Title: Can waist circumference provide a new "third" dimension to BMI when predicting percentage body fat in children? Insights using allometric modelling.

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Abstract

Introduction: Body mass index (BMI) is often criticised for not being able to distinguish between lean and fat tissue. Waist circumference (WC), adjusted for stature, is proposed as an alternative weight-status index, as it is more sensitive to changes in central adiposity.

Purpose: To combine the three dimensions of height, mass and WC to provide a simple, meaningful and more accurate index associated with percentage body fat (BF%).

Methods: We employed a four independent sample design. Sample 1 consisted of 551 children (320 boys) (Mean ± S.D. of age = 7.2 ± 2.0 years), recruited from London, UK. Samples 2, 3 and 4 consisted of 5387 children (2649 boys) aged 7-17 years recruited from schools in Portugal. Allometric modelling was used to identify the most effective anthropometric index associated with BF%. The data from sample 2, 3 and 4 were used to confirm and cross validate the model derived in sample 1.

Results: The allometric models from all four samples identified a positive mass exponent and a negative height exponent that was approximately twice that of the mass exponent and a waist circumference exponent that was approximately half the mass exponent. Consequently, the body-shape index most strongly associated with BF% was $\mathrm{BMI}\sqrt{\mathrm{WC}}$. The $\sqrt{\mathrm{WC}}$ component of the new index can simply be interpreted as a WC "weighting" of the traditional BMI.

Conclusions: Compared to using BMI and WC in isolation, $\mathrm{BMI}\sqrt{\mathrm{WC}}$ could provide a more effective and equally non-invasive proxy for BF% in children that can be used in public and community health settings.

Introduction

Excess adiposity is a modifiable risk factor for cardiovascular disease in children and young people (1) and is also associated with several other negative health outcomes in childhood including type 2 diabetes mellitus, hypertension, non-alcoholic fatty liver disease, obstructive sleep apnea, and dyslipidemia (2). With approximately one quarter to one third of children in Europe being classified as overweight or obese (3), monitoring and assessment of adiposity status in children and young people has become important to effectively target interventions aimed at preventing or treating diseases related to excess body fatness.

Anthropometric measures remain the most popular means of weight status assessment in epidemiological studies, potentially due to their ease of administration and low cost (4,5). Despite its considerable shortcomings, body mass index (BMI) has historically been used for this purpose and its use persists in epidemiological and clinical research studies. More recently, there has been an emphasis on anthropometric alternatives to BMI such as waist circumference (WC) or waist-to-height ratio (6). This move to include measures of WC is logical as measures of centralised obesity are superior to BMI in detecting cardiovascular and cardiometabolic disease (7,8) and greater abdominal obesity is an independent risk factor in addition to BMI (9,10).

Considering or normalising for stature is essential in refining the use of anthropometric indices of adiposity status and although stature is considered when BMI is employed, BMI particularly underestimates the extent of the obesity prevalence (11,12), irrespective of what cut-off values are employed, particularly in

children. Children's WC grows naturally with height and age so it is imperative to be able to scale their WC for differences in body size. Recent work employing allometric modelling has highlighted the importance of scaling WC for stature in culturally diverse samples of children (13) as it enables more accurate identification of factors associated with excessive WC as children grow into adulthood. Given that WC is associated with cardiovascular disease risk factors in children (14), this could then be used as a key tool in the assessment of adiposity status for prevention and treatment purposes in instances where adiposity status is important. However, there remains debate regarding which anthropometric measures may best explain actual adiposity. This study sought to address this issue by investigating the possibility that both WC and BMI might be combined to provide a simple, meaningful and more accurate index associated with percentage body fat. Hence the purpose of the current study was to incorporate WC as a third dimension (in addition to mass and height) to predict percentage body fat using allometric modelling.

Methods

Study Design

This study employed a four independent sample design. In sample 1, we compared the contribution of body mass, height and WC to percentage body fat in a sample of British children (sample 1, details below). We then used allometric modelling to identify the most effective anthropometric index to predict percentage body fat. Using the three separate, independent samples of Portuguese children (details also below), we then performed the same analysis to examine if the models identified in sample 1 were consistent with samples 2, 3 and 4 thereby, cross

validating the model developed in sample 1 with data from the three independent samples of Portuguese children.

