve understanding of the effects of disease and treatments. We also calculated values for fat-free mass, fat mass, fat-free mass index and fat mass index by the 4C model for each sex for the

following z-score cut-offs: -2, -1.67, -1.33, 0, 1.33, 1.67 and 2, equivalent to percentiles of 2.3%, 9.2%, 25.2%, 50%, 74.8%, 90.8% and 97.7% respectively.

Using this statistical approach, all data were converted to SDS format, and subsequent analyses on those aged 5-20 years were undertaken using Datadesk ® 6.1 (Data Description Inc., Ithaca, New York). The mean of the four individual skinfold SD scores was also calculated. We then quantified the agreement between the individual SDS with the reference 4C SDS. If growth charts are to be adopted by clinicians, they will need to know if rankings from one technique (eg skinfolds) are consistent with ranking by another (eg DXA, or the 4C model). Expressing the data in SDS format aids such a comparison, first because it enables the chart rankings to be compared, rather than the raw data, and second because body composition techniques produce outputs in different units (eg kg for DXA, kg/m^3 for density, mm for skinfolds, cm^2/ohms for BIA), preventing direct comparisons.

Correlation coefficients were calculated for all the adiposity and fat-free mass outcomes in each sex. Pearson correlation coefficients were calculated, on the assumption that associations between different z-scores were expected to be linear. For central adiposity, we also calculated correlations of SDS for DXA trunk fat and waist girth. Sex-specific regression analysis was undertaken, predicting 4C fat mass SDS from each individual adiposity SDS, and 4C fat-free mass SDS from individual fat-free mass, TBW or HT^2/Z SDS. The slopes and intercepts were assessed for difference from 1 and 0 respectively, and the SEE calculated. Bland-Altman analysis (36) was used to illustrate agreement with 4C SDS values for DXA whole body SDS, BIA SDS and average skinfold SDS. A minority of the subjects (27 boys, 23 girls, ie 9.3% of the sample) were of non-European ethnicity, however this sample size was considered too small to allow ethnic variability in body composition to be addressed.

Results

Valid data were obtained on 533 individuals. Data on 32 other individuals were discarded because either one or more of the basic measurements was unsuccessful (n = 16; mostly very young children), or the modelling was unsuccessful (n = 16) as indicated by spurious body composition data. As indicated in **Figure 1**, a wide range of BMI SDS was apparent at all ages. There was no significant correlation between BMI SDS and age in either sex.

Table 1 provides data on anthropometry SDS values, and the range of % fat by sex. On average, our sample was heavier and taller than the UK reference data of the early 1990s ($p<0.005$ in all cases). Females unsurprisingly had significantly greater % fat than males ($p<0.0001$, adjusted for age). The prevalence of obesity was 11.5% and 14.7 % in males and females respectively, and was uncorrelated with age. The numbers by pubertal stage 1-5 were as follows: male 98; 60; 28; 24; 50, female 87; 48; 34; 22; 80, and two others not recorded.

Figure 2 shows LMS centiles for 4C fat-free mass, 4C fat mass, 4C fat-free mass index and 4C fat mass index respectively against age for each sex. Fat-free mass increased with age in an s-shaped association in both sexes, but reached substantially higher values in males. This sex difference was reduced but remained apparent when adjusted for height, in the form of fat-free mass index. Fat mass had no discernible curvilinear association with age, which is due in part to differing age-associations of individual fat depots, as proxied by the four skinfold thicknesses (data not shown). **Tables 2 to 5** give z-score and centile reference data for each of fat-free mass, fat mass, fat-free mass index and fat mass index by the 4C model, for each sex.

Table 6 shows correlation coefficients for adiposity SDS indices by sex. All coefficients were ≥ 0.68 ($p<0.0001$**). Table 7** shows coefficients and standard errors for intercepts and slopes for the regression of 4C fat mass SDS on each individual adiposity SDS values, together with SEE values. No intercept differed significantly from 0, however most

slopes were significantly lower than 1, the exception being DXA fat mass SDS in females. For DXA fat mass in males, the upper 95% confidence interval of the slope was just below 1 (0.983). The smallest SEE values were obtained from DXA fat mass SDS (0.33 SDS in males, 0.21 SDS in females) whereas values for skinfolds were ~0.5 to ~0.6 SDS. Thus, in most cases individual SDS underestimated 4C fat SDS in those with higher adiposity, with this effect being minimal for DXA whole-body data. **Figure 3** illustrates Bland-Altman analysis of agreement between 4C and DXA values for fat mass SDS, showing no systematic trend in bias across the range of adiposity, but greater random inconsistency in those of low adiposity.

Table 8 shows correlation coefficients for SDS for indices of fat-free mass by sex. All correlations were ≥0.80 ($p<0.0001$). **Table 9** shows coefficients and standard errors for intercepts and slopes for the regression of 4C fat-free mass SDS on each individual proxy SDS value, together with SEE values. No intercept differed significantly from 0, however most slopes were significantly lower than 1, the exceptions being DXA fat-free mass SDS in both sexes, and TBW SDS in both sexes. SEE values were ~0.2 for DXA whole body SDS, ~0.2 for TBW SDS, and ~0.44 for BIA SDS. Figure 3 illustrates Bland-Altman analysis of agreement between 4C and DXA values for fat-free mass SDS in males and females, showing no variability in bias across the range of fat-free mass SDS.

The r^2 values calculated from Tables 6 and 8 indicate that DXA fat SDS accounts for 88% and 96% of the variance in 4C fat SDS in males and females respectively, while DXA fat-free SDS accounts for 96% and 94% of the variance in 4C fat-free SDS in males and females respectively. In both sexes, agreement is better for fat-free SDS than fat SDS (Figure 3), which shows poorer consistency between methods in those with low adiposity. For central fat, the correlation of DXA trunk fat SDS and waist SDS was 0.81 in males and 0.83 in females. Waist SDS therefore explains 66% and 69% of the variance in trunk fat SDS in males and females respectively.

Figure 4 shows the association between 4C fat-free mass SDS and BIA SDS in each sex. The r^2 values from Table 8 indicate that height^2/Z accounts for 83 and 81% of the variance in 4C fat-free SDS in males and females respectively. Figure 4 also shows the association between 4C fat mass SDS and mean of 4 skinfold SDS in each sex. For each of the sum of four skinfolds, density, DXA indices and 4C fat mass, the r^2 values calculated from Table 6 indicate that each individual adiposity SDS accounts for 66-96% and 61-96% of the variance in the other SDS in males and females respectively.

Discussion

Although reference data for children's body composition have long been desired, their development is complicated by the difficulty of obtaining accurate measurements. Advances in modelling, combining several raw measurements, have allowed accurate 4C data to be obtained in children ≥4 years (31, 32). This approach is unlikely to be widely applied in clinical practice or research studies, due to its expense and requirement for sophisticated equipment. Several techniques are used more routinely, including skinfolds, DXA and BIA, however each method uses different approaches to convert raw measurements to final body composition values (37, 38)

Over the past two decades, various pediatric body composition reference data have been reported, including skinfold data in Spain (19) and the US (18), BIA data for the US (20), Turkey (21) and Japan (22), and DXA data for Sweden (23), Holland (24) and the US (25, 39). These represent an advance over BMI, which can assess nutritional status but not fat and fat-free masses, or their regional distribution. However, because of the different theoretical assumptions and population variability in body size and nutritional status, these heterogeneous datasets cannot easily be compared. No study has previously reported

reference data for a wide range of outcomes, which would allow future studies to benefit from converging on a common dataset, regardless of which technique was used.

We have attempted to resolve this problem, by developing reference charts and SDS for both the accurate 4C model and a number of simpler techniques, across the age range 5-20 years. We have further described correlations between SDS calculated using the different techniques, and have shown medium-to-high agreement in all cases. Thus, whether measurements are made using skinfold calipers, DXA, BIA, densitometry, isotopes or the 4C model, there is relatively good ranking consistency, although different techniques cannot be used interchangeably when monitoring individuals over time. These new data will aid both single assessments of children, and also longitudinal monitoring over time. They are suitable for use in conditions in which there is no acute perturbation of water distribution (oedema).

