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Scaling of Adult Human Bone and Skeletal Muscle Mass to Height in the United States Population

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Abstract

Objectives: The scaling of structural components to body size is well studied in mammals, although comparable human observations in a large and diverse sample are lacking. The current study aimed to fill this gap by examining the scaling relationships between total body and regional bone and skeletal muscle (SM) mass with body size, as defined by stature, in a nationally representative sample of the US population.

Methods: Subjects were 17,126 non-Hispanic (NH) white, NH black, and Mexican American men and women, age 18 years, evaluated in the National Health and Nutrition Examination Survey who had total body and regional bone mineral (BMin) and lean soft tissue (LST) mass measured by dual-energy X-ray absorptiometry. BMin and appendicular LST served as surrogate bone and SM mass measures, respectively. The allometric model, $BMin$ or $LST = \alpha(\text{height})^\beta$, in logarithmic form was used to generate scaling exponents.

Results: The findings were similar across all sex and race groups: body mass scaled to height with powers of ~ 2.0 (mean $\beta \pm SE$, 1.94 ± 0.08 - 2.29 ± 0.09) while total body and appendicular BMin and appendicular LST scaled to height with consistently larger powers than those for body mass (e.g., all $p < 0.05$ in NH white men and women); the largest BMin and LST scaling powers to height were observed in the lower extremities.

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AUTHOR CONTRIBUTIONS

Authors' contributions to manuscript: SBH, PH, MH, DT, and JMS designed research; SBH, PH, and JMS conducted research; SBH, MH, and JMS provided essential materials; SBH, PH, FB, MH, DT, and JMS analyzed data; SBH, PH, FB, MH, DT, JMS wrote paper; SBH, PH, FB, MH, DT, DT, JMS had primary responsibility for final content.

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CONFLICT of INTEREST

The authors and their close relatives and their professional associates have no financial interests in the study outcome, nor do they serve as an officer, director, member, owner, trustee, or employee of an organization with a financial interest in the outcome or as an expert witness, advisor, consultant, or public advocate on behalf of an organization with a financial interest in the study outcome.

Conclusions: Bone and SM mass, notably those of the lower extremities, increase as proportions of body mass with greater adult height. Metabolic and biomechanical implications emerge from these observations, the first of their kind in a representative adult US population sample.

Keywords

Body composition; adiposity; muscularity; allometric analysis; nutritional assessment

INTRODUCTION

Galileo, in his 1638 treatise *Dialogues Concerning Two New Sciences*, introduced the concept that with greater body mass animal bone diameters must increase to a relatively greater extent than their lengths in order to maintain the same strength (Galilei, 1914). The implication of this proposed scaling relation is that larger animals would have a greater percentage of their body mass devoted to structural support (Calder, 1996). Three centuries later Kayser and Heusner (1964), Pitts and Bullard (1968), and Prange, Anderson, and Rahn (1979) supported Galileo's hypothesis by showing that skeletal mass in mammals scales to body mass with powers greater than 1. That is, large mammals have a greater proportion of their body mass as skeleton compared to their small counterparts. Extensive discussions and re-analyses of these early studies followed in subsequent publications (Biewener, 2005; Campione & Evans, 2012; Christiansen, 2002; Garcia & da Silva, 2004; Prothero, 1995), but few question the empirical observation that large terrestrial animals have a greater relative amount of skeletal support than do small animals (Calder, 1996; Prothero, 1995).

Skeletal muscle is attached to and is functionally associated with bone in both animals (Lang, 2011) and humans (Vesely & Peters, 1972). Although skeletal muscle mass appears to scale isometrically to body mass across mammals (Calder, 1996; Muchlinski, Hemingway, Pastor, Omstead, & Burrows, 2018; Muchlinski, Snodgrass, & Terranova, 2012; Raichlen, Gordon, Muchlinski, & Snodgrass, 2010), slight positive allometry is reported in primates (power of 1.05 vs. 0.99 in non-primate mammals (Muchlinski et al., 2012)).

These structural scaling relations observed across mammals, including primates, are relevant in the context of previous human studies showing that people who have a large body size, as defined by stature, have a lower whole body mass-specific heat production rate at rest than do people who are short; (Heymsfield, 2018; Heymsfield et al., 2009; Heymsfield, Thomas, Bosy-Westphal, & Muller, 2018). Stature is a useful phenotypic measure of body size in humans as body mass increases as height² across adults, after controlling for age and adiposity, as first reported by Quetelet (1835) and later confirmed and extended upon by others (Cole, 1991). Resting heat production in adults thus scales to height with powers smaller than those of body mass, or less than about 2.

One theory advanced to explain these metabolic observations at the anatomic level is that people who are tall have a larger proportion of their body mass as low-metabolic rate bone and skeletal muscle than do people who are short and who weigh less (Heymsfield, Thomas, et al., 2018). To the extent that people who are tall have a larger proportion of their body

mass devoted to structural components compared to those who are short is largely unknown. Support for this hypothesis derives from the earlier interspecific observations in mammals, including primates. Relevant studies that are generalizable across adult humans varying in sex, age, and race/ethnicity have not been reported.