Participants

Four independent samples were recruited in the present study. Institutional ethics approval was obtained from Middlesex University (sample 1) and the University of Porto (samples 2, 3 and 4) respectively, and written parental informed consent were provided prior to any data collection. Samples consisted of children in the age range 4-15 years.

- Sample 1 consisted of 551 children (320 boys) aged 4-10 years old (Mean ± S.D. of age = 7.2 ± 2.0 years), recruited from primary schools within the city of London, UK.

- Sample 2 consisted of 1277 children (593 boys) aged 10-17 years (Mean ± S.D. of age = 12 ± 2.06 years) recruited from schools in the North and Central regions of mainland Portugal, as well as from the Azores Islands. Within the sample there were a small number of 16 and 17-year-old children. These were combined into the 15 year old group, i.e., 15+, for analysis (see 15).

- Sample 3 consisted of 1745 children (859 boys) aged 7-17 years old, recruited as part of the Active Vouzela project in the midlands of Portugal (see 16).

- Sample 4 consisted of 2365 children (1197 boys) aged 8-17 years old, recruited as part of the Portuguese sibling study on growth, fitness, lifestyle and health. (see 17**).**

Procedures

The procedures used for data collection in both samples were identical and employed the same measurement techniques. Anthropometric measurements were carried out individually with children wearing shorts and t-shirt and without shoes. Height (m) and body mass (kg) were recorded to the nearest cm and 0.1 kg respectively using a stadiometer (SECA Instruments Ltd., Hamburg, Germany) and electronic weighing scales (Tanita, Tokyo, Japan), respectively. BMI was calculated as kg/m^2. For all samples percent body fat (BF%) was determined using bioelectrical impedance analysis (sample 1: Tanita BF350, Tanita, Tokyo, Japan; samples 2, 3 and 4: Tanita BC-418, Tokyo, Japan). WC was assessed using a non-stretchable anthropometric tape measure, placed midway between the 10th rib and superior iliac crest in line with recommended guidelines (18).

Statistical Methods

The association between BF% and body size was analyzed using two proportional allometric models similar to those used to analyze the association between skinfolds and body size (19). The first model (Eq.1) incorporates height (H) and mass (M) as the body-size dimensions and the second (Eq.2) added WC as a third additional variable/dimension.

$$BF\% = a \cdot H^{b_1} \cdot M^{b_2}, \tag{1}$$

$$BF\% = a \cdot H^{b_1} \cdot M^{b_2} \cdot WC^{b_3}, \tag{2}$$

where 'a' is the scaling constant that is allowed to vary between the children's age groups and sex, and b_1, b_2 and b_3 are the stature, mass and WC scaling exponents respectively.

Both proportional allometric models (Eqs 1 and 2) can be linearized with a log-transformation that will naturally overcome the positive skewness in such data [e.g., sample 1, the skewness for boys' BF%=0.77 (SE=0.128); skewness for girls' BF%=1.04 (SE=0.143)]. ANCOVA was then used to estimate the effects of age and sex as fixed factors on log-transformed BF% [Ln(BF%)] having controlled for differences in body shape using the confounding body-size covariates (log-transformed stature, mass and WC). The concept of body shape is defined as the ratio of two (or more) body-size dimensions, such as the reciprocal ponderal index ($H/M^{0.333}$), that yields a 'dimensionless' ratio variable reflecting body shape (see 20).

Results

Sample 1

Descriptive statistics of key variables from each of the four samples are given in Table 1a-d.

Results from the first stage of the analysis using sample 1, (model 1) identified a significant main effect by age (due to a steady decline in BF% in the older children (age, P<0.001, see Figure 1), plus a main effect due to sex (P<0.001), but with no age-by-sex interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.576). The allometric model for Ln(BF%) identified the height exponent to be -2.39 (SE=0.22; 95% CI -2.83 to -1.96) and the mass exponent to be 1.4 (SE=0.055; 95% CI 1.292 to 1.507). With a positive

mass exponent and a negative height exponent that is approximately twice that of the mass exponent, the body shape ratio most strongly associated with BF% would appear to be BMI. The fitted exponents from Sample 1 using Model 1 are summarized in row 1 of Table 2.

