Scaling of body composition to height: relevance to height-normalized indexes

Steven B Heymsfield, Moonseong Heo, Diana Thomas, and Angelo Pietrobelli

ABSTRACT

Background: Body weight scales to height with a power of $\approx 2$, thus forming the basis of body mass index (weight/height$^2$). The corresponding scaling of body composition to height has not been established in a representative sample of US adults.

Objective: The aim of the study was to examine the scaling of weight, fat, fat-free mass, and bone mineral content to height.

Design: Adult non-Hispanic white (NHW), non-Hispanic black (NHB), and Mexican American National Health and Nutrition Examination Survey (NHANES) participants were included in allometric analyses if they had complete age, weight, height, and body-composition data as measured by dual-energy X-ray absorptiometry. Powers of height in allometric regression models were developed for each measure and adjusted for age.

Results: The analyses included 13,183 subjects (6699 NHW, 3015 NHB, and 3469 Mexican American). The scaling of weight to height across sex-race groups provided powers (mean ± SE) ranging from 1.85 ± 0.12 in Mexican American women to 2.48 ± 0.17 in Mexican American men. Powers of height for body composition similarly ranged widely and were often outside the 95% CI for a power of 2. Of the 3 body-composition measures, the mean age-adjusted powers of height rounded to 2 as the nearest integer in 16 of 18 sex-race groups.

Conclusions: Adult weight and body composition scale to height with variable age-adjusted powers that are sometimes outside the 95% CI for a power of 2 but frequently round to 2 as the nearest integer. These observations have implications for developing height-adjusted body-composition indexes.

INTRODUCTION

Body mass index (BMI; weight/height$^2$) is now universally applied as a measure of human adiposity (1–4). This approach is founded on 2 main assumptions: that adult body weight scales approximately as height$^2$ (2, 3) and that once weight is adjusted for height$^2$, adults within each sex group have approximately the same proportion of body weight as fat, independent of height (2, 5, 6). This critical second assumption implies that fat and related fat-free mass (FFM) (ie, weight – fat) also scale similar to weight as approximately height$^2$. Despite the importance of this hypothesis, few studies have examined how fat and fat-free mass (FFM) scale to height, particularly in a large well-defined sample with a broad range of characteristics as might apply in the general population. In addition, new and improved methods are providing estimates of these 2 compartments among populations and in individuals with the expanded use of body-composition indexes (fat/height$^2$ and FFM/height$^2$) aimed at controlling for between-subject differences in height (7, 8).

Recent small-scale studies suggest that FFM and related skeletal muscle and bone mineral mass scale to height with powers approximating 2 (2). Bone mineral, a measure of skeletal weight, tended to scale minimally higher to height than FFM and skeletal muscle mass in these studies (2), although the differences in power were not large (ie, height$^{-2.3}$ compared with height$^{-2.6}$). In support of this observation, mammalian skeletal weight scales approximately as weight$^{0.11}$ and predicts that human bone mineral will scale to height with powers larger than those for FFM and skeletal muscle mass (9). Fat mass in these small studies did not scale significantly to height, and there is no physiologic basis for the presence of a significant association between percentage body weight as fat and stature (2, 5, 6). On the assumption that percentage of body weight as fat is independent of height, fat mass should then also scale as height$^2$.

The 2004 National Health and Nutrition Examination Survey (NHANES) included body-composition measurements by dual-energy X-ray absorptiometry (DXA) on a large and diverse sample of noninstitutionalized US adults and children (10, 11). These recently released observations provide the important opportunity to critically test the hypothesis that fat, FFM, and bone mineral scale approximately as height$^2$ in a large and diverse sample representative of the US population. Our focus was to test this hypothesis in adult (age $\geq 18$ y) NHANES participants.

SUBJECTS AND METHODS

Experimental design

Details about the DXA system and the measurement procedure are provided elsewhere (7, 10, 11). The DXA body-composition data were adjusted before release as previously reported (http://www.cdc.gov/nchs/nhanes).

