RESEARCH NOTE

Accounting for height in indices of body composition during childhood and adolescence [version 1; peer review: 1 approved with reservations]

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Abstract
Correlations of body composition with height vary by age and sex during childhood. Standard approaches to accounting for height in measures of body composition (dividing by height (in meters)) do not take this into account. Using measures of total body mass (TBM), fat mass (FM) and fat free mass (FFM) at ages nine, 11, 13, 15 and 18 years from a longitudinal UK cohort study (ALSPAC), we calculated indices of body composition at each age by dividing measures by height (in meters). We then produced age-and sex-specific powers of height using allometric regressions and calculated body composition indices by dividing measures by height raised to these powers. TBM, FM and FFM divided by height were correlated with height up-to age 11 in females. In males, TBM and FM divided by height were correlated with height up-to age 15 years while FM divided by height was correlated with height up-to age 11 years. Indices of body composition using age-and sex-specific powers of height, rather than height in meters, should be used to adjust body composition for height when measures of adiposity/mass independent of height are required.

Keywords
ALSPAC, public health, obesity, methodology

This article is included in the Avon Longitudinal Study of Parents and Children (ALSPAC) gateway.
Introduction
A key consideration in the use of any measure of body composition (such as fat mass (FM), fat free mass (FFM) or TBM) is the extent to which the measure requires complete adjustment for height, a subject of much research since the 19th century. BMI remains correlated with height in populations of different ethnicities and during certain periods of childhood and adolescence; this correlation may not be problematic if the goal is to derive a measure of body composition that is maximally correlated with later cardiometabolic risk, even if some of this correlation with later health risk is driven by height. However, if a measure of excess adiposity independent of height is required, then removal of correlations of body composition with height is essential. This is also important when comparing body composition between groups with different heights.

In adults, division of measures of body composition by height generally yields measures that are independent of height. In childhood, the correlation between body composition and height varies with age and also by sex. Many studies have examined adjustment of body composition for height, though few have been conducted in contemporary populations and included repeated measures of body composition across childhood and adolescence or measures of TBM, FM and FFM measured directly through gold-standard approaches.

Using direct repeated measures of TBM, FM and FFM at ages nine, 11, 13, 15, and 18 years from dual-energy X-ray absorptiometry (DEXA) scans in the Avon Longitudinal Study of Parents and Children (ALSPAC), we examine the powers of height required to yield height-invariant measures of body composition during childhood and adolescence using the approach developed by Benn et al.

Methods
Study participants
ALSPAC is a prospective birth cohort study in Southwest England. Pregnant women resident in one of the three Bristol-based health districts with an expected delivery date between April 1, 1991 and December 31, 1992 were invited to participate. The study has been described elsewhere in detail. Ethical approval for the study was obtained from the ALSPAC Ethics and Law Committee and the Local Research Ethics Committees. The study website contains details of all the data that is available through a fully searchable data dictionary.

Data
Whole body less head FM and lean mass (fat free mass) were derived from whole body DEXA scans assessed at ages nine, 11, 13, 15, and 18 using a Lunar prodigy narrow fan beam densitometer. At each clinic, standing height was measured to the last complete mm using the Harpenden Stadiometer and weight was measured to the nearest 0.1kg using the Tanita Body Fat Analyser (Model TBF 305).

Statistical analysis
Benn et al. proposed a “power-type index” as an approach to adjusting weight for height. In sum, this method involves dividing adiposity measures such as weight by height to the power of some constant (p). These constants may differ from the standard constant used to account for height in measures of body composition (p=2 gives the index Quetelet’s index, now commonly known as BMI, while p=3 gives a form of ponderal index). In this paper, we applied the “power-type index” approach to repeated measures of body composition in the ALSPAC. TBM (kg), FM (kg) and FFM (kg) were divided by height in meters squared (m^2) to derive BMI (kg/m^2), fat mass index (FMI) (kg/m^2) and fat-free mass index (FFMI) (kg/m^2) at each age. Next, we regressed the log of mass (TBM, FM, FFM) at each clinic on the log of height at each age and for each sex separately. This model is given by the equation log y = log α + β log x + log ε, where y is mass (TBM, FM, or FFM), x is height, β is the scaling exponent or power, α is the proportionality constant, and ε is a multiplicative error term. Using the powers of height produced from these regressions, we calculated a second set of height-invariant body composition indices; TBM, FM and FFM divided by height raised to the power of each age-and sex-specific β (TBM/H^β, FM/H^β, FFM/H^β). We then examined the residual correlation of both sets of indices separately (BMI (kg/m^2), TBM/H^β (kg/m^3), FM (kg/m^2), FFM/H^β (kg/m^3)) with height by age and sex. All analyses were performed using Stata version 15.