From our clinical experience, children with specific diseases are often able to undergo only a subset of body composition measurements. For example, many patients are too sick to undergo plethysmography or DXA, but can have BIA or TBW measured at the bedside (40, 41). Some obese children are too large to be successfully scanned by DXA, and are difficult to measure using skinfold calipers, but can undergo plethysmography (42). Where hydration varies beyond the normal range, and where patients are able to undergo a wider range of measurements, the 4C model is ideal, as we have demonstrated for obesity (29), acute lymphoblastic leukaemia (30) and cystic fibrosis (43). Thus, our reference data should substantially increase the capacity of clinicians to acquire and interpret data in a wide range of diseases, contributing to a range of components of clinical management. For more general community studies of nutritional status, TBW is the most accurate field method (32, 44), and can be applied in combination with our published reference data for hydration (38).

Comparing between techniques for adiposity, the highest correlations with 4C fat mass SDS were found for whole-body DXA fat mass SDS, with coefficients of 0.98 in females and

0.94 in males, and SEE of ~0.2 SDS. The next best technique was density SDS, while the individual skinfolds performed slightly less well (correlations ranging from 0.78 to 0.84 and SEE of ~0.6 SDS), but the average of the four skinfold SDS values had a correlation very similar to that of density in both sexes and SEE of ~0.4 SDS. For 4C fat-free mass SDS, DXA whole-body fat-free mass SDS likewise showed the highest correlations in both sexes, 0.98 in males and 0.97 in females, and SEE of ~0.2 SDS. Other outcomes also showed high ranking consistency, with the least successful being DXA arm fat-free mass SDS (correlations of 0.86 in males and 0.88 in females and SEE of ~0.5 SDS). For both primary outcomes, therefore, DXA whole-body SDS proved most consistent for accurate ranking individuals against the reference method, explaining 88% to 96% of the variance in 4C SDS values.

While absolute accuracy of DXA remains imperfect (42, 45, 46), its use for categorising relative fat and fat-free masses on the basis of whole body measurement therefore appears the best simpler option, if the 4C model is not available. Nevertheless, caution is required before extrapolating our findings to other DXA instrumentation. Pediatric cross-calibration studies have shown relatively good agreement between different machines from a single manufacturer (47, 48), but poorer agreement between different manufacturers' machines (49), and further research is required using other DXA instrumentation. Furthermore, for both DXA and other techniques, consistency between 4C SDS and other SDS was poorer for adiposity at the lower end of the scale, especially in males, whereas for fat-free mass, techniques ranked with consistency across the whole range of the outcome (Figures 3 and 4). Thus, even DXA is a poor option compared to the 4C model when attempting to rank adiposity in leaner individuals.

Ideally, interpretation of body composition data requires adjustment for body size. This is particularly evident when children grow between two measurement occasions, but is also important if making a baseline assessment of patients who may have abnormal weight or

height for their age. BMI represents the established index of weight adjusted for height in pediatric clinical practice. BMI may be divided into two components, the fat-free mass index and fat mass index. Each of these is adjusted for height, and unlike %fat, the fat mass index is not confounded by variability in fat-free mass and therefore represents a more objective index of adiposity (17, 50). However, it has also been shown that whilst fat-free mass scales with height^2, fat mass scales with height raised to a higher power, eg height^6 in 9 year-old children (50). There is currently uncertainty over how best to adjust pediatric body composition data for size (51), and our new reference data for 4C fat-free mass index and fat mass index therefore represent a pragmatic preliminary attempt, which we intend to address further in future work.

A limitation of our study is that we are unable to extend the age range below 5 years. We have collected a large amount of isotope and skinfold data from 6 weeks to 4 years (52), however these were collected a decade earlier than those reported here, and there is a poor statistical fit between the two datasets, most likely due to differential exposure to obesogenic environmental factors. Many patients requiring body composition assessment are aged <5 years, however further technical advances are required before our approach can be applied to this age range. A second limitation is that we were unable to include all possible techniques (eg MRI, TOBEC), or instrumentation. Our Lunar DXA data may not be appropriate for other manufacturers' instrumentation, while our BIA data were collected using standing instrumentation in combination with foot-plates and hand-grips, and hence will not be entirely consistent with data collected from supine individuals using adhesive electrodes. However, standing BIA removes a degree of inter-observer error, as it avoids the need to place electrodes on anatomical landmarks. A third limitation is that ethnic variability in our sample was not adequate to allow us to explore this issue in our analysis.

In summary, we have described the measurements available in our new reference dataset and provided examples of how the data can be presented; there are many alternative formats and a large amount of additional data are available from each of the two-component techniques. We anticipate that the most appropriate use of the reference data will vary in clinical and research settings. To facilitate their use by clinicians and researchers, we intend to make the data available through an internet portal, allowing individual raw data for each technique to be entered with age and sex data, to calculate SDS (7). The graphs will also be available for download. While for some purposes (eg evaluating cardiovascular risk) BMI SDS remains adequate for differentiating clinical status (53,54), growth charts that allow partitioning of weight into its fat and fat-free components are likely to be valuable for monitoring more immediate effects of disease and response to treatment (16).

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References

1. Tanner JM, Whitehouse RH. Revised standards for triceps and subscapular skinfolds in British children. Arch Dis Child 1975; 50: 142-5.

2. Tanner JM. Growth as a monitor of nutritional status. Proc Nutr Soc 1976; 35: 315-22.

3. Tanner JM, Whitehouse RH. Clinical longitudinal standards for height, weight, height velocity, weight velocity, and stages of puberty. Arch Dis Child 1976; 51: 170-9.

4. Tanner JM, Davies PS. Clinical longitudinal standards for height and height velocity for North American children. J Pediatr 1985; 107: 317-29.

5. Wells JC, Fewtrell MS. Measuring body composition. Arch Dis Child 2006; 91: 612-617.

6. Cole TJ, Freeman JV, Preece MA. Body mass index reference curves for the UK, 1990. Arch Dis Child 1995; 73: 25-9.

7. Cole TJ, Freeman JV, Preece MA. British 1990 growth reference centiles for weight, height, body mass index and head circumference fitted by maximum penalized likelihood. Stat Med 1998; 17: 407-29.

8. Lindgren G, Strandell A, Cole T, Healy M, Tanner J. Swedish population reference standards for height, weight and body mass index attained at 6 to 16 years (girls) or 19 years (boys). Acta Paediatr 1995; 84: 1019-28.

9. Luciano A, Bressan F, Zoppi G. Body mass index reference curves for children aged 3-19 years from Verona, Italy. Eur J Clin Nutr 1997; 51: 6-10.

10. Nysom K, Molgaard C, Hutchings B, Michaelsen KF. Body mass index of 0 to 45-y-old Danes: reference values and comparison with published European reference values. Int J Obes 2001; 25: 177-84.

11. Leung SS, Cole TJ, Tse LY, Lau JT. Body mass index reference curves for Chinese children. Ann Hum Biol 1998; 25: 169-74.

12. Davies PS, Day JM, Cole TJ. Converting Tanner-Whitehouse reference tricep and subscapular skinfold measurements to standard deviation scores. Eur J Clin Nutr 1993; 47: 559-66.

13. Cole TJ, Bellizzi MC, Flegal KM, Dietz WH. Establishing a standard definition for child overweight and obesity worldwide: international survey. BMJ 2000; 320: 1240-3.

14. Cole TJ, Flegal KM, Nicholls D, Jackson AA. Body mass index cut offs to define thinness in children and adolescents: international survey. BMJ 2007; 335: 194.

15. Ahima RS. Adipose tissue as an endocrine organ. Obesity 2006; 14 Suppl 5: 242S-9S.

16. Wells JC, Fewtrell MS. Is body composition important for paediatricians? Arch Dis Child 2008; 93: 168-72.

17. Wells JC. A critique of the expression of paediatric body composition data. Arch Dis Child 2001; 85: 67-72.

18. Addo OY, Himes JH. Reference curves for triceps and subscapular skinfold thicknesses in US children and adolescents. Am J Clin Nutr 2010; 91: 635-42.

19. Moreno LA, Mesana MI, Gonzalez-Gross M, Gil CM, Ortega FB, Fleta J, Wärnberg J, León J, Marcos A, Bueno M. Body fat distribution reference standards in Spanish adolescents: the AVENA Study. Int J Obes 2007; 31: 1798-805.

20. Chumlea WC, Guo SS, Kuczmarski RJ, Flegal KM, Johnson CL, Heymsfield SB, Lukaski HC, Friedl K, Hubbard VS. Body composition estimates from NHANES III bioelectrical impedance data. Int J Obes 2002; 26: 1596-609.