The publicly available National Health and Nutrition Examination Survey (NHANES) database (Centers for Disease Control and Prevention (CDC) & National Center for Health Statistics (NCHS), 2008–2013) provides a unique opportunity to establish the total body and regional scaling relations of bone and skeletal muscle mass in a population sample of non-institutionalized adults residing in the United States. The NHANES data set includes surrogate measures of both total body and regional bone and skeletal muscle mass across three race/ethnic groups, non-Hispanic (NH) white, NH black, and Mexican Americans. Accordingly, we specifically examined the hypothesis stating that with greater body size, as defined by stature, bone and skeletal muscle increase as proportions of body mass across men and women independently of age and race/ethnicity. A secondary aim was to define regional bone and skeletal muscle scaling patterns aimed at exploring previously reported biomechanical observations and theories (Alexander, 2004; Frost, 2000).

METHODS

Study Design

Data from the representative 1999–2006 NHANES sample (Centers for Disease Control and Prevention (CDC) & National Center for Health Statistics (NCHS), 2008–2013) was evaluated as described earlier by Kelly, Wilson, and Heymsfield (2009), Schoeller et al. (2005), and Schuna et al. (2015). The protocol was approved by the institutional review board of the National Center for Health Statistics (NCHS), Centers for Disease Control and Prevention, and all participants provided written informed consent.

The data presented in the current report extends a series of studies by our group on adult human scaling relations describing body size and shape (Heymsfield, Peterson, Thomas, Heo, & Schuna, 2016; Heymsfield et al., 2014; Schuna et al., 2015). In the current study we specifically focus on the musculoskeletal system hypothesis and this information is presented in the paper's tables and figures. We also integrate this new information with relevant data from our previous reports in Supplementary Information I tables. We draw on some of these earlier findings to characterize the musculoskeletal mass scaling relations reported herein.

Participants

The sample included adult (age ≥ 18 years) men and women NHANES participants who had whole-body dual-energy X-ray absorptiometry (DXA) scans. Pregnant women and amputees were excluded from the evaluated sample. Additional sample details are summarized in Tables S1 and S2. There were 4406, 2035, and 2256 NH white, NH black, and Mexican American men participants, respectively; and 4235, 2045, and 2149 women participants, respectively.

Body Composition

Each DXA scan was segmented into four body regions (head, trunk [including neck], arms, legs; Supplementary Information I, Figure S1) and each region was further partitioned into bone mineral content, lean soft tissue (LST), and fat. Total fat and body mass were used to derive an estimate of percent (%) fat. DXA system training protocols and procedures are reported in Kelly et al. (2009), NCHS guidelines (Centers for Disease Control and Prevention (CDC) & National Center for Health Statistics (NCHS), 2008b), and NHANES documents (Centers for Disease Control and Prevention (CDC) & National Center for Health Statistics (NCHS), 2008a).

Bone mineral, also referred to as bone ash, is a relatively stable fraction of dry bone mass (Calder, 1996; Snyder et al., 1975) and herein we report values as bone mineral content as measured by DXA (Kelly et al., 2009). We refer to bone mineral content throughout the remaining text as “bone mineral mass”. In a demonstration section we convert bone mineral mass to absolute dry fat-free bone mass as equal to bone mineral mass/0.65 according to Reference Man (Snyder et al., 1975).

The LST mass of the arms and legs measured by DXA served as a surrogate measure of appendicular skeletal muscle mass (Kim et al., 2004; Kim, Wang, Heymsfield, Baumgartner, & Gallagher, 2002). The combined LST mass of all four extremities provided a measure of total body skeletal muscle mass as previously reported (Kim et al., 2002). Over three fourths of total body skeletal muscle mass is in the extremities (Kim et al., 2002) and the R^2 for appendicular LST versus total body skeletal muscle mass as estimated by magnetic resonance imaging (MRI) is 0.96 with a small addition to the R^2 (0.965) when age is added as a prediction model covariate (Kim et al., 2004; Kim et al., 2002). In the demonstration section we use appendicular (extremity) LST mass to derive an estimate of total body skeletal muscle mass using the conversion equation reported by Kim et al. (2002). The Kim conversion equation was derived and validated using magnetic resonance imaging as the reference for total body skeletal muscle mass.

Statistical Methods

The allometric model, $Y = \alpha X^\beta e$, was used to evaluate bone mineral and LST scaling relations with Y dependent variable (i.e., bone mineral or LST mass), X predictor variable (i.e., height), β the scaling exponent or power, α the proportionality constant, and e the multiplicative error (e) (Schuna et al., 2015). The natural logarithmic form of the model was used to conduct these analyses. The model's independent variables included height, age, and %fat. Both age and adiposity are independent determinants of bone mineral and skeletal muscle mass after controlling for stature (Heymsfield et al., 2014; Schuna et al., 2015). The allometric analysis approach is described in earlier reports (Schuna et al., 2015) and presented in additional detail below. Models were developed for the head, trunk, arms, legs, and whole-body. The relative scaling relationships between the evaluated components (i.e., bone mineral and LST) and body mass are also described; since bone mineral or LST mass = $\alpha_1(\text{height})^{\beta_1}$ and body mass = $\alpha_2(\text{height})^{\beta_2}$, then bone mineral mass/body mass or LST mass/body mass = $\alpha_1/\alpha_2(\text{height})^{\beta_1-\beta_2}$. Positive or negative differences between β_1 and β_2

indicate greater or smaller bone mineral or LST component proportions of body mass, respectively.