Results
The sample included 7,160 participants (3,637 female and 3,533 male) with at least one measure of TBM, FM and FFM over the five time points. Females tended to be shorter in height, have higher TBM and FM and lower FFM at each age compared with males (Table 1).

In females, BMI, FMI and FFMI were correlated with height up-to age 11. In males, BMI and FMI were correlated with height at up-to age 15 years while FMI was correlated with height in males up-to age 11 years.

Powers of height from the allometric regression for TBM were approximately three at age nine in females and males. Powers for FBM reduced with age and contained two within their confidence interval at age 15 for females and at age 18 for males, suggesting that division of mass by height at these ages would provide height-invariant measures of body composition.

Powers for FFM were greater than two for both sexes at age nine and 11. In males at age 13, powers increased further but decreased thereafter. In females, powers for FFM decreased after age 11. In both sexes, powers for FFM were close to two at age 18. Powers for FM were approximately five and six for females and males at age nine. Powers contained two within their confidence intervals for females by age 13 and by age 15 for males. Body composition indices created using these age- and sex-specific powers of height had no residual correlation with height at any age (Table 2).

Discussion
Using five measures of TBM, FM and FFM from nine to 18 years, we have shown that division of measures of mass by height...
yields indices of body composition that remain correlated with height at young ages in both males and females. In contrast, the use of age-and sex-specific powers of height generates indices that are not correlated with height. Our findings are comparable to previous analyses. For instance, an analysis of White European, Black African and South Asian children (N=1,999) also showed that the optimal power of height for adjustment of FM was approximately five up to age 12, and began to decline from 13 years onwards yielding a power of about two by age 15. Our findings of powers for TBM were also shown in a

**Table 1.** Anthropometric characteristics of females and males by age and correlation of body composition divided by height with height at each age.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Height (meters)</th>
<th>TBM (kg) Mean (SD)</th>
<th>FM (kg) Mean (SD)</th>
<th>FFM (kg) Mean (SD)</th>
<th>TBM (kg/m²) Correlation with height (r)</th>
<th>FM (kg/m²) Correlation with height (r)</th>
<th>FFM (kg/m²) Correlation with height (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Females (N=3,637)</strong></td>
<td></td>
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<tr>
<td>Age 9 (N=3,575)</td>
<td>9.9 (0.3)</td>
<td>1.39 (0.06)</td>
<td>35.0 (7.5)</td>
<td>9.7 (5.0)</td>
<td>23.6 (3.2)</td>
<td>0.308</td>
<td>0.204</td>
</tr>
<tr>
<td>Age 11 (N=3,416)</td>
<td>11.8 (0.2)</td>
<td>1.51 (0.07)</td>
<td>44.5 (10.0)</td>
<td>12.9 (6.6)</td>
<td>29.3 (4.5)</td>
<td>0.271</td>
<td>0.331</td>
</tr>
<tr>
<td>Age 13 (N=2,947)</td>
<td>13.8 (0.2)</td>
<td>1.62 (0.06)</td>
<td>54.3 (10.1)</td>
<td>16.3 (7.3)</td>
<td>35.2 (4.0)</td>
<td>0.076</td>
<td>0.010</td>
</tr>
<tr>
<td>Age 15 (N=2,441)</td>
<td>15.4 (0.3)</td>
<td>1.65 (0.06)</td>
<td>58.8 (10.3)</td>
<td>18.8 (7.9)</td>
<td>37.0 (3.9)</td>
<td>-0.019</td>
<td>-0.096</td>
</tr>
<tr>
<td>Age 18 (N=2,110)</td>
<td>17.8 (0.4)</td>
<td>1.65 (0.06)</td>
<td>62.5 (11.9)</td>
<td>21.5 (9.3)</td>
<td>38.0 (4.2)</td>
<td>-0.048</td>
<td>-0.094</td>
</tr>
<tr>
<td><strong>Males (N=3,633)</strong></td>
<td></td>
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</tr>
<tr>
<td>Age 9 (N=3,660)</td>
<td>9.9 (0.3)</td>
<td>1.40 (0.06)</td>
<td>34.4 (7.5)</td>
<td>7.3 (5.0)</td>
<td>25.5 (3.2)</td>
<td>0.304</td>
<td>0.114</td>
</tr>
<tr>
<td>Age 11 (N=3,533)</td>
<td>11.7 (0.2)</td>
<td>1.50 (0.07)</td>
<td>42.6 (10.0)</td>
<td>10.4 (6.6)</td>
<td>30.1 (4.5)</td>
<td>0.304</td>
<td>0.246</td>
</tr>
<tr>
<td>Age 13 (N=3,056)</td>
<td>13.8 (0.2)</td>
<td>1.65 (0.06)</td>
<td>54.4 (10.1)</td>
<td>11.0 (7.3)</td>
<td>40.9 (4.0)</td>
<td>0.208</td>
<td>0.456</td>
</tr>
<tr>
<td>Age 15 (N=2,674)</td>
<td>15.4 (0.3)</td>
<td>1.74 (0.06)</td>
<td>63.8 (10.3)</td>
<td>11.2 (7.9)</td>
<td>49.7 (3.9)</td>
<td>0.117</td>
<td>0.208</td>
</tr>
<tr>
<td>Age 18 (N=2,687)</td>
<td>17.8 (0.4)</td>
<td>1.79 (0.06)</td>
<td>72.0 (11.9)</td>
<td>13.7 (9.3)</td>
<td>55.1 (4.2)</td>
<td>-0.031</td>
<td>-0.052</td>
</tr>
</tbody>
</table>