21. Kurtoglu S, Mazicioglu MM, Ozturk A, Hatipoglu N, Cicek B, Ustunbas HB. Body fat reference curves for healthy Turkish children and adolescents. Eur J Pediatr 2010; 169: 1329-35.

22. Nakao T, Komiya S. Reference norms for a fat-free mass index and fat mass index in the Japanese child population. J Physiol Anthropol Appl Human Sci 2003; 22: 293-8.

23. Alwis G, Rosengren B, Stenevi-Lundgren S, Duppe H, Sernbo I, Karlsson MK. Normative dual energy X-ray absorptiometry data in Swedish children and adolescents. Acta Paediatr 2010; 99: 1091-9.

24. van der Sluis IM, de Ridder MA, Boot AM, Krenning EP, de Muinck Keizer-Schrama SM. Reference data for bone density and body composition measured with dual energy x ray absorptiometry in white children and young adults. Arch Dis Child 2002; 87: 341-7.

25. Ogden CL, Li Y, Freedman DS, Borrud LG, Flegal KM. Smoothed percentage body fat percentiles for U.S. children and adolescents, 1999-2004. Natl Health Stat Report 2011; (43): 1-7.

26. Freeman JV, Cole TJ, Chinn S, Jones PR, White EM, Preece MA. Cross sectional stature and weight reference curves for the UK, 1990. Arch Dis Child 1995; 73: 17-24.

27. Chomtho S, Fewtrell MS, Jaffe A, Williams JE, Wells JC. Evaluation of arm anthropometry for assessing pediatric body composition: evidence from healthy and sick children. Pediatr Res 2006; 59: 860-5.

28. Racette SB, Schoeller DA, Luke AH, Shay K, Hnilicka J, Kushner RF. Relative dilution spaces of 2H- and 18O-labeled water in humans. Am J Physiol 1994;67: E585-E90.

29. Haroun D, Wells JC, Williams JE, Fuller NJ, Fewtrell MS, Lawson MS. Composition of the fat-free mass in obese and nonobese children: matched case-control analyses. Int J Obes 2005; 29: 29-36.

30. Murphy AJ, Wells JC, Williams JE, Fewtrell MS, Davies PS, Webb DK. Body composition in children in remission from acute lymphoblastic leukemia. Am J Clin Nutr 2006; 83: 70-4.

31. Fuller NJ, Jebb SA, Laskey MA, Coward WA, Elia M. Four-component model for the assessment of body composition in humans: comparison with alternative methods, and evaluation of the density and hydration of fat-free mass. Clin Sci 1992; 82: 687-93.

32. Wells JC, Fuller NJ, Dewit O, Fewtrell MS, Elia M, Cole TJ. Four-component model of body composition in children: density and hydration of fat-free mass and comparison with simpler models. Am J Clin Nutr 1999; 69: 904-12.

33. Wells JC, Haroun D, Williams JE, Darch T, Eaton S, Viner R, Fewtrell MS. Evaluation of lean tissue density for use in air displacement plethysmography in obese children and adolescents. Eur J Clin Nutr 2011; 65: 1094-101.

34. Kiebzak GM, Leamy LJ, Pierson LM, Nord RH, Zhang ZY. Measurement precision of body composition variables using the lunar DPX-L densitometer. J Clin Densitom 2000; 3: 35-41.

35. VanItallie TB, Yang MU, Heymsfield SB, Funk RC, Boileau RA. Height-normalized indices of the body's fat-free mass and fat mass: potentially useful indicators of nutritional status. Am J Clin Nutr. 1990; 52: 953-9.

36. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1: 307-10.

37. Fomon SJ, Haschke F, Ziegler EE, Nelson SE. Body composition of reference children from birth to age 10 years. Am J Clin Nutr 1982; 35(5 Suppl): 1169-75.

38. Wells JC, Williams JE, Chomtho S, Darch T, Grijalva-Eternod C, Kennedy K, Haroun D, Wilson C, Cole TJ, Fewtrell MS. Pediatric reference data for lean tissue properties: density and hydration from age 5 to 20 y. Am J Clin Nutr 2010; 91: 610-8.

39. Butte NF, Hopkinson JM, Wong WW, Smith EO, Ellis KJ. Body composition during the first 2 years of life: an updated reference. Pediatr Res 2000; 47(5): 578-85.

40. Wells JC, Mok Q, Johnson AW, Lanigan JA, Fewtrell MS. Energy requirements and body composition in stable pediatric intensive care patients receiving ventilatory support. Food Nutr Bull 2002; 23 (3 Suppl): 95-8.

41. Sullivan PB, Alder N, Bachlet AM, Grant H, Juszczak E, Henry J, Vernon-Roberts A, Warner J, Wells J. Gastrostomy feeding in cerebral palsy: too much of a good thing? Dev Med Child Neurol 2006; 48: 877-82.

42. Wells JC, Haroun D, Williams JE, Wilson C, Darch T, Viner RM, Eaton S, Fewtrell MS. Evaluation of DXA against the four-component model of body composition in obese children and adolescents aged 5-21 years. Int J Obes 2010; 34: 649-55.

43. Williams JE, Wells JC, Benden C, Jaffe A, Suri R, Wilson CM, Fewtrell MS. Body composition assessed by the 4-component model and association with lung function in 6-12-y-old children with cystic fibrosis. Am J Clin Nutr 2010; 92: 1332-43.

44. Parker L, Reilly JJ, Slater C, Wells JC, Pitsiladis Y. Validity of six field and laboratory methods for measurement of body composition in boys. Obes Res 2003;11: 852-8.

45. Gately PJ, Radley D, Cooke CB, Carroll S, Oldroyd B, Truscott JG, Coward WA, Wright A. Comparison of body composition methods in overweight and obese children. J Appl Physiol 2003; 95: 2039-46.

46. Williams JE, Wells JC, Wilson CM, Haroun D, Lucas A, Fewtrell MS. Evaluation of Lunar Prodigy dual-energy X-ray absorptiometry for assessing body composition in healthy persons and patients by comparison with the criterion 4-component model. Am J Clin Nutr 2006; 83: 1047-54.

47. Crabtree NJ, Shaw NJ, Boivin CM, Oldroyd B, Truscott JG. Pediatric in vivo cross-calibration between the GE Lunar Prodigy and DPX-L bone densitometers. Osteoporos Int 2005; 16: 2157-67.

48. Pludowski P, Jaworski M, Matusik H, Kobylinska M, Klimek P, Lorenc RS. The evaluation of consistency between body composition assessments in pediatric population using pencil beam and fan beam dual-energy x-ray absorptiometers. J Clin Densitom 2010; 13: 84-95.

49. Pearson D, Horton B, Green DJ. Cross Calibration of Hologic QDR2000 and GE Lunar Prodigy for Whole Body Bone Mineral Density and Body Composition Measurements. J Clin Densitom 2011; 14: 294-301.

50. Wells JC, Cole TJ. Adjustment of fat-free mass and fat mass for height in children aged 8 y. Int J Obes 2002; 26: 947-52.

51. Wells JC, Cole TJ. Disentangling the size and adiposity components of obesity. Int J Obes 2011; 35: 548-9.

52. Wells JC, Fewtrell MS, Davies PS, Williams JE, Coward WA, Cole TJ. Prediction of total body water in infants and children. Arch Dis Child 2005; 90: 965-71.

53. Sun Q, van Dam RM, Spiegelman D, Heymsfield SB, Willett WC, Hu FB. Comparison of dual-energy x-ray absorptiometric and anthropometric measures of adiposity in relation to adiposity-related biologic factors. Am J Epidemiol 2010; 172: 1442-54.

54. Steinberger J, Jacobs DR, Raatz S, Moran A, Hong CP, Sinaiko AR. Comparison of body fatness measurements by BMI and skinfolds vs dual energy X-ray absorptiometry and their relation to cardiovascular risk factors in adolescents. Int J Obes 2005; 29: 1346-52.