Analyses were conducted with the statistical software application R (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria) while utilizing the “survey” (Lumley, 2004, 2010) and “mitools” (Lumley, 2014) packages to yield nationally representative estimates accounting for the complex, multistage probability design of NHANES. To account for non-response, non-coverage, and oversampling of some groups, all models included appropriate sample weights. Standard errors were calculated via Taylor series linearization and statistical significance was defined at $p < 0.05$. Summary statistics of the sample, including bone mineral mass and LST mass, were computed using the “svymean” function and presented as $\text{mean} \pm \text{SE}$ for each of the six sex (men, women) by race/ethnic groupings (NH white, NH black, Mexican American).

Scaling analyses, as defined by the allometric equation, were conducted across the six sex by race/ethnic groupings while controlling age and %fat. For each sex by race/ethnic grouping, separate regression models were fitted using the “svyglm” function with bone mineral or LST mass as the dependent variable and height, age, and %fat as independent variables. To ensure appropriate interpretability of the scaling exponent, all model variables were log-transformed.

Sex-specific between-race/ethnicity comparisons (3 comparisons for each variable) of sample characteristics, bone mineral and LST masses, and derived scaling exponents were evaluated with a series of dummy-variable regression models using the “svyglm” function while employing a Bonferroni-correction ($p < 0.05/3 = 0.0167$).

To account for the multiply-imputed structure of NHANES body composition data (5 imputed data sets), separate analyses were conducted for each imputed data set and the resulting estimates were averaged using the “MIcombine” function. Confidence intervals and critical t-statistic values associated with multiply-imputed model estimates were derived using degrees of freedom (df) calculated according to Barnard and Rubin’s method (Barnard & Rubin, 1999). The complete-data df used in this determination was 59 (number of primary sampling units – number of sampling strata).

The study included men and women in three race/ethnic groups and each group had five whole-body/regional (total body mass, head, trunk, arms, legs) bone mineral and LST mass estimates. The complex inter-relations emerging from these multiple estimates are simplified by presentation of representative examples and integrated summaries within the Results section. In the concluding demonstration section of Results we model the effects of increasing height on the percentages of body mass as bone and skeletal muscle while holding age and body mass index (BMI) constant. Multiple regression models were developed for bone mineral, skeletal muscle, and musculoskeletal (bone mineral + skeletal muscle) mass with weight, height, and age set as predictor variables. These models were developed using conventional mixed stepwise multiple regression analysis and they were confirmed using one hundred-fold cross-validation. Additional information on the NHANES

data set, R code, and related links used in the current study are provided in Supplementary Information II, III, and R-code.

RESULTS

Sample Characteristics

The evaluated sample, 17,126 NHANES participants (8,697 men, 8,429 women), is described in Table S1. Between race/ethnicity comparisons (p-values) for the demographic and body composition variables within sex groups are presented in Tables 1 and S2.

The men and women across all three race/ethnic groups were similar in mean age, ranging from about 36 to 38 years in Mexican Americans to 45 to 47 years in the NH white participants (Table S2). Men and women, on average, were overweight or obese with BMI ranging from about 28 to 32 kg/m².

Men had more bone mineral mass than women (Table 1); within sex groups the largest bone mineral mass was in NH blacks and the smallest in Mexican Americans. The same sex and race/ethnicity pattern was present for LST mass.

Scaling Relations

Total and Regional Body Mass—The allometric analyses for total and regional body mass are summarized in Table S3. Between race/ethnicity statistical comparisons for each variable within sex groups are shown in the table. Body mass scaled to height with powers ranging from 2.02±0.06 to 2.29±0.09 in men and from 1.94±0.08 to 1.99±0.09 in women. Arm and trunk mass scaled to height with powers the same or minimally smaller than those of total body mass while leg mass scaled to height with consistently larger powers than those of total body mass. Head mass scaled to height with low powers ranging from 0.75±0.05 to 0.98±0.07. The smaller β -values for total body mass in women extended mainly to the β -values for the arms and less so for the legs.

Appendicular mass, the combined mass of all four extremities, scaled to height with powers consistently larger than those of total body mass. The observed total and regional body mass scaling patterns were similar across both men and women in the three race/ethnic groups.

Integration. The fraction of body mass as leg (i.e., leg mass/body mass = height ^{$\beta_1 - \beta_2$} , with β_1 and β_2 the respective scaling powers shown in Table S3 for leg and body mass) was thus larger with greater height among the groups, the same or minimally smaller as arm and trunk mass, and substantially smaller for head mass. With greater height, the fraction of total body mass as appendicular mass, the combined sum of arm and leg weights, also increased. These scaling patterns along with statistical comparisons between the respective regional and body mass scaling exponents are shown in Figures 1 and 2 for representative NH white participants.