**FM; fat mass, FFM; fat free mass, TBM; total body mass.**

**Table 2.** Powers used to obtain height-invariant indices of body composition by age and sex and residual correlations of these with height during childhood and adolescence.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>TBM</th>
<th>TBM/height</th>
<th>FF M</th>
<th>FFM/height</th>
<th>FM</th>
<th>FFM/height</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Females</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Age 9</td>
<td>3.1 (3.0, 3.2)</td>
<td>0.017</td>
<td>2.3 (2.3, 2.4)</td>
<td>-0.002</td>
<td>5.1 (4.8, 5.4)</td>
<td>0.018</td>
</tr>
<tr>
<td>Age 11</td>
<td>3.0 (2.9, 3.1)</td>
<td>-0.006</td>
<td>2.6 (2.6, 2.7)</td>
<td>-0.012</td>
<td>4.1 (3.7, 4.4)</td>
<td>0.010</td>
</tr>
<tr>
<td>Age 13</td>
<td>2.3 (2.2, 2.5)</td>
<td>0.005</td>
<td>2.1 (2.0, 2.1)</td>
<td>0.009</td>
<td>3.0 (2.6, 3.4)</td>
<td>0.010</td>
</tr>
<tr>
<td>Age 15</td>
<td>2.0 (1.8, 2.1)</td>
<td>0.005</td>
<td>1.8 (1.7, 1.9)</td>
<td>0.001</td>
<td>2.2 (1.8, 2.6)</td>
<td>-0.007</td>
</tr>
<tr>
<td>Age 18</td>
<td>1.8 (1.6, 2.0)</td>
<td>0.015</td>
<td>1.8 (1.7, 1.9)</td>
<td>0.002</td>
<td>1.7 (1.3, 2.1)</td>
<td>-0.009</td>
</tr>
<tr>
<td><strong>Males</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age 9</td>
<td>3.1 (3.0, 3.2)</td>
<td>0.004</td>
<td>2.2 (2.1, 2.2)</td>
<td>-0.040</td>
<td>6.4 (6.0, 6.8)</td>
<td>0.048</td>
</tr>
<tr>
<td>Age 11</td>
<td>3.1 (3.0, 3.2)</td>
<td>0.028</td>
<td>2.4 (2.3, 2.5)</td>
<td>-0.001</td>
<td>5.4 (5.0, 5.7)</td>
<td>0.006</td>
</tr>
<tr>
<td>Age 13</td>
<td>2.7 (2.6, 2.8)</td>
<td>0.012</td>
<td>2.9 (2.8, 3.0)</td>
<td>-0.007</td>
<td>1.8 (1.3, 2.2)</td>
<td>0.054</td>
</tr>
<tr>
<td>Age 15</td>
<td>2.4 (2.3, 2.6)</td>
<td>0.002</td>
<td>2.5 (2.4, 2.6)</td>
<td>-0.005</td>
<td>2.3 (1.8, 2.8)</td>
<td>0.025</td>
</tr>
<tr>
<td>Age 18</td>
<td>1.9 (1.7, 2.1)</td>
<td>0.016</td>
<td>1.9 (1.8, 2.0)</td>
<td>-0.002</td>
<td>1.8 (1.1, 2.6)</td>
<td>0.030</td>
</tr>
</tbody>
</table>

**β is the scaling exponent or power from an allometric regression of log mass (TBM, FM or FFM) on log height.**
combined analysis of three waves of the US National Health and Nutrition Examination Survey together with 11 other published studies.1

Implications
Although measures divided by height remain correlated with height at several ages, most correlations were less than 0.3, suggesting that 95% of body composition variability ($R^2$) is explained by height.2 Therefore, depending on the study population and the research question, the bias induced by using measures which remain correlated with height may be small. This bias will be far greater when comparing groups that differ markedly in height.2 Thus the approach used here may be useful when height differences exist between groups, with standardisation (subtract the mean and divide by the standard deviation) to allow for comparison of mixed age/sex groups.