Table 1. Summary statistics for anthropometry and weight status by sex

	Males (n = 261)			Females (n = 272)		
	Mean	SD	Range	Mean	SD	Range
Weight SDS	0.31	1.08	-2.42, 3.44	0.42	1.10	-2.75, 3.46
Height SDS	0.21	0.96	-2.09, 3.28	0.34	1.02	-2.77, 3.42
BMI SDS	0.24	1.15	-2.99, 3.49	0.31	1.15	-3.33, 3.32
% fat (4C model)*	19.2	8.0	4.9, 45.5	27.0	8.0	11.7, 46.9
	Prevalence			Prevalence		
Overweight (%)	9.2			10.7		
Obese (%)	11.5			14.7		

* % fat different between sexes $p<0.0001$, using multiple regression analysis to assess significance of female gender adjusting for age.

SD – standard deviation. SDS – standard deviation scores calculated using UK reference data (6,25). Overweight categorised as BMI SDS > 1.04 (85th centile). Obese categorised as BMI SDS > 1.64 (95th centile).

Table 2. Fat-free mass reference data for males and females, by z-score or percentile

Age (y)	Males							Females						
	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0
5.0	12.76	13.89	15.08	16.35	17.70	19.13	20.64	11.24	12.27	13.39	14.60	15.91	17.33	18.86
6.0	14.10	15.37	16.72	18.16	19.69	21.31	23.03	12.83	14.02	15.30	16.70	18.21	19.85	21.62
7.0	15.32	16.73	18.23	19.83	21.54	23.34	25.26	14.49	15.84	17.31	18.91	20.64	22.51	24.55
8.0	16.56	18.12	19.79	21.56	23.45	25.45	27.58	16.23	17.77	19.45	21.26	23.24	25.38	27.71
9.0	18.02	19.76	21.62	23.61	25.73	27.98	30.38	17.88	19.61	21.49	23.54	25.77	28.20	30.83
10.0	19.66	21.62	23.72	25.98	28.38	30.95	33.68	19.56	21.49	23.60	25.89	28.39	31.12	34.08
11.0	21.60	23.85	26.28	28.88	31.67	34.64	37.83	21.62	23.79	26.16	28.74	31.56	34.63	37.98
12.0	24.06	26.71	29.56	32.63	35.94	39.48	43.27	24.23	26.66	29.31	32.21	35.37	38.82	42.58
13.0	27.24	30.36	33.75	37.41	41.35	45.59	50.14	27.06	29.71	32.61	35.76	39.19	42.93	47.00
14.0	31.09	34.72	38.65	42.91	47.50	52.44	57.75	29.67	32.46	35.49	38.77	42.34	46.21	50.41
15.0	35.03	39.06	43.41	48.12	53.19	58.64	64.50	31.62	34.46	37.54	40.87	44.48	48.38	52.59
16.0	38.55	42.82	47.43	52.39	57.73	63.46	69.59	32.81	35.67	38.76	42.10	45.70	49.59	53.78
17.0	41.35	45.74	50.47	55.55	60.99	66.82	73.05	33.46	36.32	39.41	42.75	46.34	50.21	54.38
18.0	43.45	47.90	52.68	57.80	63.28	69.13	75.38	33.71	36.57	39.67	43.00	46.58	50.45	54.61
19.0	45.02	49.50	54.30	59.43	64.92	70.77	77.00	33.75	36.62	39.71	43.04	46.63	50.49	54.65
20.0	46.24	50.73	55.54	60.68	66.17	72.01	78.22	33.86	36.73	39.82	43.15	46.73	50.59	54.75

Z-score equivalents in centiles as follows: -2 = 2.3%; -1.67 = 9.2%; -1.33 = 25.2%; 0 = 50%; 1.33 = 74.8%; 1.67 = 90.8%; 2 = 97.7%

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Table 3. Fat mass reference data for males and females, by z-score or percentile

Age	Males							Females						
(y)	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0
5.0	1.37	1.77	2.32	3.11	4.26	6.00	8.72	1.60	2.12	2.87	3.97	5.59	8.09	12.06
6.0	1.61	2.09	2.76	3.71	5.11	7.25	10.62	2.02	2.67	3.60	4.95	6.95	9.99	14.78
7.0	1.85	2.40	3.18	4.31	5.97	8.52	12.60	2.45	3.23	4.34	5.94	8.29	11.85	17.41
8.0	2.08	2.71	3.61	4.91	6.84	9.84	14.66	2.89	3.80	5.09	6.92	9.61	13.66	19.94
9.0	2.30	3.01	4.03	5.50	7.72	11.18	16.81	3.34	4.38	5.84	7.91	10.93	15.44	22.37
10.0	2.52	3.31	4.44	6.10	8.61	12.56	19.04	3.81	4.97	6.59	8.89	12.23	17.17	24.72
11.0	2.73	3.60	4.85	6.70	9.51	13.97	21.37	4.28	5.57	7.36	9.88	13.51	18.86	26.97
12.0	2.93	3.89	5.26	7.30	10.42	15.42	23.80	4.76	6.18	8.13	10.86	14.78	20.52	29.15
13.0	3.13	4.16	5.66	7.89	11.34	16.90	26.33	5.26	6.80	8.91	11.85	16.04	22.14	31.23
14.0	3.32	4.44	6.06	8.49	12.28	18.43	28.96	5.77	7.43	9.69	12.84	17.29	23.72	33.24
15.0	3.51	4.71	6.45	9.09	13.22	19.99	31.70	6.29	8.07	10.48	13.82	18.52	25.26	35.17
16.0	3.70	4.97	6.84	9.69	14.18	21.59	34.55	6.82	8.72	11.28	14.81	19.74	26.77	37.03
17.0	3.87	5.23	7.23	10.28	15.14	23.23	37.53	7.37	9.38	12.09	15.79	20.94	28.24	38.82
18.0	4.05	5.48	7.61	10.88	16.12	24.92	40.62	7.93	10.05	12.90	16.78	22.14	29.68	40.53
19.0	4.21	5.73	7.99	11.48	17.11	26.64	43.85	8.50	10.74	13.72	17.76	23.32	31.09	42.18
20.0	4.38	5.97	8.36	12.08	18.11	28.41	47.21	9.08	11.43	14.55	18.75	24.49	32.46	43.76

Z-score equivalents in centiles as follows: -2 = 2.3%; -1.67 = 9.2%; -1.33 = 25.2%; 0 = 50%; 1.33 = 74.8%; 1.67 = 90.8%; 2 = 97.7%

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Table 4. Fat-free mass index reference data for males and females, by z-score or percentile

Age	Males							Females						
(y)	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0
5.0	11.59	12.13	12.68	13.25	13.84	14.43	15.04	10.75	11.16	11.61	12.11	12.68	13.33	14.07
6.0	11.59	12.13	12.69	13.27	13.87	14.49	15.14	10.88	11.32	11.81	12.35	12.94	13.59	14.33
7.0	11.50	12.03	12.59	13.17	13.79	14.43	15.11	10.98	11.47	12.00	12.57	13.20	13.89	14.64
8.0	11.43	11.95	12.50	13.09	13.72	14.39	15.10	11.05	11.59	12.18	12.81	13.49	14.22	15.03
9.0	11.48	11.99	12.55	13.15	13.79	14.49	15.25	11.10	11.69	12.33	13.01	13.76	14.56	15.43
10.0	11.61	12.15	12.72	13.35	14.03	14.78	15.59	11.16	11.80	12.49	13.24	14.05	14.93	15.89
11.0	11.80	12.38	13.02	13.71	14.48	15.32	16.27	11.31	12.00	12.75	13.56	14.44	15.40	16.45
12.0	12.05	12.71	13.44	14.24	15.14	16.15	17.28	11.57	12.29	13.09	13.95	14.91	15.95	17.11
13.0	12.45	13.19	14.02	14.95	15.98	17.15	18.49	11.89	12.64	13.47	14.39	15.40	16.52	17.77
14.0	12.98	13.81	14.74	15.76	16.91	18.20	19.65	12.24	13.01	13.85	14.80	15.84	17.01	18.33
15.0	13.55	14.46	15.46	16.56	17.78	19.13	20.63	12.57	13.33	14.18	15.12	16.18	17.37	18.72
16.0	14.07	15.06	16.12	17.28	18.53	19.88	21.36	12.84	13.58	14.41	15.33	16.37	17.56	18.91
17.0	14.51	15.57	16.69	17.87	19.13	20.45	21.86	13.03	13.75	14.54	15.43	16.44	17.60	18.93
18.0	14.87	15.99	17.15	18.36	19.60	20.88	22.19	13.18	13.85	14.60	15.45	16.41	17.52	18.81
19.0	15.14	16.33	17.53	18.74	19.96	21.19	22.42	13.28	13.91	14.61	15.40	16.31	17.37	18.60
20.0	15.34	16.60	17.83	19.05	20.24	21.41	22.57	13.35	13.93	14.58	15.32	16.18	17.17	18.35