1 From the Pennington Biomedical Research Center, Baton Rouge, LA (SBH); the Department of Epidemiology and Public Health, Albert Einstein College of Medicine, New York, NY (MH); the Department of Mathematical Sciences, Montclair State University, Montclair, NJ (DT); and the Pediatric Unit, Verona University Medical School, Verona, Italy (AP).

2 No external support was provided for the design, implementation, analysis, or interpretation of the data presented in the current study.

3 Address correspondence to SB Heymsfield, Pennington Biomedical Research Center, 6400 Perkins Road, Baton Rouge, LA 70808. E-mail: steven.heymsfield@pbr.edu.

Received July 6, 2010. Accepted for publication December 29, 2010. First published online January 19, 2011; doi: 10.3945/ajcn.110.007161.
www.cdc.gov/nchs/nhanes/dxx/dxa.htm; page 9). Adjustment of the body-composition values, as was done for the NHANES data, had no effect on the outcome of the height powers as reported in the current study. The NHANES study group collected the whole-body DXA data using 3 mobile examination centers between 1999 and 2004; compiled data were released on the Centers for Disease Control and Prevention website (http://www.cdc.gov/nchs/nhanes.htm). The present study sample included all adults aged ≥18 y who had complete demographic information (sex, age, weight, height, and race). Women were excluded from the DXA examination if they had a positive pregnancy test at the time of the evaluation or were currently pregnant. Both men and women were excluded if their reported weight or height exceeded the DXA scan table limits of 300 lb (136 kg) and 77 inches (196 cm), respectively. The 3 largest NHANES race groupings were analyzed and included non-Hispanic whites, non-Hispanic blacks, and Mexican Americans. We analyzed the body-composition scaling relations to height within each sex and race group with exclusion of the other smaller race categories. Three components were evaluated in the current analysis in addition to body weight, fat mass, FFM, and bone mineral content. We also included an analysis of bone mineral density as measured by DXA.

**Statistical methods**

For all statistical analyses, we took into account sampling strata, primary sampling units, and sampling weights, which are elements of the multistage cluster sampling design of NHANES III (http://www.cdc.gov/nchs/nhanes.htm). In particular, the sampling weights to the pooled NHANES data from 1999 to 2004 were reassessed in accordance with the NHANES data analysis guideline (http://www.cdc.gov/nchs/data/nhanes/nhanes_03_04/nhanes_analytic_guidelines_dec_2005.pdf). We applied SAS PROC SURVEYMEANS for descriptive statistics and SAS PROC SURVEYREG for the allometric modeling (SAS Institute, Cary, NC). Furthermore, a large portion of the NHANES DXA measurement data were missing and were thus imputed 5 times by the National Center for Health Statistics (NCHS; http://www.cdc.gov/nchs/nhanes/dxx/dxa.htm); we applied descriptive statistics and the allometric modeling to each imputed data set, which yielded 5 results for each analysis. These 5 results were pooled into a single final result for each analysis based on the pooling method proposed by Rubin (12).

The age-adjusted association between body weight and body-composition measures with height can be described by the allometric model \( Y = aX^\beta \), where \( Y \) is the outcome, \( X \) the predictor variable (ie, height), \( \beta \) is the scaling exponent (ie, power), \( Z \) is the age covariate with power \( \gamma \), and \( \varepsilon \) is the proportionality constant (13). The simple allometric model can be expressed in logarithmic form as \( \log Y = \log x + \beta \log X + \gamma \log Z + \varepsilon \), where \( \varepsilon \) is the error term. Weight and body-composition measures, expressed in \( \log \_e \) form, were set as dependent variables and height and age as independent variables in the regression models. Five values are presented for each developed multiple regression model: \( \alpha \) (intercept), \( \beta \) (height), \( \gamma \) (age), \( R^2 \), and \( P \) value. We also present height powers ± SE in the text for the evaluated measures within each sex and race group. Subject demographic characteristics are presented as means ± SEMs. Statistical significance was declared when a 2-sided \( P \) value was <0.05.