The optimal approach to producing an adiposity index remains debated and this approach is one of several that could be considered. Reference curves for FFMI and FMI which divide indices by height throughout childhood and adolescence may prove useful where common units between groups and over time are required and when complete adjustment for height is not required.2 Related to this, it should be noted that complete adjustment of body composition for height is not always necessary, particularly when the aim of a study is to derive a measure of body composition that is maximally correlated with later disease risk rather than acquiring a measure which reflects adiposity independent of height.3

Limitations
There are several strengths to our analysis including the contemporary nature of our cohort, the availability of direct adiposity measures from gold-standard DEXA scans and the analysis of powers required to account for height from mid-childhood to the end of adolescence for each sex separately. We have not been able to examine whether powers of height vary by ethnicity due to too few participants of non-White ethnicity and the generalisability of our findings may be limited to more socially advantaged populations of White ethnicity, given the characteristics of the ALSPAC cohort.

Conclusion
At young ages, and particularly around the time of puberty, dividing measures of body composition by height leads to residual correlations with height. We demonstrate a simple, established but underused method for deriving indices of body composition that are independent of height during childhood and adolescence using repeated measures of body composition in a contemporary prospective cohort study.

Data availability statement
Underlying data
The ALSPAC website contains details of all the data that is available through a fully searchable data dictionary http://www.bristol.ac.uk/alspac/researchers/our-data. Any researcher wanting to use ALSPAC data must complete an ALSPAC Research Proposal Form describing the proposed collaboration and send it to the ALSPAC Executive (alspac-exec@bristol.ac.uk). Further details can be found elsewhere.

Grant information
This work was supported by the Wellcome Trust through a core programme grant to The Avon Longitudinal Study for Parents and Children (ALSPAC) [102215].

The UK Medical Research Council, Wellcome [102215] and the University of Bristol provide core support for ALSPAC. LMOK is supported by a UK Medical Research Council Population Health Scientist fellowship [MR/M014509/1]. LDH and AF are supported by Career Development Awards from the United Kingdom Medical Research Council [MR/M020894/1 and MR/M009351/1, respectively].

The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Acknowledgements
We are extremely grateful to all the families who took part in this study, the midwives for their help in recruiting them, and the whole ALSPAC team, which includes interviewers, computer and laboratory technicians, clerical workers, research scientists, volunteers, managers, receptionists and nurses.

References


Open Peer Review

Current Peer Review Status: ?

Version 1

Reviewer Report 16 July 2019

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Tim J. Cole

Population, Policy and Practice Programme, UCL Institute of Child Health, London, UK

An interesting and well-written paper. I have three comments.

1. The Introduction states: “if a measure of excess adiposity independent of height is required, then removal of correlations of body composition with height is essential.” However, this ignores the fact that height is itself a measure of excess adiposity, and to adjust for it leads to a biased assessment. The reason why height is a measure of adiposity is because it relates to developmental age – on average, taller children are more mature, and hence fatter, and particularly so in puberty. This is why the optimal height power increases with age until puberty and then drops back to 2 – it reflects the impact of developmental age on adiposity. My 1986 paper showed that the optimal height power for BMI is low in infancy and peaks during puberty at around 3, the shape of the curve being similar to the height velocity curve (something I should have mentioned then but have only just realised). So it is only in adulthood, when height growth has stopped, that the power falls back to 2. So the question is this: does one want an index of adiposity that is uncorrelated with height at all ages, even if the raised power in puberty reflects the fact that taller children are fatter at that age, or does one want an index whose correlation with height reflects the true impact of height on adiposity at each age? This needs more discussion.

2. Table 2 shows small but non-zero correlations of the optimal indices with height, which are counter-intuitive. It would be worth explaining in the Methods why this is. The correlation between log(index) and log(height) is zero by definition, and antilogging them introduces slight nonlinearity.

3. The optimal powers in Table 2 would be interesting to see plotted as smooth curves against age, as the shapes differ by outcome and also to some extent by sex. The FFM curves peak at 11 for girls and 13 for boys, corresponding to age at peak height velocity. This makes sense, as height and FFM are closely linked in developmental terms, so when height is changing fastest its impact on FFM is greatest. This does not apply to the same extent to FM, where the peaks are earlier. So for FM adiposity related to height is strongest before puberty, which is intriguing.
References

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

*Competing Interests:* This work builds on work I published in 1986

*Reviewer Expertise:* statistics of human growth and development

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.