Z-score equivalents in centiles as follows: -2 = 2.3%; -1.67 = 9.2%; -1.33 = 25.2%; 0 = 50%; 1.33 = 74.8%; 1.67 = 90.8%; 2 = 97.7%

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Table 5. Fat mass index reference data for males and females, by z-score or percentile

Age	Males							Females						
(y)	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0	Z=-2.0	Z=-1.33	Z=-0.67	Z=0	Z=0.67	Z=1.33	Z=2.0
5.0	1.41	1.79	2.26	2.84	3.56	4.45	5.53	1.59	1.99	2.53	3.30	4.42	6.14	8.90
6.0	1.24	1.60	2.06	2.65	3.38	4.32	5.49	1.67	2.11	2.70	3.54	4.77	6.63	9.58
7.0	1.11	1.44	1.88	2.45	3.20	4.17	5.45	1.75	2.22	2.86	3.77	5.10	7.10	10.24
8.0	1.12	1.46	1.92	2.54	3.38	4.52	6.10	1.83	2.33	3.03	4.01	5.43	7.56	10.87
9.0	1.29	1.69	2.23	2.98	4.03	5.55	7.76	1.91	2.45	3.19	4.24	5.75	8.00	11.47
10.0	1.45	1.89	2.50	3.37	4.66	6.59	9.61	1.98	2.56	3.35	4.46	6.06	8.42	12.00
11.0	1.51	1.95	2.59	3.52	4.93	7.17	10.91	2.07	2.68	3.51	4.68	6.35	8.79	12.44
12.0	1.45	1.88	2.49	3.40	4.83	7.20	11.43	2.16	2.80	3.68	4.90	6.63	9.12	12.80
13.0	1.35	1.75	2.32	3.18	4.57	6.96	11.49	2.26	2.93	3.85	5.11	6.88	9.41	13.07
14.0	1.28	1.65	2.19	3.02	4.37	6.76	11.54	2.36	3.06	4.01	5.32	7.12	9.65	13.26
15.0	1.23	1.59	2.10	2.90	4.23	6.61	11.54	2.47	3.20	4.18	5.51	7.33	9.85	13.38
16.0	1.20	1.55	2.06	2.84	4.15	6.54	11.53	2.59	3.34	4.35	5.70	7.52	10.01	13.43
17.0	1.22	1.58	2.10	2.90	4.24	6.69	11.84	2.71	3.49	4.51	5.88	7.69	10.13	13.43
18.0	1.32	1.70	2.27	3.14	4.60	7.25	12.78	2.84	3.64	4.68	6.05	7.84	10.22	13.38
19.0	1.48	1.92	2.56	3.55	5.19	8.17	14.31	2.98	3.79	4.85	6.21	7.98	10.29	13.31
20.0	1.67	2.16	2.89	4.01	5.87	9.21	16.01	3.12	3.95	5.01	6.37	8.11	10.35	13.22

Z-score equivalents in centiles as follows: -2 = 2.3%; -1.67 = 9.2%; -1.33 = 25.2%; 0 = 50%; 1.33 = 74.8%; 1.67 = 90.8%; 2 = 97.7%

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Table 6. Correlations for adiposity outcomes expressed in standard deviation score (SDS) format

Males: / Females:	Biceps	Triceps	Subscap	Suprailiac	Mean skinfold	Density	4C fat mass	DXA fat mass	DXA arm fat	DXA leg fat	DXA trunk fat
Biceps	-	0.86	0.78	0.76	0.92	-0.79	0.84	0.82	0.87	0.81	0.79
Triceps	0.82	-	0.74	0.82	0.93	-0.82	0.83	0.83	0.86	0.81	0.81
Subscapular	0.68	0.78	-	0.78	0.90	-0.75	0.81	0.84	0.82	0.81	0.83
Suprailiac	0.69	0.80	0.79	-	0.92	-0.82	0.83	0.84	0.83	0.81	0.85
Mean skinfold	0.88	0.94	0.90	0.91	-	-0.87	0.90	0.91	0.92	0.88	0.89
Density	-0.77	-0.82	-0.76	-0.81	-0.88	-	-0.90	-0.87	-0.86	-0.83	-0.86
4C fat mass	0.78	0.84	0.80	0.80	0.89	-0.93	-	0.94	0.92	0.93	0.94
DXA fat mass	0.77	0.84	0.81	0.79	0.89	-0.88	0.98	-	0.95	0.97	0.98
DXA arm fat	0.81	0.87	0.80	0.79	0.91	-0.88	0.95	0.97	-	0.92	0.94
DXA leg fat	0.75	0.82	0.75	0.75	0.85	-0.86	0.95	0.97	0.93	-	0.93
DXA trunk fat	0.75	0.82	0.82	0.80	0.88	-0.87	0.96	0.98	0.95	0.93	-

Pearson correlation coefficients: male values above diagonal, female values below diagonal. All correlations significant $p<0.0001$

N = 245 males, 259 females

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Table 7. Intercepts, slopes and standard errors of the estimate for the regression of 4C fat mass SDS on individual adiposity SDS

Predictor	Males					Females				
	Intercept	SE	Slope	SE	SEE	Intercept	SE	Slope	SE	SEE
Biceps	0.044	0.036	0.840	0.036	0.55	0.032	0.040	0.802	0.041	0.63
Triceps	0.027	0.036	0.836	0.036	0.56	0.028	0.034	0.856	0.035	0.54
Subscapular	0.046	0.038	0.821	0.038	0.58	0.032	0.038	0.828	0.039	0.60
Suprailiac	0.037	0.037	0.862	0.038	0.58	0.037	0.039	0.820	0.039	0.61
Mean skinfold	0.038	0.026	0.837	0.026	0.40	0.028	0.027	0.826	0.027	0.41
Density	-0.017	0.028	-0.892	0.027	0.43	0.021	0.024	-0.927	0.024	0.38
DXA fat mass	0.018	0.021	0.941	0.021	0.33	0.010	0.013	0.979	0.013	0.21
DXA arm fat	0.002	0.025	0.926	0.025	0.39	0.017	0.018	0.946	0.018	0.30
DXA leg fat	0.006	0.024	0.931	0.024	0.37	-0.002	0.019	0.951	0.019	0.30
DXA trunk fat	0.010	0.023	0.923	0.022	0.35	-0.0.004	0.017	0.962	0.017	0.27

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4C fat mass SDS regressed on each individual adiposity SDS

All slopes significantly different from 1 ($p<0.05$) except for DXA fat mass in girls

SE – standard error; SEE – standard error of the estimate

N = 245 males, 259 females

Table 8. Correlations for fat-free mass outcomes expressed in standard deviation score (SDS) format

Males:	Total body	4C FFM	DXA FFM	DXA arm FFM	DXA leg FFM	DXA trunk	Height^2/Z
Females:	water					FFM	
Total body water	-	0.98	0.95	0.84	0.92	0.91	0.90
4C FFM	0.99	-	0.98	0.86	0.95	0.94	0.91
DXA FFM	0.96	0.97	-	0.88	0.96	0.97	0.91
DXA arm FFM	0.86	0.88	0.89	-	0.83	0.80	0.86
DXA leg FFM	0.94	0.95	0.96	0.84	-	0.87	0.89
DXA trunk FFM	0.91	0.93	0.97	0.82	0.87	-	0.86
Height^2/Z	0.90	0.90	0.90	0.84	0.87	0.86	-

Pearson correlation coefficients: male values above diagonal, female values below diagonal. All correlations significant $p<0.0001$

N = 245 males (except BIA, n = 195), 259 females (except BIA, n = 227)

FFM – fat free mass

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Table 9. Intercepts, slopes and standard errors of the estimate for the regression of 4C fat-free mass SDS on individual fat-free mass SDS