Total and Regional Bone Mineral and LST Mass

Total Mass. The allometric analyses for total and regional bone mineral and LST mass are summarized in Table 2. The table provides within-sex group between race/ethnicity

statistical comparisons. Total bone mineral mass scaled to height with powers consistently larger than those for body mass, ranging from 2.09 ± 0.06 for NH black women to 2.40 ± 0.10 for NH black men. Total LST mass scaled to height with powers approximately the same as those for total body mass, about 2.0.

Integration.: Total body bone mineral mass scaled to height with powers larger than those of body mass and thus, with greater height, the skeleton increased as a fraction of body mass. Total LST mass scaled to height with powers similar to those of body mass and thus, with greater height, LST remained a relatively stable fraction of body mass.

Regional Mass.: The general pattern of regional bone mineral and LST mass (Figure 3) is similar to that of the corresponding total mass estimates (Figure 1). Both components scaled to height with lower powers for head (<1), intermediate powers for arms and trunk (~ 2), and high powers for leg (>2).

All of the bone mineral powers, except for head, scaled to height with values larger than the corresponding values for total body mass. The largest differences from body mass scaling were for leg bone mineral mass (Figure 3).

By contrast, arm and trunk LST mass scaled to height with powers close to those of total body mass, about 2, although the values for trunk were all minimally smaller than those for body mass across the six sex and race/ethnic groups. Leg LST mass scaled to height with consistently larger powers than 2 (Figure 3). The pattern and statistical significance of scaling differences between body mass and regional bone mineral and LST mass is shown in Figure 4 for NHANES NH white men and women.

Appendicular Mass.: Extremity bone mineral and LST mass both scaled to height with powers significantly larger (2.48 ± 0.07 to 2.87 ± 0.08 and 2.19 ± 0.09 to 2.40 ± 0.11 ; e.g., for NH white men and women, all $p < 0.01$, Figure 2) than the corresponding whole-body mass powers of about 2. This observed scaling pattern was consistent across all of the sex and race/ethnic groups.

Integration.: Consistent with the observation that the fraction of body mass as total leg mass increased with height, both leg bone mineral and LST mass similarly increased as a fraction of body mass with greater height. All leg scaling exponents exceeded those for the corresponding arm exponents for all six groups. The inverse applied for head composition while arm and trunk bone mineral and LST mass increased and remained relatively stable proportions of body mass, respectively. The combined LST mass of all four extremities scaled to height with larger powers than those of body mass, indicating that skeletal muscle mass increased as a fraction of body mass with greater height.

Appendicular LST mass increased relative to body mass with height, but total body LST remained a stable proportion of body mass with greater height. The difference between the two can be accounted for by smaller LST scaling powers for trunk and head mass, anatomic regions that include non-muscle LST as brain and visceral organs, respectively. Most of the

larger total body skeletal muscle mass observed in tall people can be accounted for by their greater lower extremity muscle mass.

Bone and Skeletal Muscle—Taken collectively, these observations suggest that total body bone and skeletal muscle mass and the composite musculoskeletal system are larger fractions of body mass in tall people compared to their short counterparts. This observation is demonstrated for the six groups of men and women in Figures S2, S3, and S4 for bone, skeletal muscle, and musculoskeletal mass, respectively. As shown in the figures, all three components increase as percentages of body mass with greater height (range set at 150 cm to 200 cm) with the prediction models (Table S4) empirically set at age 25 years and BMI 22 kg/m²; the one exception was for bone mass in the NH black women in whom the percentage bone was larger at the short height equation setting. Men had a larger percentage of their weight as skeletal muscle and musculoskeletal mass than women (~40% to 45% vs. ~30 to 35% and ~45–50% vs. 35–40%); the percentages of all three components were larger for NH black participants than either NH whites or Mexican Americans. The relative increase in musculoskeletal mass with greater height tended to be larger in men than in women.

DISCUSSION

In the current study, we present new data combined with findings from earlier reports (Heymsfield et al., 2016; Heymsfield et al., 2014; Schuna et al., 2015) to provide a comprehensive examination of how bone and skeletal muscle mass, two main components of the musculoskeletal system, vary across people differing in body size as defined by stature. Our findings across men and women in a nationally representative sample strongly support earlier observations in mammals (Calder, 1996; Christiansen, 2002; Garcia & da Silva, 2004; Kayser & Heusner, 1964; Pitts & Bullard, 1968; Prange et al., 1979), and primates in particular (Muchlinski et al., 2018; Muchlinski et al., 2012), that with greater body size, both bone and skeletal muscle mass increase as proportions of body mass. Moreover, we established regional body mass patterns showing that relatively larger scaling effects (β -values) are observed in the lower extremities of adult humans compared to other body regions. The proportions of the human musculoskeletal system are thus distinctly allometric, relative to height, a robust finding that applied across men and women in the three evaluated race/ethnic groups. These main observations are summarized pictorially in Figure 5 by findings in the NH white men whose results are representative of all six evaluated groups.