The second analysis for sample 1 (model 2) also identified a significant main effect of age (again due to a steady decline in BF% in the older children (age, P<0.001)), plus a significant main effect due to sex (P<0.001), again with no interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.614). The allometric model for Ln(BF%) identified the height exponent to be -2.32 (SE=0.25; 95% CI -2.81 to -1.84), the mass exponent to be 1.13 (SE=0.091; 95% CI 0.95 to 1.30) and the WC exponent to be 0.64 (SE=0.12; 95% CI 0.40 to 0.88). Note that the confidence interval of the WC exponent estimate encompasses 0.5 (i.e. the square-root transformation). With a positive mass exponent and a negative height exponent that is approximately twice that of the mass exponent and WC exponent that is approximately half the mass exponent, the body shape most strongly associated with BF% would appear to be $\mathrm{BMI}\sqrt{\mathrm{WC}}$. The fitted exponents from Sample 1 using Model 2 are summarized in row 2 of Table 2.

To assess the benefit of using the product/interaction term $\mathrm{BMI}\sqrt{\mathrm{WC}}$ compared with BMI alone when predicting BF% from Study 1, we repeated the above ANCOVA on untransformed BF% (using age and sex as fixed factors) adopting BMI as the covariate. We then repeated the same ANCOVA adopting the product/interaction term $\mathrm{BMI}\sqrt{\mathrm{WC}}$ also as the covariate. The ANCOVA using BMI as the covariate resulted in a BMI slope parameter of 1.736 (SE=0.058; 95%CI 1.623 to 1.85) and an R^2 = 0.614. The ANCOVA on BF% (same fixed factors) using the

product/interaction $BMI\sqrt{WC}$ term as the covariate resulted in a significant $BMI\sqrt{WC}$ interaction term 1.787 (SE=0.057: 95%CI 1.675 to 1.90) and an R^2 = 0.671. The fitted BMI and BMI*√WC slope parameters from the ANCOVA analyses of untransformed BF% from Sample 1 are summarized in row 1 of Table 3.

Sample 2

Descriptive statistics of key variables from sample 2 are given in Table 1b

When data were analysed using sample 2, analysis (model 1) identified a significant main effect by age (once again due to a steady decline in BF% in the older children (age, P<0.001), see Figure 2a), plus a main effect due to sex (P<0.001), with a significant interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.789). The allometric model for Ln(BF%) identified the height exponent to be -2.54 (SE=0.11; 95% CI -2.75 to -2.33) and the mass exponent to be 1.24 (SE=0.023; 95% CI 1.19 to 1.28). Once again, with a positive mass exponent and a negative height exponent that is approximately twice that of the mass exponent, the body shape most strongly associated with BF% would also appear to be BMI. The fitted exponents from Sample 2 using Model 1 are summarized in row 3 of Table 2.

The second analysis for sample 2 (model 2) also identified a significant main effect by age, again due to a steady decline in BF% in the older children (age, P<0.001), plus a significant main effect due to sex (P<0.001), with a significant interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.798). The allometric model for Ln(BF%) identified the height exponent to be -2.05 (SE=0.125; 95% CI -2.29 to -1.80), the mass exponent to be 0.867 (SE=0.056; 95% CI 0.758 to 0.976) and the WC exponent to be 0.61

(SE=0.084; 95% CI 0.44 to 0.77). As with sample 1, the confidence interval of the estimated WC exponent from sample 2 encompasses 0.5 (i.e. the square-root transformation). With a positive mass exponent and a negative height exponent that is a more than twice that of the mass exponent and WC exponent that is approximately 0.6, the body shape most strongly associated with BF% would once again appear to be $\mathrm{BMI}\sqrt{\mathrm{WC}}$ similar to that from sample 1. The fitted exponents from Sample 2 using Model 2 are summarized in row 4 of Table 2.