**RESULTS**

**Subjects**

The characteristics of the subjects at baseline are shown in Table 1. The sample included 6696 men: 3419 non-Hispanic whites, 1504 non-Hispanic blacks, and 1773 Mexican Americans. The non-Hispanic white men were older than the other 2 groups of men, whereas the Mexican American men were shorter than the other 2 groups of men. The 3 groups of men had similar BMIs (≈28). The sample also included 6487 women: 3280 non-Hispanic whites, 1511 non-Hispanic blacks, and 1696 Mexican Americans. A similar age and height pattern was present across the 3 race groups of women, as was observed in the men. The non-Hispanic black women had the highest group mean BMI (≈31), the Mexican American women had an intermediate BMI (≈29), whereas the non-Hispanic white women had a mean BMI similar to that of the men (≈28). Although the actual number of included subjects depends on the outcome variables because of missing data (for some subjects, even imputation was not considered reasonable), only a small number of subjects (<2%) were excluded from the analysis for every combination of sex, race, and body-composition measure.

**TABLE 1**

Subject characteristics

<table>
<thead>
<tr>
<th>Age</th>
<th>Weight</th>
<th>Height</th>
<th>BMI</th>
<th>Fat</th>
<th>FFM</th>
<th>BMC</th>
<th>BMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>kg</td>
<td>cm</td>
<td>kg/m²</td>
<td>kg</td>
<td>kg</td>
<td>g</td>
<td>g/cm²</td>
</tr>
<tr>
<td>Men</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NHW (n = 3419)</td>
<td>45.3 ± 0.4</td>
<td>88.3 ± 0.3</td>
<td>177.5 ± 0.1</td>
<td>28.0 ± 0.1</td>
<td>26.0 ± 0.2</td>
<td>62.3 ± 0.2</td>
<td>2373 ± 10.5</td>
</tr>
<tr>
<td>NHB (n = 1504)</td>
<td>41.1 ± 0.4</td>
<td>87.0 ± 0.7</td>
<td>177.0 ± 0.1</td>
<td>27.7 ± 0.2</td>
<td>23.3 ± 0.4</td>
<td>63.7 ± 0.4</td>
<td>2961 ± 18.0</td>
</tr>
<tr>
<td>MEX (n = 1773)</td>
<td>36.4 ± 0.4</td>
<td>80.5 ± 0.5</td>
<td>170.0 ± 0.2</td>
<td>27.7 ± 0.1</td>
<td>23.3 ± 0.3</td>
<td>57.1 ± 0.3</td>
<td>2485 ± 12.5</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NHW (n = 3280)</td>
<td>47.3 ± 0.4</td>
<td>73.7 ± 0.5</td>
<td>163.1 ± 0.1</td>
<td>27.7 ± 0.2</td>
<td>30.5 ± 0.3</td>
<td>43.3 ± 0.2</td>
<td>2094 ± 6.5</td>
</tr>
<tr>
<td>NHB (n = 1511)</td>
<td>42.9 ± 0.4</td>
<td>83.1 ± 0.5</td>
<td>163.1 ± 0.2</td>
<td>31.2 ± 0.2</td>
<td>35.1 ± 0.4</td>
<td>48.0 ± 0.2</td>
<td>2331 ± 10.4</td>
</tr>
<tr>
<td>MEX (n = 1696)</td>
<td>38.1 ± 0.7</td>
<td>71.8 ± 0.7</td>
<td>157.7 ± 0.2</td>
<td>28.9 ± 0.3</td>
<td>30.2 ± 0.5</td>
<td>41.6 ± 0.3</td>
<td>2016 ± 8.4</td>
</tr>
</tbody>
</table>

1 All values are means ± SEMs. BMC, bone mineral content; BMD, bone mineral density; FFM, fat-free mass; MEX, Mexican American; NHB, non-Hispanic black; NHW, non-Hispanic white. The results of the dual-energy X-ray absorptiometry measurements were based on the pooling of results from the 5 data sets imputed by the National Center for Health Statistics. All of the means and SEMs were obtained with the National Health and Nutrition Examination Survey (NHANES) sampling design effects taken into account.
Allometric analyses

The results of allometric analyses are summarized in Table 2. Height and age were statistically significant in all prediction models unless otherwise noted.