Concordance with Earlier Studies

Bone Mineral—While there are relatively few comparable human studies, our findings largely concur with those reported in mammals as a whole. With respect to bone mineral, the scaling relations to body mass have been reported and collectively reviewed multiple times over the past four decades. The published scaling powers vary depending on animal body mass and habitat (Christiansen, 1999, 2002; Prothero, 1995), anatomic location of bones evaluated (Alexander, Jayes, Maloiy, & Wathuta, 1979; Campione & Evans, 2012; Garcia & da Silva, 2004), mammalian subclass (Campione & Evans, 2012; Christiansen, 1999, 2002; Prothero, 1995), body proportions (Ruff, 2000), and whether the evaluated specimens were

bone mineral ash, dry bone, or fresh whole bone mass (Calder, 1996). There is general agreement that, for land mammals weighing more than 20 kg, skeletal weight scales to body mass with powers greater than 1, approximately 1.1 (Prothero, 1995), and that the fraction of body mass as bone increases with larger animal size. In the current study we observed uniform scaling of whole body and regional bone mineral mass to height with larger powers corresponding to those of body mass, with the exception of head bone mineral, across men and women in all three race/ethnic groups. Specifically, bone mineral mass in the whole body and three of the evaluated anatomic regions scaled to height with powers larger than those for the corresponding powers of body mass. The largest height scaling powers were for bone mineral mass of the lower extremities. The percentage of body mass as bone in our representative adult example increased from about 5.5% by ~0.1%–0.6% between the heights of 150 cm and 200 cm for both the men and women, NH black women the only exception in whom predicted bone mass decreased as a fraction of body mass between the two height extremes (Supplementary Information I, Figure S2).

Skeletal Muscle—Even fewer studies are reported for skeletal muscle mass scaling to body size than for bone. As with bone, evaluated muscle specimens, muscle groups, and measurement methods varied between studies (Alexander, Jayes, Maloiy, & Wathuta, 1981; Calder, 1996; Muchlinski et al., 2018; Muchlinski et al., 2012; Raichlen et al., 2010). Calder (1996) reviewed the available literature and concluded that in mammals skeletal muscle scales isometrically to body mass (i.e., with a power of 1) as did Raichlen et al. (2010). Muchlinski also confirmed Calder's observations (Muchlinski et al., 2012), reporting a power of 0.99 for skeletal muscle scaling to body mass in mammals as a whole but with a larger power, 1.05, in the subgroup of primates (Muchlinski et al., 2012). Alexander found that in mammals in general, when he excluded bipedal hoppers, distal leg muscles scaled to body mass with powers of about 1.0 and proximal muscles with powers of about 1.1 (Alexander et al., 1981). In the current study, using appendicular LST as a surrogate for total body skeletal muscle mass, we observed consistently larger scaling powers to height than for body mass, largely accounted for by lower extremity LST (Figure 3).

The percentage of body mass as skeletal muscle in our representative adult example increased from about 40% by ~2%–3% and from about 30% by ~1%–3% between the heights of 150 cm and 200 cm for men and women, respectively (Supplementary Information I, Figure S4). While our findings are generally in line with percentages reported earlier in mammals, including primates (Muchlinski et al., 2018; Muchlinski et al., 2012), we show evident sexual dimorphism in relative muscularity in humans and the potential influence of race/ethnicity with NH blacks having the largest proportions of body mass as bone and skeletal muscle compared to NH whites and Mexican Americans. These observations confirm several earlier studies reporting increased bone and skeletal muscle mass in African Americans relative to Caucasians of comparable age and size (Heymsfield et al., 2014).

Metabolic Implications

A main motivation for the current study was to further our quantitative understanding of the mechanisms underlying energy expenditure scaling relations in humans, with implications

for scaling relationships in mammals as a whole (Heymsfield, 2018; Heymsfield, Thomas, et al., 2018). Large animals and humans, characterized respectively by body mass and height, have lower mass-specific resting metabolic rates compared to their small counterparts (Heymsfield & Pietrobelli, 2010). One explanation for body size-related variation in mass-specific metabolic rate is variation in organ proportions with a shift in body composition with greater height to low metabolic rate components (i.e., to a larger proportion of body weight as bone and skeletal muscle bone [~ 15 kcal/kg/d] and to a smaller proportion of brain, liver, and kidney [>200 kcal/kg/d]) (Heymsfield, Peterson, et al., 2018). The current study and earlier reports (Heymsfield, Peterson, et al., 2018; Heymsfield, Thomas, et al., 2018) strongly support this theory. Notably, brain mass, including head mass as shown in the current study, scale to height with low powers and decrease as a fraction of body mass with greater height (Heymsfield, Thomas, et al., 2018). By contrast, and as also shown in the current study, people who are tall have a larger fraction of their body mass accounted for by low-metabolic rate structural support than do people who are small. Our findings indicate that the largest proportion of this structural support is present in the lower extremities and includes both bone and skeletal muscle mass. The current study provides quantitative scaling estimates of bone and skeletal muscle mass that can be used in future energy metabolism modeling studies.