To assess the benefit of using the product term $\mathrm{BMI}\sqrt{\mathrm{WC}}$ compared with BMI when predicting BF% from Study 2, we repeated the above ANCOVA on untransformed BF% (using age and sex as fixed factors) adopting BMI as the covariate. We then repeated the same ANCOVA adopting the product term $\mathrm{BMI}\sqrt{\mathrm{WC}}$ also as the covariate. The fitted BMI and BMI*√WC slope parameters from the ANCOVA analyses of untransformed BF% from Sample 2 are summarized in row 2 of Table 3.

Sample 3

Descriptive statistics of key variables from sample 3 are given in Table 1c

Results from the first stage of the analysis using sample 3, (model 1) identified a significant main effect by age (due to a steady decline in BF% in the older children (age, P<0.001), plus a main effect due to sex (P<0.001), with a significant interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.796), see Figure 2b. The fitted exponents from Sample 3 using Model 1 are summarized in row 5 of Table 2. With a positive mass exponent and a negative height exponent that is twice that of the mass exponent, the body shape ratio most strongly associated with BF% would appear to be BMI

The second analysis for sample 3 (model 2) also identified a significant main effect by age, again due to a steady decline in BF% in the older children (age, P<0.001), plus a significant main effect due to sex (P<0.001), with a significant interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.803). The fitted exponents from Sample 3 using Model 2 are summarized in row 6 of Table 2. As with sample 1, the confidence interval of the estimated WC exponent from sample 3 encompasses 0.5 (i.e. the square-root transformation). With a positive mass exponent and a negative height exponent that is a more than twice that of the mass exponent and WC exponent that is approximately 0.5, the body shape most strongly associated with BF% would once again appear to be $\mathrm{BMI}\sqrt{\mathrm{WC}}$ similar to that from sample 1.

To assess the benefit of using the product term $\mathrm{BMI}\sqrt{\mathrm{WC}}$ compared with BMI when predicting BF% from Study 3, we repeated the above ANCOVA on untransformed BF% (using age and sex as fixed factors) adopting BMI as the covariate. We then repeated the same ANCOVA adopting the product term $\mathrm{BMI}\sqrt{\mathrm{WC}}$ also as the covariate. The fitted BMI and BMI*√WC slope parameters from the ANCOVA analyses of untransformed BF% from Sample 3 are summarized in row 3 of Table 3.

Sample 4

Descriptive statistics of key variables from sample 4 are given in Table 1d

Results from the initial analysis on Ln(BF%) from sample 4, (model 1) identified the same main effects of age (due to a steady decline in BF% in the older children; P<0.001), and sex (P<0.001), with a significant interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.77), see Figure 2c. The fitted exponents from Sample 4 using Model 1 are summarized in row 7 of Table 2. With a positive mass exponent and a negative height exponent that is approximately twice that of the mass exponent, the body shape ratio most strongly associated with BF% would appear to be BMI.

The second analysis for sample 4 (model 2) also identified significant main effects of age and sex (both P<0.001), with a significant interaction, having controlled for differences in body size/shape (assuming the same body shape) (R^2 = 0.78). The fitted exponents from Sample 4 using Model 2 are summarized in row 8 of Table 2. As with sample 1, the confidence interval of the estimated WC exponent from sample 4 was 0.31, a little lower than the previous 3 samples. Again, with a positive mass exponent and a negative height exponent that is more than twice that of the mass exponent and WC exponent that is a little less than 0.5, the body shape most strongly associated with BF% would once again appear to be $BMI\sqrt{WC}$ not dissimilar to that from sample 1.

To assess the benefit of using the product term $BMI\sqrt{WC}$ compared with BMI when predicting BF% from Study 4, we repeated the above ANCOVA on untransformed BF% (using age and sex as fixed factors) adopting BMI as the covariate. We then repeated the same ANCOVA adopting the product term $BMI\sqrt{WC}$ also as the covariate. The fitted BMI and BMI*√WC slope parameters from the

ANCOVA analyses of untransformed BF% from Sample 4 are summarized in row 4 of Table 3.