Weight

After adjustment for age, weight scaled to height; mean (±SE) powers ranged from 2.11 ± 0.12 in non-Hispanic white men to 2.48 ± 0.14 in Mexican American men. Weight scaled to height; powers ranged from 1.72 ± 0.09 in non-Hispanic white women to 1.95 ± 0.17 in non-Hispanic black women.

FFM

As for weight, FFM scaled with powers that were higher in men than in the corresponding groups of women (Figure 1). The range of height powers for FFM was similar to that observed for weight: from 1.86 ± 0.06 in non-Hispanic white women to 2.32 ± 0.12 in the non-Hispanic black men. The R² values were almost double for FFM models than for the corresponding values for weight, and the SEEs were also smaller.

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height</td>
<td>Age</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>NHW</td>
<td>2.11</td>
</tr>
<tr>
<td></td>
<td>NHB</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>MEX</td>
<td>2.48</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td>NHW</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td>NHB</td>
<td>2.32</td>
</tr>
<tr>
<td></td>
<td>MEX</td>
<td>2.27</td>
</tr>
<tr>
<td>Fat (kg)</td>
<td>NHW</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>NHB</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>MEX</td>
<td>2.98</td>
</tr>
<tr>
<td>BMC (g)</td>
<td>NHW</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td>NHB</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>MEX</td>
<td>2.35</td>
</tr>
<tr>
<td>BMD (g/cm²)</td>
<td>NHW</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>NHB</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>MEX</td>
<td>0.7</td>
</tr>
</tbody>
</table>

1. The model for each outcome variable has the general form \( \log Y = \log \alpha + \beta \log X + \gamma \log Z + \epsilon \), where \( \epsilon \) is the error term with age added as an adjusting covariate. BMC, bone mineral content; BMD, bone mineral density; FFM, fat-free mass; MEX, Mexican American (\( n = 1773 \) M, 1696 F); NHB, non-Hispanic black (\( n = 1504 \) M, 1511 F); NHW, non-Hispanic white (\( n = 3419 \) M, 3280 F). The results for the dual-energy X-ray absorptiometry measurements were based on the pooling of results from the 5 data sets imputed by the National Center for Health Statistics. All of the results were obtained with the National Health and Nutrition Examination Survey (NHANES) sampling design effects taken into account. All models are \( P < 0.001 \).

2. \( P > 0.05 \).

FIGURE 1. Age-adjusted powers (±95% CI) observed for the scaling of weight (W), fat (F), fat-free mass (FFM), and bone mineral content (BMC) to height in non-Hispanic white (NHW), non-Hispanic black (NHB), and Mexican American (MEX) men and women who were participants in the National Health and Nutrition Examination Survey (NHANES). The model for each outcome variable, as presented in Table 2, has the general form \( \log Y = \log \alpha + \beta \log X + \gamma \log Z + \epsilon \), where \( \epsilon \) is the error term with age added as an adjusting covariate.

Fat

Fat scaled to height with powers that tended to be greater than for FFM in men, ranging from 2.22 ± 0.22 in non-Hispanic white men to 2.98 ± 0.31 in Mexican American men. Fat scaled to height in women with powers ranging from 1.51 ± 0.17 in non-Hispanic white women to 1.94 ± 0.29 in non-Hispanic black women.

Bone mineral

Bone mineral content scaled to height with the smallest range of powers among the measured compartments, from 2.07 ± 0.08 in non-Hispanic black women to 2.41 ± 0.12 in non-Hispanic black men. The powers of height for weight and the 3 body compartments are shown in Figure 1 for the sex and race groups. Most of the measures, as is also evident in Table 2, scaled approximately at or modestly above or below a height power of 2. Only one height power reached 3: fat mass in Mexican American men.

The 95% CIs for the powers of height are also presented in Figure 1. The 95% CIs for 7 of 12 measures in women included a height power of 2, whereas the 95% CI for 4 of the 12 measures in men included a height power of 2. The 95% CIs for bone mineral content ranged between 1.9 and 2.6 and had the smallest 95% CI among the measures. Fat had the largest 95% CI for the power of height, ranging between 1.2 and 3.6. Of the 24 total measures, 22 rounded to 2 as the nearest integer. Of the 18 body-composition measures, 16 rounded to 2 as the nearest integer.