Biomechanical Implications

The skeletons of people who are tall are not simply proportionally expanded versions of those observed in people who are short. First, we observed a significant increase in the fraction of body mass as bone with greater height, the largest relative increase present in the lower extremities. Notably, with greater load or force as represented by body mass (i.e., as height⁻²), leg bone mass increased as height^{-2.7}. This leg bone scaling pattern, consistent across all evaluated groups, likely represents two effects related to stature. First, the lengths of bones such as the femur, tibia, and fibula might be a larger fraction of height in people who are tall versus those who are short. Second, to accommodate the increasing body mass load with greater height, leg bone cross-sectional areas must also increase to preserve their strength, fracture resistance, and reserve. While we cannot derive an exact value for leg bone cross-sectional areas in the current study, Bjornerem et al. (2013) found that with a height increase from ~ 150 to ~ 180 cm in women, distal tibia total cross-sectional areas doubled, from ~ 400 to ~ 800 mm². However, the taller women also had thinner tibial cortices with increased porosity resulting in lower total and cortical volumetric bone densities. Bjornerem et al. (2013) hypothesize that these adaptations improve bone bending strength while maintaining the compressive strength needed for load bearing.

Taken collectively, these observations relating bone structure and composition to stature may explain why significant correlations are observed between height and fracture risk, notably of the hip and non-vertebral skeleton (Armstrong et al., 2016; Bjornerem et al., 2013; Compston et al., 2014). One theory, advanced by Bjornerem et al. (2013) is that a relatively light skeleton in tall women might maintain mobility during youth but become a liability later in life when bone demineralization prevails. Important gaps remain in developing a full human skeletal biomechanical model related to stature, an observation that suggests this is a potentially fruitful future area of research.

Study Limitations

The findings of the current study are based on two surrogate measures, one for bone mass and the other for skeletal muscle mass. The bone mass estimates are likely robust as close associations are present between bone mineral mass and dry bone mass (Calder, 1996; Snyder et al., 1975). Moreover, bone mineral mass as quantified by DXA agrees well with *in vitro* estimates of bone mineral ash and *in vivo* with total body calcium (Heymsfield et al., 1990). As noted earlier, we also were not able to quantify several bone features related to biomechanical associations of interest as variables such as cross-sectional bone area are not evaluable using current DXA technologies.

Skeletal muscle mass estimates by DXA are based on a series of linkages beginning with the assumed stable association between appendicular LST and muscle and then the similarly assumed stable relation between appendicular and whole-body skeletal muscle mass (Kim et al., 2004; Kim et al., 2002). As noted in Methods, validation studies report high correlations between DXA-measured appendicular LST and whole-body skeletal muscle mass as measured by MRI (Kim et al., 2004; Kim et al., 2002). Some concerns are also raised for DXA LST calibration and therefore absolute skeletal muscle mass predictions may vary between system manufacturers and software versions (Schoeller et al., 2005). Recently developed automated MRI analysis software will allow for comparable large sample human studies of skeletal muscle mass in the future (Borga et al., 2018).

These limitations notwithstanding, an important strength of the current study was the large (>17,000 evaluable participants) and diverse NHANES sample that allowed us to discern relatively small and generalizable differences in scaling patterns independently of potentially confounding factors such as age and adiposity. Previously reported studies of adult human body size scaling relations relied on relatively small samples, often less than several hundred ethnically and racially mixed participants (Heymsfield et al., 2009; Heymsfield, Gallagher, Mayer, Beetsch, & Pietrobelli, 2007).

CONCLUSIONS

The current report extends earlier studies in mammals (Biewener, 2005; Calder, 1996; Campione & Evans, 2012; Christiansen, 2002; Garcia & da Silva, 2004; Pitts & Bullard, 1968; Prange et al., 1979), including primates (Muchlinski et al., 2018; Muchlinski et al., 2012) documenting the allometric relations between bone, skeletal muscle, and the musculoskeletal system as a whole and body size, as defined in our human participants by stature, in a representative sample of the adult US population. The extensive whole body and regional DXA body composition estimates acquired in the large NHANES cohort revealed that with greater height, the two main musculoskeletal system components bone and skeletal muscle, increased as proportions of body mass with the main contributions accounted for by lower extremity components. These observations provide an initial basis for extending metabolic and biomechanical concepts, particularly when formulating future studies that will be made possible using emerging practical technologies that have the potential to further map bone and skeletal muscle structure *in vivo*.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations:

CI	confidence interval
df	degrees of freedom
DXA	dual-energy x-ray absorptiometry
LST	lean soft tissue
Mex Am	Mexican American
MRI	magnetic resonance imaging
NCHS	National Center for Health Statistics
NH	non-Hispanic
NHANES	National Health and Nutrition Survey
SD	standard deviation
SE	standard error; %fat, percentage body fat

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Total Body and Regional Mass

Figure 1.

Powers observed ($\beta \pm SE$) for total body (TB) and regional (head, trunk, arms, legs) body mass scaled to height in the NH white men and women. Horizontal lines are placed at the levels of the total body mass powers. Additional data details are presented in Table S3. ***, $p < 0.001$ versus total body mass power; no asterisk, $P = NS$ versus total body power.