Predictor	Males					Females				
	Intercept	SE	Slope	SE	SEE	Intercept	SE	Slope	SE	SEE
Total body water	0.009	0.013	0.985	0.013	0.20	-0.002	0.009	0.987	0.009	0.15
DXA FFM	0.002	0.013	0.973	0.013	0.21	-0.006	0.014	0.977	0.014	0.23
DXA arm FFM	0.003	0.033	0.864	0.032	0.51	-0.014	0.030	0.881	0.030	0.48
DXA leg FFM	0.000	0.021	0.947	0.021	0.33	-0.007	0.020	0.949	0.020	0.32
DXA trunk FFM	0.002	0.022	0.920	0.022	0.34	-0.004	0.023	0.933	0.023	0.37
$Height^2/Z$	-0.012	0.030	0.911	0.030	0.42	-0.012	0.029	0.901	0.029	0.44

4C fat-free mass SDS regressed on each individual fat-free mass SDS

All slopes significantly different from 1 ($p<0.05$) except TBW in both sexes and DXA fat-free mass in both sexes

SE – standard error; SEE – standard error of the estimate; FFM – fat-free mass

N = 245 males (except BIA, n = 195), 259 females (except BIA, n = 227)

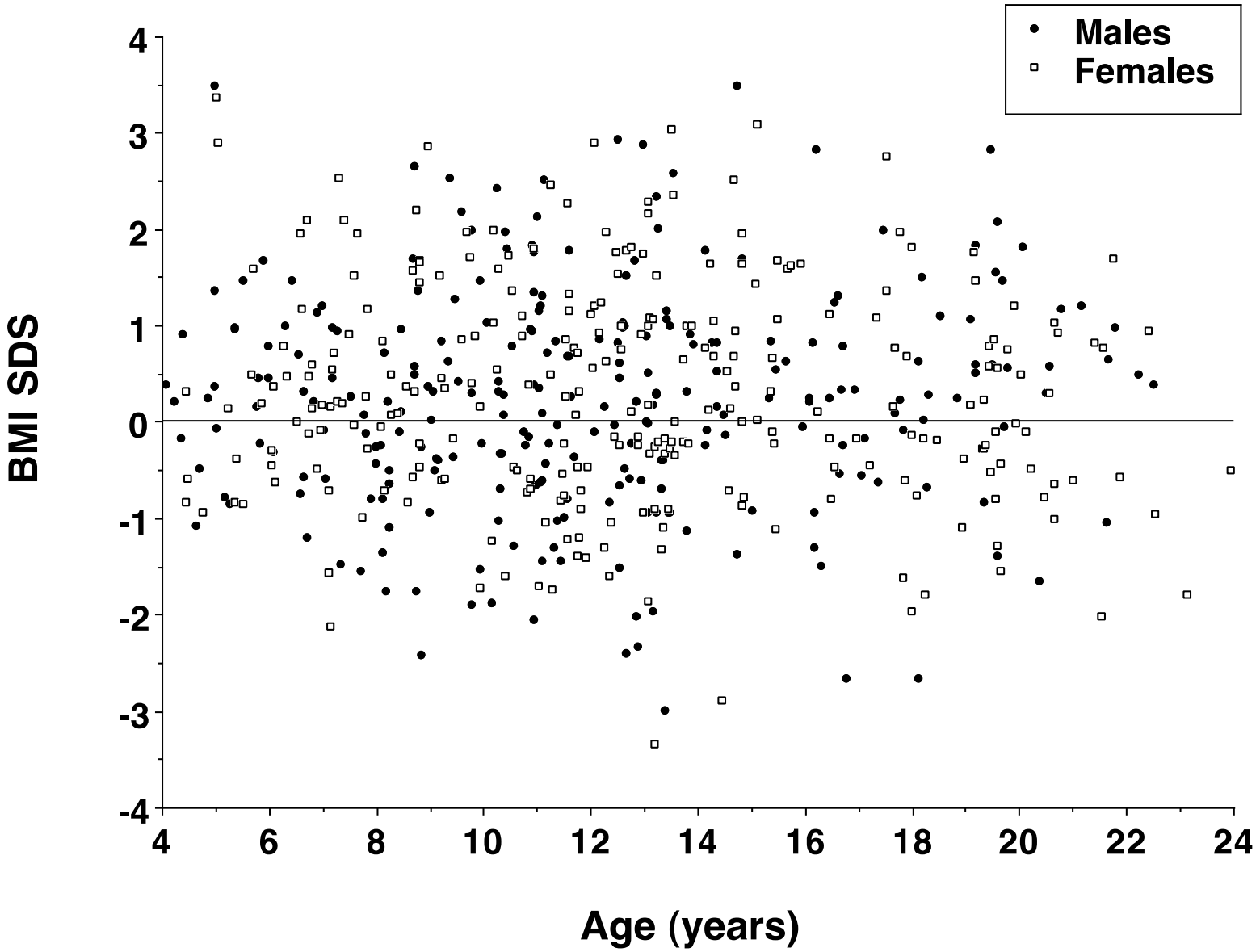
Legends for illustrations

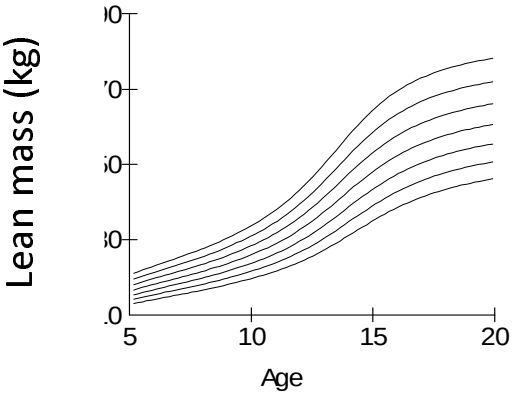
Figure 1. Distribution of body mass index standard deviation score (BMI SDS) against age in the sample. N = 261 males and 272 females.

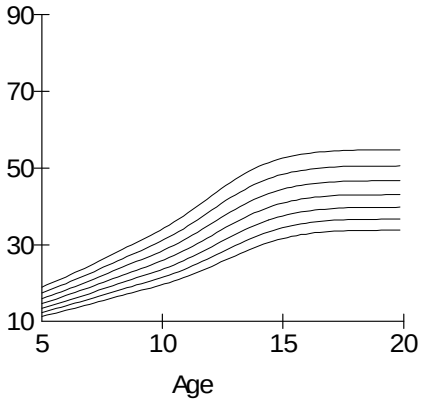
Figure 2. Centiles for fat-free mass, fat mass, fat-free mass index and fat mass index by the 4-component model for males (n = 261, left hand panel) and females (n = 272, right hand panel). The 2nd, 9th, 25th, 50th, 75th, 91st and 98th centiles are displayed.

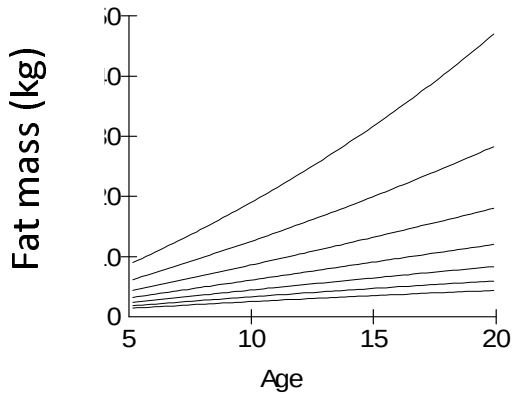
Figure 3. Bland Altman plots illustrating agreement between DXA fat-free mass SDS and 4C fat-free mass SDS (upper panel), and DXA fat SDS and 4C fat mass SDS (lower panel), in males (n = 245, left hand side) and females (n = 259, right hand side). The scatter plot shows agreement between techniques in individuals, the dotted lines show mean bias and the limits of agreement (±2 standard deviations of the bias).

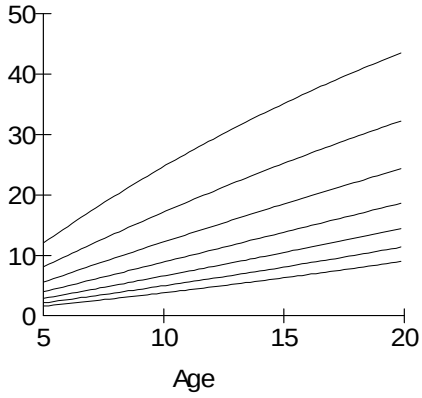
Figure 4. Bland Altman plots illustrating agreement between $Height^2/Z$ SDS and DXA fat-free mass SDS (upper panel), and the average of 4 skinfold SDS and 4C fat mass SDS (lower panel), in males (n = 195 for BIA and 245 for skinfolds, left hand side) and females (n = 227 for BIA and 259 for skinfolds, right hand side). The scatter plot shows agreement between techniques in individuals, the dotted lines show mean bias and the limits of agreement (±2 standard deviations of the bias).