Discussion

This study sought to investigate whether combining both WC and BMI might provide a simple, meaningful and more accurate index associated with BF% in children. Using four independent samples and an allometric modelling approach, this study is the first to suggest that introducing WC as a third dimension, alongside mass and height might provide a more effective and equally non-invasive means to predict BF% in children, as compared to BMI. The results presented here are supportive of work by other authors that has suggested WC is important as a predictor of pediatric adiposity (11,12,13). However, much of this prior work has positioned WC as a separate measure to BMI or combined it with stature to produce the waist-to-height ratio (11, 12, 13). Prior work using allometry (Nevill et al Am J Hum Bio Colombian) has emphasised the need to consider both WC and stature in children to scaling waist circumference for stature in culturally diverse samples of children (6) to enable more accurate identification of factors associated with excessive WC as children grow into adulthood. The findings of the present study align with this assertion but uniquely, the allometric approach employed identified an anthropometric index that includes three dimensions of body shape as the based predictor of body fatness, including stature and mass in the form of BMI alongside WC.

The initial analyses (fitting the allometric model using Eq.1 to the BF% data from all four samples), identified a positive mass exponent and a negative height

exponent that was approximately twice the mass exponent, confirming that BMI ($kg \cdot m^{-2}$) was the optimal mass-to-height ratio or body shape associated with BF% (see the exponents using Model 1 in rows 1, 3, 5 and 7 in Table 2). These initial analyses also revealed significant main effects due to age and sex. Sample 1's results plotted in Figure 1 also suggest that for the same "BMI" shape, boys have less fat (suggesting more muscle) than girls, and that the reduced BF% observed in the older boys and girls further suggests that the muscle mass is proportionally greater in the older boys and girls. Because these children are relatively young (from 5 to 10 yrs.), the gap is not increasing in the older age groups, i.e., the age group-by-sex interaction was not significant ($P > 0.05$).

In contrast, the log-transformed BF% results from sample 2 plotted in Figure 2 suggest that boys have less fat (i.e., more lean mass) than girls for the same "BMI" body shape, but because these children are older (compared to sample 1), the gap between boys and girls is increasing in the older boys age groups (from 10 to 15 yrs.), i.e., the age group-by-sex interaction was significant $P < 0.001$). We speculate that this interaction is due to the older boys experiencing a further reduction in body fat and an increase in muscle mass, as they go through puberty (Pietrobelli et al., 1998).

However, by far the most insightful findings from the current study come from fitting the allometric model 2 (Eq.2) to the BF% data from the four samples. All allometric models identified similar albeit slightly reduced height and mass exponents to those obtained when fitting model (Eq.1), that reinforces the need for the mass-to-height ratio BMI when predicting BF% (see Model 2 parameters in rows 2, 4, 6 and 8 in Table 2). The multiplicative model (Eq.2) also identifies significant WC (all $P < 0.001$) as further postive predictors of BF%, with similar WC exponents in

the four samples, estimated to be approximately 0.5. The confidence intervals of three out of the four WC exponent estimates indeed encompass 0.5. Based on these mass, height and WC exponents fitted using the allometric model (Eq.2), we suggest a new index, $\mathrm{BMI}\sqrt{\mathrm{WC}}$, to predict BF%. We can interpret the $\sqrt{\mathrm{WC}}$ component of the new index as simply a statistical or mathematical "weighting" of BMI. Note, this is a multiplicative contribution of both BMI and WC rather than an additive contribution, epmhpasising the interaction of the two terms when predicting BF%.

The benefit of using $\mathrm{BMI}\sqrt{\mathrm{WC}}$ compared with BMI when predicting the BF% data from the four samples was obtained by repeating the ANCOVAs (using age group and sex as fixed factors) on untransformed BF% as the response variable adopting both $\mathrm{BMI}\sqrt{\mathrm{WC}}$ and BMI as separate covariates. The ANCOVA for BF% from sample 1 using BMI*sqrt(WC) as the covariate resulted in an $R^2 = 0.671$. This greater R^2 looks encouraging. However, comparing the R^2 obtained from the same ANCOVAson the BF% from samples 2, 3 and 4, i.e., comparing BMI with $\mathrm{BMI}\sqrt{\mathrm{WC}}$ as the covariates, were less convincing, see Table 3. The R^2 obtained from using $\mathrm{BMI}\sqrt{\mathrm{WC}}$ as the covariate in samples 2 and 3 were only marginal greater than using BMI as the covariate, and in the case of sample 4, no benefit was observed.