Appendicular Mass

Figure 2. Powers observed ($\beta \pm \text{SE}$) for total body (TB) mass and total appendicular (App) mass and composition [bone mineral (Min) and LST] scaled to height in the NH white men and women. Horizontal lines are placed at the levels of the total body mass powers. Additional data details are presented in Table S3. *, **, and ***, $p < 0.05$, 0.01 , and 0.001 versus total body mass power.

Figure 3. Powers observed ($\beta \pm SE$) for total body (TB) mass and total body and regional bone mineral (Min) and LST mass scaled to height in the NH white men and women. Horizontal lines are placed at the levels of the total body Mass powers. Additional data details are presented in Table S3. ** and ***, $p < 0.01$ and 0.001 versus total body mass power; no asterisk, $P = NS$ versus total body power.

Figure 4. Differences ($\beta^1 - \beta^2$) between regional bone mineral (β^1) or LST (β^1) and total body mass powers (β^2) for the allometric model [$BMin$ or $LST = \alpha(\text{height})^\beta$] in NHANES NH white men and women. Negative and positive power differences translate to smaller and larger respective bone mineral and LST fractions of body mass. Statistical comparisons of β -values for each component and body mass are shown in Figure 3.

Musculoskeletal Mass

Figure 5.

Powers ($\beta \pm \text{SE}$) observed for representative NH white men for key study observations. From left to right, powers are for whole-body and regions; skeletal muscle mass; and leg LST and bone mineral. The powers shown for total body skeletal muscle and bone mass are from appendicular LST total body bone mineral, respectively. Whole body or regional powers larger or smaller than the power for weight scaled to height (2.02 ± 0.06) translate to larger or smaller component percentages of body mass, respectively. Statistical comparisons of whole body and regional β -values to those of body mass are shown in Figures 1-3.

Table 1.

Body mass and composition of the selected sample[†].

Variable	Men			Women		
	NHW	NHB	MA	NHW	NHB	MA
Body Mass (kg)	89.4 ± 0.4 ^a	89.1 ± 0.6 ^a	81.5 ± 0.6 ^b	74.6 ± 0.4 ^a	83.8 ± 0.5 ^b	72.9 ± 0.6 ^c
Bone Mineral (kg)						
Total	2.75 ± 0.01 ^a	2.99 ± 0.02 ^b	2.50 ± 0.01 ^c	2.11 ± 0.01 ^a	2.33 ± 0.01 ^b	2.03 ± 0.01 ^c
Head	0.50 ± 0.002 ^a	0.54 ± 0.003 ^b	0.47 ± 0.003 ^c	0.49 ± 0.002 ^a	0.55 ± 0.002 ^b	0.50 ± 0.004 ^a
Trunk	0.70 ± 0.003 ^a	0.75 ± 0.005 ^b	0.65 ± 0.004 ^c	0.55 ± 0.002 ^a	0.60 ± 0.004 ^b	0.54 ± 0.004 ^c
Arms	0.46 ± 0.002 ^a	0.50 ± 0.002 ^b	0.41 ± 0.003 ^c	0.30 ± 0.001 ^a	0.34 ± 0.001 ^b	0.28 ± 0.001 ^c
Legs	1.09 ± 0.005 ^a	1.19 ± 0.007 ^b	0.97 ± 0.006 ^c	0.77 ± 0.002 ^a	0.85 ± 0.004 ^b	0.72 ± 0.004 ^c
Appendicular	1.55 ± 0.006 ^a	1.69 ± 0.008 ^b	1.38 ± 0.009 ^c	1.07 ± 0.003 ^a	1.19 ± 0.005 ^b	1.00 ± 0.005 ^c
LST Mass (kg)						
Total	60.6 ± 0.2 ^a	62.3 ± 0.3 ^b	55.7 ± 0.3 ^c	42.0 ± 0.1 ^a	46.4 ± 0.2 ^b	40.5 ± 0.2 ^c
Head	3.4 ± 0.01 ^a	3.6 ± 0.01 ^b	3.4 ± 0.01 ^c	2.8 ± 0.01 ^a	3.1 ± 0.01 ^b	2.9 ± 0.01 ^c
Trunk	30.3 ± 0.1 ^a	29.4 ± 0.2 ^b	27.7 ± 0.2 ^c	21.6 ± 0.1 ^a	22.3 ± 0.1 ^b	20.9 ± 0.1 ^c
Arms	7.7 ± 0.03 ^a	8.4 ± 0.05 ^b	7.2 ± 0.05 ^c	4.2 ± 0.02 ^a	5.1 ± 0.03 ^b	4.2 ± 0.03 ^a
Legs	19.2 ± 0.06 ^a	21.0 ± 0.12 ^b	17.4 ± 0.09 ^c	13.4 ± 0.06 ^a	15.9 ± 0.08 ^b	12.5 ± 0.08 ^c
Appendicular	26.9 ± 0.09 ^a	29.4 ± 0.17 ^b	24.6 ± 0.13 ^c	17.6 ± 0.07 ^a	21.0 ± 0.10 ^b	16.7 ± 0.11 ^c

[†] Results are presented as $\bar{X} \pm SE$. Between race/ethnicity comparisons for each variable within sexes were conducted using the unpaired t-test procedure for sample survey data with Bonferroni-correction to maintain the familywise error rate at 0.05. Values with different superscript letters are significantly different at $p < 0.05/3 = 0.0167$. Abbreviations: LST, lean soft tissue; MA, Mexican American; NHB, non-Hispanic black; NHW, non-Hispanic white.