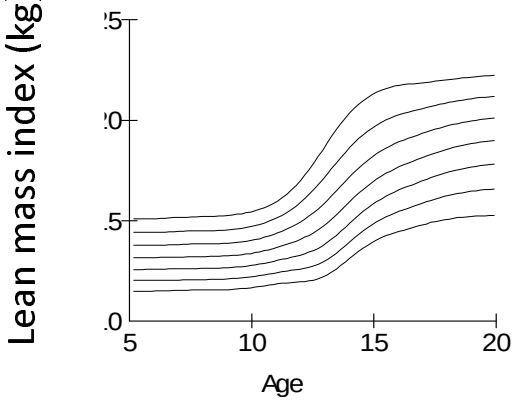


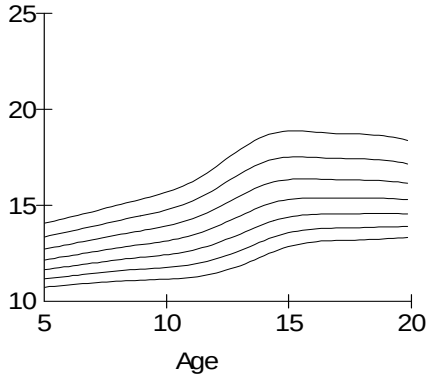

Lean mass (kg)
5
10
15
20
Age

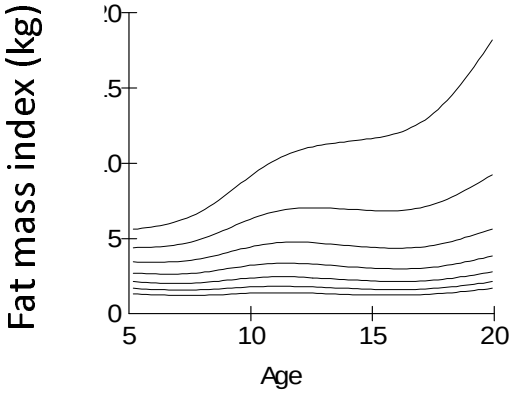

90
70
50
30
10
5
10
15
20
Age

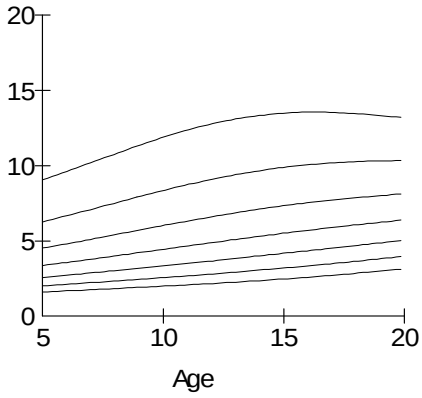

Fat mass (kg)
0
5
10
15
20
Age

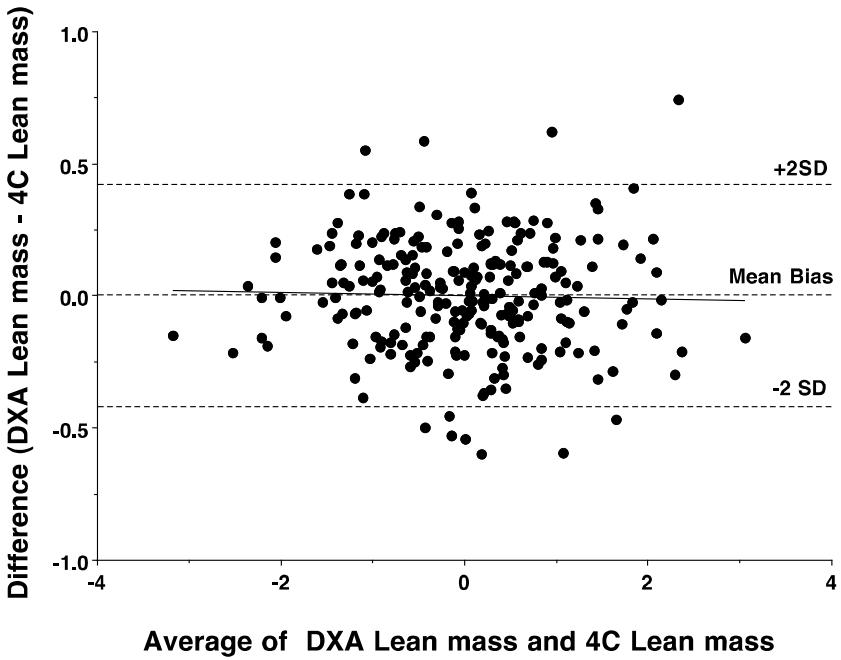

50
40
30
20
10
0
5
10
15
20
Age

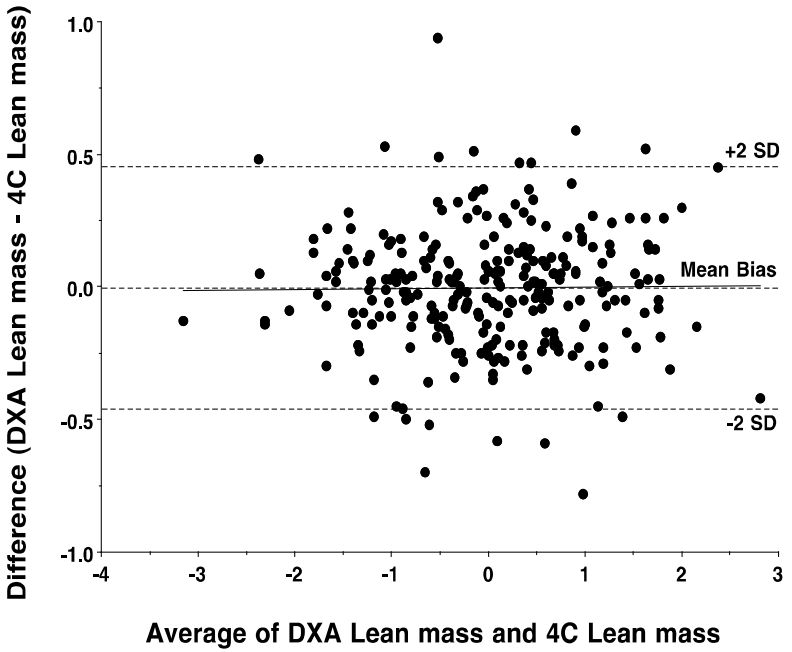

Lean mass index (kg)
5
10
15
20
Age

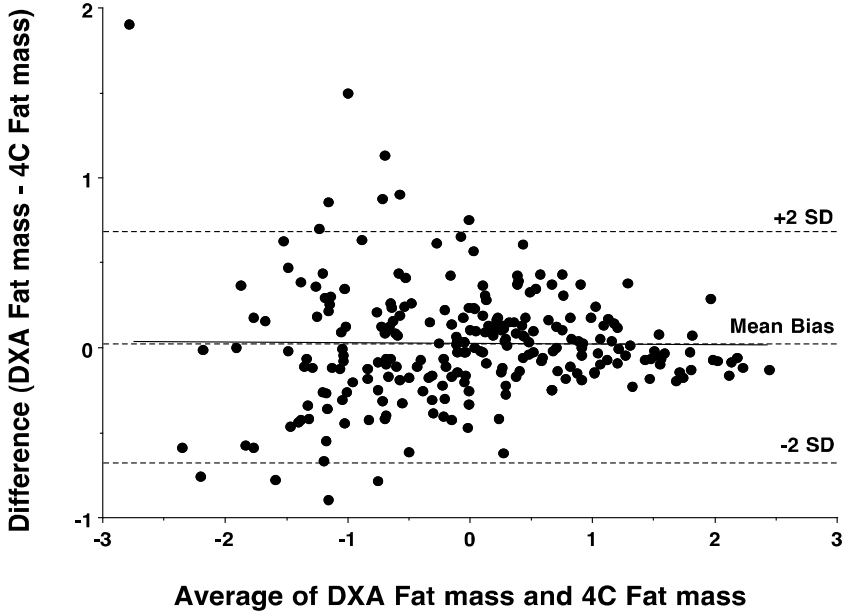