These results may appear somewhat contradictory. On the one hand, all four WC exponents obtained using the allometric model Eq. 2 (see Table 2) identified highly significant Ln(WC) covariates, suggesting the importance that √WC should be making (as a weighting for BMI) when predicting BF%. This was supported when $\mathrm{BMI}\sqrt{\mathrm{WC}}$ was used as a covariate in the ANCOVA predicting untransformed BF% for sample 1 (see row 1 of table 3). This benefit was greatly reduced in samples 2, 3 and 4 as seen in rows 2,3, 4 of Table 3. One explanation for these contradictory

findings is possibly due to the fact that the body shape of lean children are geometrically similar to each other (13, 21). The more geometrically similar a child's body shape, the more likely that one body-shape dimension is a surrogate for other body-shape dimensions. For example, WC and height will be directly proportional to each other in contrast to body-size dimensions when subjects are less geometrically similar to each other (e.g., in adults).

The current study examined this issue in two culturally distinct and independent samples of children (UK children in sample 1 and Portuguese children in samples 2, 3 and 4). This is a strength of the current work and demonstrates the possibility that $\text{BMI}\sqrt{\text{WC}}$ might improve the prediction of BF% in European children from different countries. However, we are aware that the four samples were not matched for age or ethnicity. This should be considered a limitation and future work would be welcome examining the utility of $\text{BMI}\sqrt{\text{WC}}$ in predicting fatness in other groups of children to substantiate the results presented here. The current study provides encoraging evidence that $\text{BMI}\sqrt{\text{WC}}$ is effective in predicting BF% in children but, as there are changes in body composition and body shape moving from adolescence into adulthood, and adulthood into older adulthood, the new $\text{BMI}\sqrt{\text{WC}}$ index may prove effective with pediatric populations. Future work examining whether $\text{BMI}\sqrt{\text{WC}}$ is likely to be effective in predicting BF% in adults would therefore be welcome. One of the reasons why authors advocate the use of BMI, and latterly use of WC, has persisted as proxies for body fatness is due to the ease of administration and low cost (4,5). Importantly, the assessment of $\text{BMI}\sqrt{\text{WC}}$ is no more time consuming or onerous than BMI and WC separately. It may however provide a more

precise anthropometric proxy for children's body fatness for use in public and community health settings, compared to when BMI and WC are used in isolation.