The powers observed for fat and FFM scaled to height tended to track with each other and, as expected, with powers of body weight scaled to height (Table 2). For example, the lowest power of weight scaled to height was observed for non-Hispanic white women (1.72) who also had the lowest model power of FFM (1.86) and the lowest power for fat (1.51). The highest power of weight scaled to height was observed for Mexican American men.
Hispanic black women to 0.71

height

weight

DISCUSSION

The current study explored the scaling of body weight and composition to height in a large, carefully collected database including 3 race groups of adult NHANES subjects. After adjusting for age and applying the simple allometric model, we found that body weight and body composition for most sex and race groups scaled to height, with powers at or modestly above a value of 2. These observations confirm and extend the findings of several earlier smaller studies (2, 3, 6). Body composition—notably fat, FFM, and bone mineral content—thus scale to height, with powers approximately similar to those observed for body weight. As expected, the highly variable fat mass variable height had the weakest model associations with height ($R^2 = 0.1–0.2$) whereas stronger model correlations were observed between FFM and bone mineral content with height ($R^2 = 0.2–0.4$).

Whereas these generalities prevail, notable exceptions were observed within the 6 sex and race groups. The powers of height observed for men across body weight and composition tended to scale somewhat higher than those for women—an observation made earlier by others (2, 3, 14). Fat mass scaled to height in Mexican American men with a power of $\approx 3$, which strongly influenced the observed power of weight scaled to height (2.5). The effect of fat scaling on body weight scaling occurs because the power of weight scaled to height reflects the weighted powers of fat and FFM. Moreover, FFM is tethered with fat mass, and the 2 increase according to the “companionship” rule first described by Forbes (14). Thus, the powers of height for all 3 measures (weight, fat, and FFM) tended to group together within each sex and race group as shown Table 2.

The scaling of weight and body composition to height as examined in our report and earlier studies are based on empirical correlations (6, 15). A volumetric or “isometric” expansion of individual body compartments and the sum of all compartments with greater height would yield powers approximating 3 (15). Inclusion of children older than $\approx 8$ y with adults in these kinds of analyses provides powers in the range of 3 and several weight indexes other than BMI incorporate height$^2$ elements (6).

However, maximal correlations were observed between adult adiposity and weight/height$^2$ compared with these other measures, as first reported by Keys et al (1) and largely confirmed in several other studies (2, 3). However, the height power of 2 is not a hard-and-fast rule, as shown by the Mexican American men in the current study. Within that group, optimal scaling of fat mass to height would approach powers closer to 3 than to 2. Moreover, fat/height$^2$ would not be independent of height in the Mexican American men; rather, tall Mexican American men in NHANES have a greater fat/height$^2$ and percentage fat than do their short counterparts. The reason that percentage fat also scales positively to height in the Mexican American men is because percentage fat resolves to fat/weight and fat $\approx H^{-2.5}$, weight $\approx H^{0.5}$, and thus percentage fat (ie, fat/weight) $\approx$ height$^{-0.5}$.

As with FFM as a whole, bone mineral content models were significantly associated with height and included height powers in the narrow range of $\approx 2.1–2.4$. Our original expectation, based on an earlier study (2), was that bone mineral content would scale to height with powers greater than those for body weight and FFM. Whereas to some extent that was the case, bone mineral content height scaling powers appeared largely unrelated to the larger FFM compartment and body weight as a whole. The skeleton, of which bone mineral is a major and reasonably constant fractional component (16), may thus be the body compartment with the strongest link to adult height and a stable compartment with slow turnover compared with soft tissue compartments. For example, at least in the short term, bone mineral content remains largely unchanged, even with substantial voluntary loss of body weight (17).