Table 2. Nationally-representative scaling powers observed for bone and LST mass in NHANES men and women^a.

Variable	Men			Women		
	NHW	NHB	MA	NHW	NHB	MA
Body Mass						
	2.02±0.06	2.29±0.09	2.14±0.07	1.97±0.06	1.94±0.08	1.99±0.09
	1.91-2.14	2.10-2.48	2.01-2.27	1.85-2.09	1.77-2.10	1.82-2.17
Bone Mineral						
Total						
	2.26 ± 0.05	2.40 ± 0.10	2.29 ± 0.08	2.32 ± 0.05 ^a	2.09 ± 0.06 ^b	2.37 ± 0.07 ^a
	2.16-2.37	2.19-2.61	2.13-2.45	2.21-2.42	1.96-2.22	2.23-2.52
Head						
	1.11 ± 0.07	1.03 ± 0.13	1.04 ± 0.12	1.26 ± 0.09	1.00 ± 0.10	1.26 ± 0.12
	0.97-1.26	0.77-1.30	0.79-1.29	1.08-1.44	0.79-1.20	1.02-1.50
Trunk						
	2.35 ± 0.08	2.63 ± 0.14	2.36 ± 0.11	2.46 ± 0.07	2.33 ± 0.08	2.48 ± 0.10
	2.20-2.50	2.33-2.92	2.15-2.57	2.32-2.60	2.16-2.50	2.27-2.69
Arms						
	2.28 ± 0.06	2.42 ± 0.12	2.34 ± 0.08	2.46 ± 0.06	2.27 ± 0.08	2.53 ± 0.09
	2.17-2.39	2.17-2.67	2.19-2.49	2.34-2.57	2.10-2.45	2.34-2.72
Legs						
	2.76 ± 0.06	2.86 ± 0.10	2.84 ± 0.08	2.85 ± 0.05 ^a	2.57 ± 0.07 ^b	3.01 ± 0.09 ^a
	2.63-2.89	2.67-3.06	2.67-3.01	2.74-2.96	2.41-2.73	2.84-3.19
Appendicular						
	2.61 ± 0.06	2.73 ± 0.10	2.69 ± 0.08	2.74 ± 0.05 ^a	2.48 ± 0.07 ^b	2.87 ± 0.08 ^a
	2.50-2.73	2.53-2.93	2.54-2.85	2.63-2.84	2.34-2.63	2.70-3.04
LST Mass						
Total						
	2.04 ± 0.05	2.26 ± 0.09	2.11 ± 0.06	1.97 ± 0.05	1.96 ± 0.08	1.99 ± 0.09
	1.93-2.14	2.07-2.44	1.98-2.24	1.86-2.08	1.79-2.13	1.81-2.17
Head						
	0.89 ± 0.04	0.97 ± 0.06	0.86 ± 0.06	0.76 ± 0.04	0.76 ± 0.07	0.69 ± 0.05
	0.80-0.98	0.84-1.10	0.73-0.98	0.67-0.85	0.62-0.90	0.59-0.80
Trunk						
	1.98 ± 0.06 ^a	2.27 ± 0.09 ^b	2.02 ± 0.07 ^{ab}	1.95 ± 0.06	1.93 ± 0.09	1.91 ± 0.09
	1.87-2.10	2.09-2.45	1.89-2.15	1.83-2.06	1.75-2.11	1.73-2.10
Arms						
	2.04 ± 0.06	2.26 ± 0.11	2.14 ± 0.09	1.92 ± 0.08	1.98 ± 0.11	1.83 ± 0.11
	1.92-2.17	2.04-2.49	1.96-2.31	1.76-2.08	1.76-2.20	1.61-2.06
Legs						
	2.34 ± 0.06	2.46 ± 0.11	2.48 ± 0.08	2.29 ± 0.06	2.25 ± 0.09	2.49 ± 0.11

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Variable	Men			Women		
	NHW	NHB	MA	NHW	NHB	MA
	2.21-2.46	2.24-2.68	2.32-2.64	2.17-2.42	2.07-2.44	2.27-2.72
Appendicular	2.25 ± 0.06	2.40 ± 0.11	2.38 ± 0.08	2.20 ± 0.06	2.19 ± 0.09	2.33 ± 0.11
	2.13-2.37	2.19-2.62	2.23-2.53	2.07-2.33	2.01-2.37	2.11-2.54

[†] Powers are expressed as $\beta \pm SE$ with 95% CI below. Between race/ethnicity comparisons for each variable within sexes were conducted using dummy-variable regression procedures for sample survey data with Bonferroni-correction to maintain the familywise error rate at 0.05. Values with different superscript letters are significantly different at $p < 0.05/3 = 0.0167$. Abbreviations: LST, lean soft tissue; MA, Mexican American; NHB, non-Hispanic black; NHW, non-Hispanic white.