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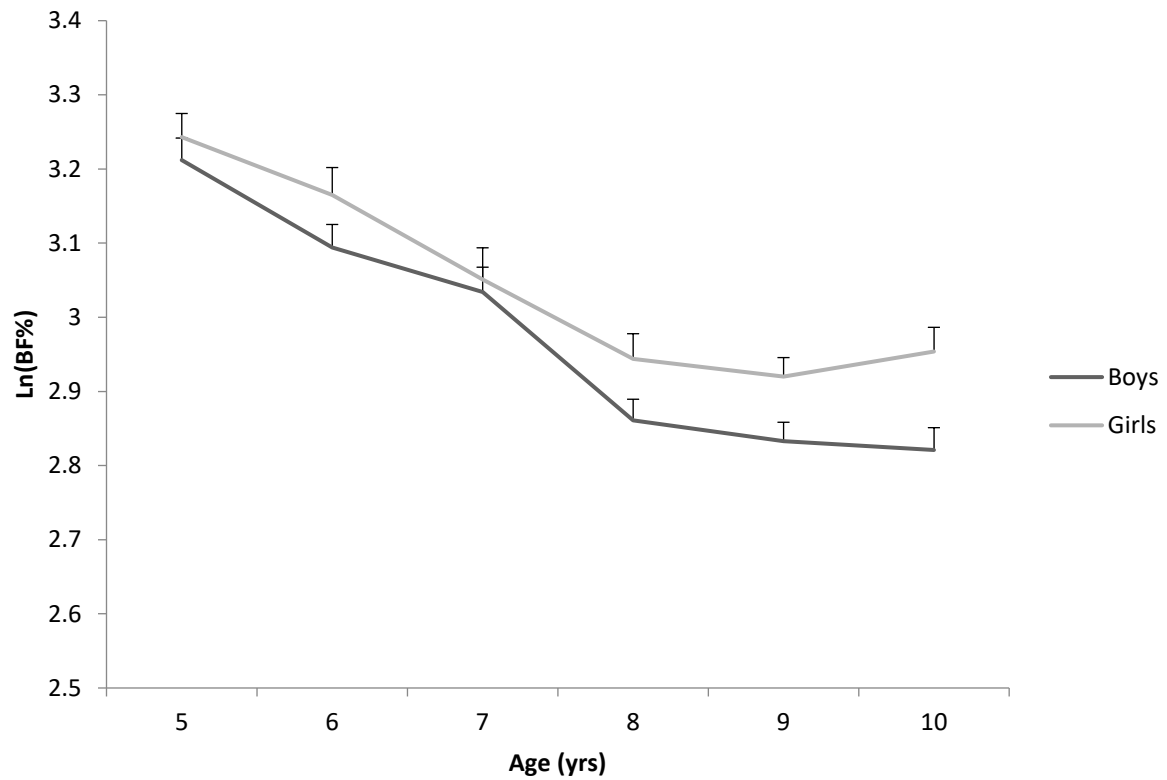
Figure 1. Differences in Ln(BF%) from Study 1 by age and sex having controlled for differences in Ln(height) and Ln(mass) both incorporated as covariates in the ANCOVA described in the methods.
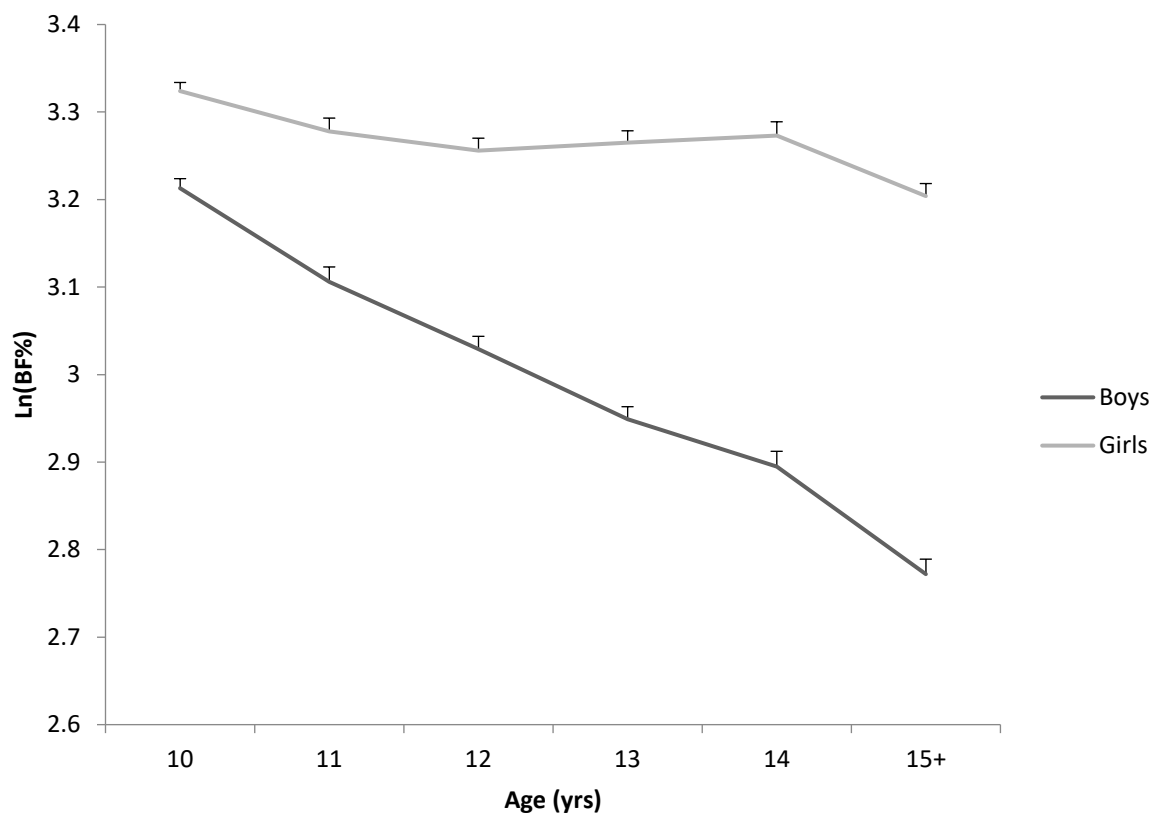