Bone mineral density, while not a major focus of the current study, also was larger with greater adult height across all sex and race groups. Areal bone mineral density, as measured by DXA, is calculated as bone mineral content divided by bone area. Our findings thus suggest that bone mineral content and bone mineral area scale differently to height, with the result that areal bone mineral density increases with greater stature. For example, our model for 50-y-old non-Hispanic white women predicts a bone mineral density of 1.05 g/cm$^2$ and 1.19 g/cm$^2$ for heights of 5 feet (152 cm) and 6 feet (183 cm), respectively. The mean ($\pm$ SD) bone mineral density in this group of women is 1.10 $\pm$ 0.10. Similar observations were reported by Kelley et al (7), which are also based on the NHANES database. If and how this calculated bone mineral density relates to actual physical properties of bone and fracture risk remains uncertain.

With respect to the validity of the regression model after the log transformation, we visually inspected Studentized residual plots against both predicted values and log(age). Although these residuals were obtained ignoring the complex sampling design of the NHANES data, the linearity assumptions underlying the regression model appeared to be well supported for every outcome variable of log(Y) across sex and race. Furthermore, Studentized residual plots against log(age) did not show any prominent nonlinear pattern supporting the linear relation between ln(Y) and ln(age) in particular. In addition, although the regression models can be extended to test whether the exponents of height are significantly different across sex and race, this testing was not the main objective of the present study. This test should, however, be a separate future study topic.

Implications

In a classic article, Benn (5) suggested adjusting weight for height as weight/height$^2$, with the exponent value of $p$ specific to the population of interest. Whereas the powers of height shown in Table 2 could be used for this purpose when applied to body compartments, the high variability of $p$ values makes this approach impractical on a large scale. Moreover, the values of $p$ may not always be known, as in the case of studying or clinically managing a small sample of non-US adults. A simple and practical alternative is to round powers to the nearest integer, which would be a value of 2 for 16 of 18 body-composition measures across sex and race groups based on the current study findings (Figure 1). This assumption is the basis of BMI and, notably, when weight is scaled to height not all powers are
positively or negatively with height. The exponent of height, was used to generate the line $y = -0.11x + 0.19$ ($R^2 = 0.99$). The regression line crosses the horizontal axis at a power of $\approx 1.7$, which indicates the value of $p$ that makes fat/height$^p$ independent of height; $p$ values $> 0$ or $< \approx 1.7$ will produce fat mass indexes that correlate positively or negatively with height.

Figure 2. Correlation coefficients from data in non-Hispanic white men for the regression of fat mass/height$^p$ compared with height for values of $p$ ranging from 1.4 to 4 in increments of 0.2. Simple linear regression analysis, the exponent of height, was used to generate the line $y = -0.11x + 0.19$ ($R^2 = 0.99$). The regression line crosses the horizontal axis at a power of $\approx 1.7$, which indicates the value of $p$ that makes fat/height$^p$ independent of height; $p$ values $> 0$ or $< \approx 1.7$ will produce fat mass indexes that correlate positively or negatively with height.

Conclusions

The 2004 NHANES database provided, in the current study, a unique opportunity to critically examine the scaling of 3 major body compartments (fat, FFM, and bone mineral content) to height. The 3 compartments generally scale similarly, with several exceptions, as body weight does to height with powers ranging between $\approx 2$ and 2.5. Powers within sex and race groups tended to rank similarly for fat and FFM, and thus body weight, as would be expected based on Forbes’ companionship rule (14). Our findings have implications for developing height-normalized body-composition indexes, with 2 main potential options: divide body compartment mass by $H^p$, with population-specific values of $p$ applied as defined in Table 2; round powers for practical application to the nearest whole number, which for most (16 of 18) of the evaluated body-composition measures is a value of 2. Although the second approach is simple, it is limited by the introduction of height bias in the height-normalized index of interest, the importance of which needs to be judged on the specific application.

The authors’ responsibilities were as follows—SBH (Principal Investigator): design, analysis, and article preparation; MH: data collection, data analysis, and article preparation; DT: analysis and article preparation; and AP: data collection, data analysis, and article preparation. None of the authors had any financial or personal conflicts of interest to declare.

REFERENCES