25
20
15
10
5
10
15
20
Age

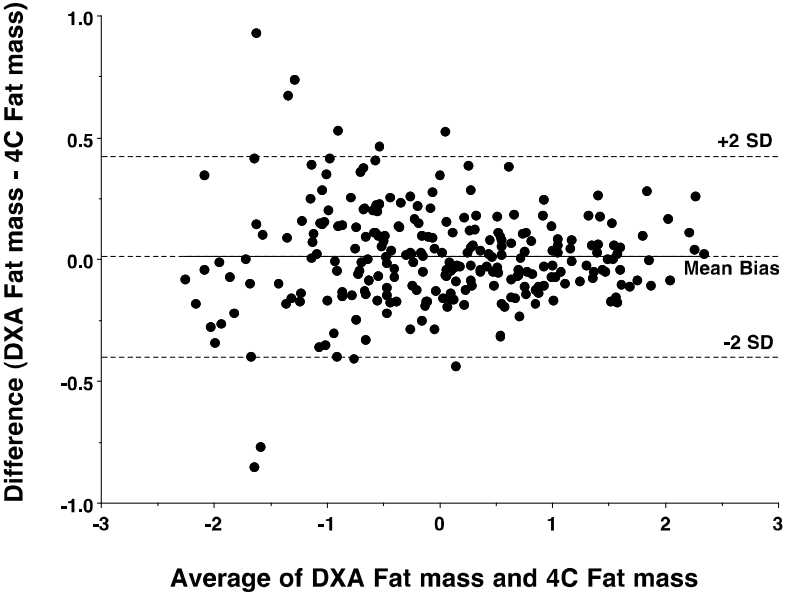

Fat mass index (kg)
5
10
15
20
Age


20
15
10
5
0
5
10
15
20
Age









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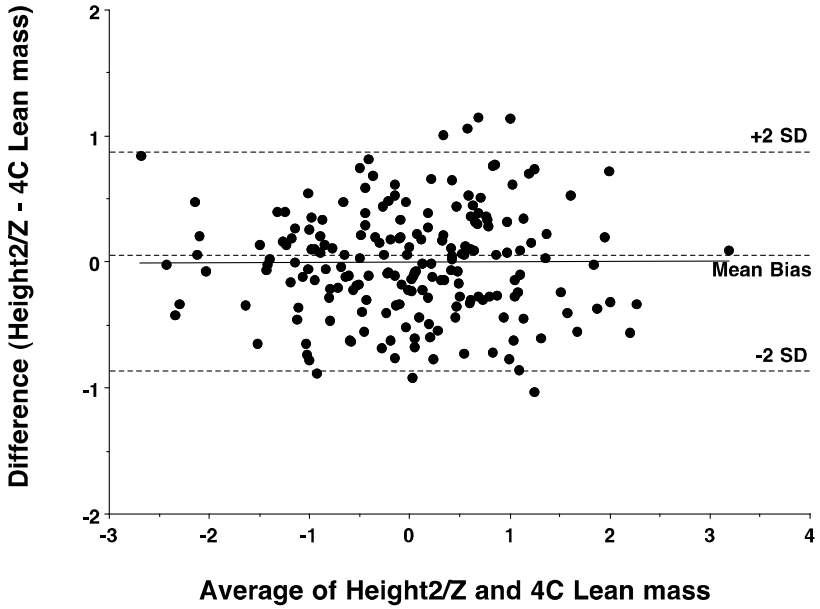

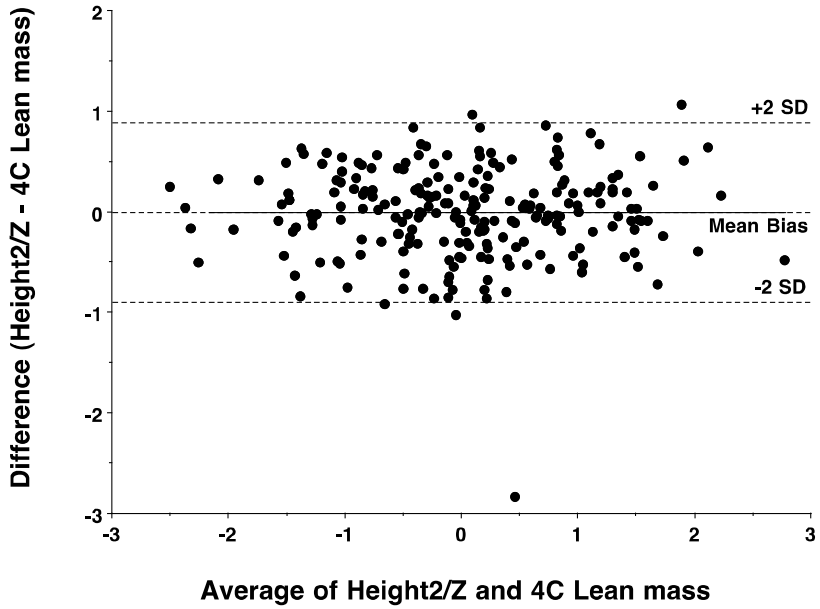

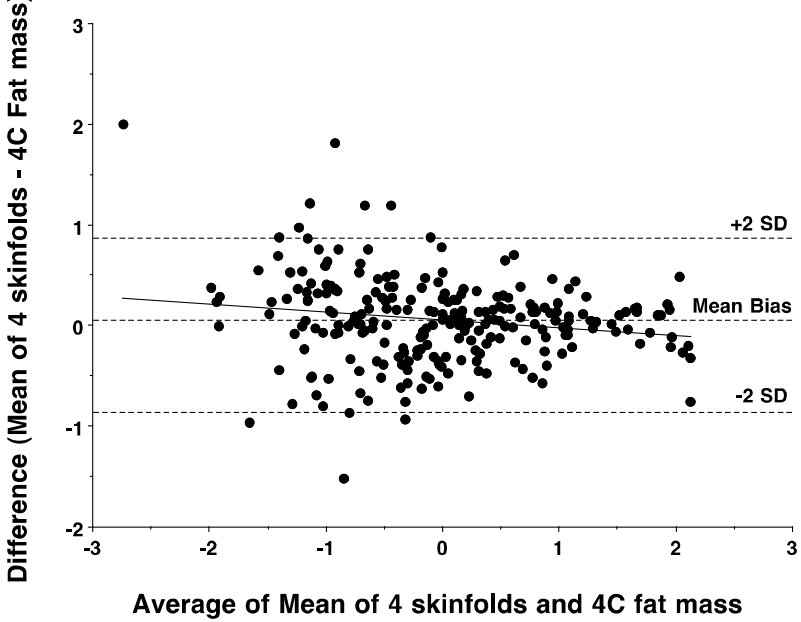

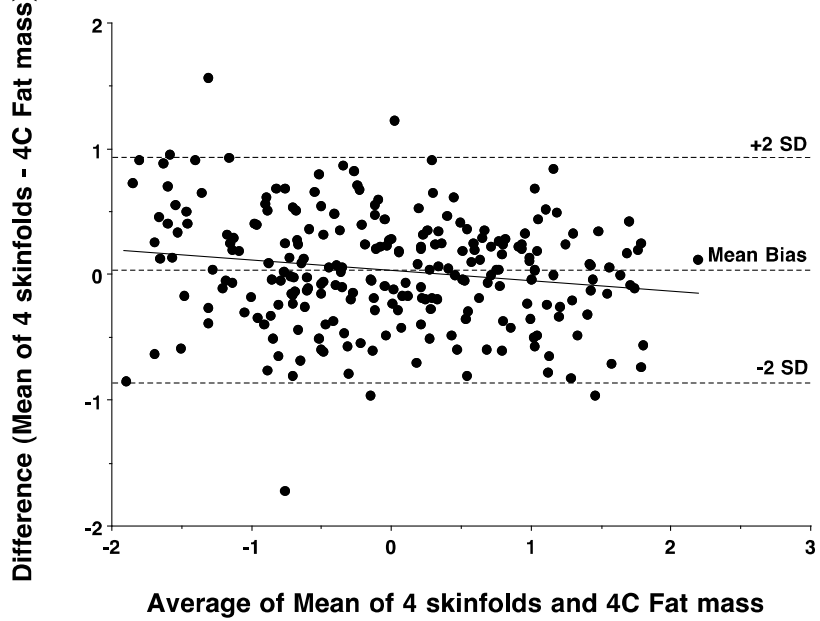

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