Figure 2. Differences in Ln(BF%) from Studies 2 (Figure 2a), 3 (Figure 2b) and 4 (Figure 2c), by age and sex having controlled for differences in Ln(height) and Ln(mass) both incorporated as covariates in the ANCOVA described in the methods.
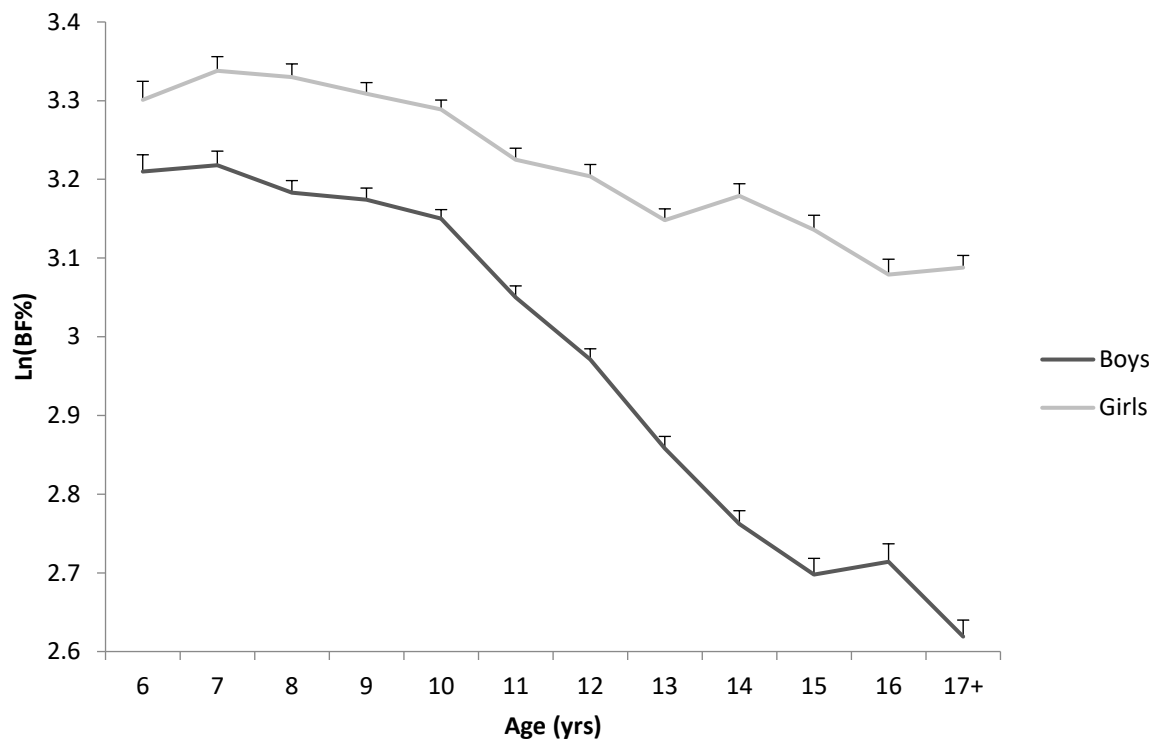
Figure 2a

Figure 2b.

Figure 2c.