Published in final edited form as:

Obes Rev. 2016 March ; 17(3): 262–275. doi:10.1111/obr.12358.

Why are there race/ethnic differences in adult body mass index–adiposity relationships? A quantitative critical review

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Summary

Body mass index (BMI) is now the most widely used measure of adiposity on a global scale. Nevertheless, intense discussion centers on the appropriateness of BMI as a phenotypic marker of adiposity across populations differing in race and ethnicity. BMI-adiposity relations appear to vary significantly across race/ethnic groups, but a collective critical analysis of these effects establishing their magnitude and underlying body shape/composition basis is lacking.

Accordingly, we systematically review the magnitude of these race-ethnic differences across non-Hispanic (NH) white, NH black and Mexican American adults, their anatomic body composition basis and potential biologically linked mechanisms, using both earlier publications and new analyses from the US National Health and Nutrition Examination Survey. Our collective observations provide a new framework for critically evaluating the quantitative relations between BMI and adiposity across groups differing in race and ethnicity; reveal new insights into BMI as a measure of adiposity across the adult age-span; identify knowledge gaps that can form the basis of future research and create a quantitative foundation for developing BMI-related public health recommendations.

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Conflict of interest statement

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.

Authors' contributions

SBH, CMP, DT, MH and JMS designed research; SBH and JMS conducted research; SBH, MH and JMS provided essential materials; SBH, CMP, DT, MH and JMS analyzed data; SBH, CMP, DT, MH and JMS wrote paper; SBH, CMP, DT, MH and JMS had primary responsibility for final content.

Supporting information

Additional Supporting Information may be found in the online version of this article, <http://dx.doi.org/10.1111/obr.12358>

Table S1. Evaluated NHANES Sample.

Table S2. Subject characteristics.

Table S3. Percent Fat Prediction Equations for Race/Ethnic Groups Evaluated in NHANES.

Figure S1. %fat versus 1/BMI for men and women NHANES participants at age 30 years and representative heights of 170 cm and 160 cm, respectively.

Figure S2. Whole-body and molecular body composition levels evaluated in the current report.

Figure S3. Differences (D) in %fat units calculated as the predicted %fat for NH white men and women at age 30 yrs with a BMI of 25 kg/m² minus the predicted values for younger and older (age 70 yrs, BMI 25 kg/m²) subjects in the corresponding 5 groups.

Keywords

Adiposity; allometric analysis; body composition; body shape; nutritional assessment

Introduction

By providing a quick estimate of adiposity, body mass index (BMI) is now universally considered a marker of wellness and disease risk (1–3). However, many reports now describe race and ethnic differences in BMI–adiposity relationships (4–7). That is, for any value of BMI, there are differences in percentage body fat (% fat) between subjects of the same sex across race and ethnic groups. The variability in BMI–adiposity associations has led to intense debate on appropriate body weight guidelines for use within specific populations (5,8–10).

Why would BMI–adiposity relations differ across race and ethnic groups? For that matter, why in general would %fat vary between subjects of the same sex, BMI and race? At the outset, answering these questions would appear to be a simple matter: at the same height and body weight, some people have a larger lean mass and smaller fat mass than others. But at another level, the answer is much more complex and delves directly into the nature of BMI and how this simple measure of shape relates to adiposity.

The importance of examining these questions is manifold: BMI is applied as an adiposity proxy for purposes ranging from the discovery of obesity genes (11) to establishing obesity rates across race/ethnic groups and nations. The foundation for linking BMI with adiposity is based on the widely held view that BMI is ‘a fairly reliable indicator of body fatness for most people’ and that ‘BMI can be considered an alternative for direct measures of body fat’ (12). The question arises as to the validity of these concepts both when BMI is applied to the individual level and when it is examined across race and ethnic groups. In this review, we focus on the latter and less well-studied topic.

Our review provides new and quantitative insights into the relationships between BMI, body shape and body composition across three adult race and ethnic groups. Our explorations reveal new insights into the associations between BMI, stature and age, and we examine potential mechanistic explanations for why the relationship between BMI and %fat differs across race and ethnic groups. We also explore waist circumference, a measure of body size, but we limit our main focus to BMI and total adiposity, and we do not critically examine topics such as ‘abdominal’ obesity (13). Our analyses are also limited to between-race and age group body shape and composition differences; we do not delve into the broader question of individual subject differences in BMI–adiposity relations.

Our review also does not address the issue of the statistical difficulty of finding the true value of height scaling exponents, which we recognize is a challenge for all allometric studies. We instead refer the interested reader to seminal manuscripts by Warton *et al.* (14), Burton (15,16) and other articles by these authors that discuss these challenges. Fortunately, though, most studies find height scaling exponents in the range of 1.1–2.5 for body mass (15) and larger studies seem to converge on the true value being close to 2.

We draw on previous analyses conducted using data from the 1999–2006 National Health and Nutrition Examination Survey (NHANES) that includes non-Hispanic (NH) white, NH black and Mexican American subjects (Supporting Information I, Tables 1 and 2) (17,18). In addition, we conducted new analyses for demonstration purposes on age-specific NHANES subgroups as a means of highlighting body shape and composition differences across race/ethnic groups. These samples and analytical methods are described in Supporting Information II.

Race/ethnic group body mass index–adiposity differences

Previous reports of adiposity differences between race and ethnic groups often rely on relatively small samples, body composition methods of questionable accuracy and precision, use of different body composition methods and instruments across the evaluated race and ethnic groups, and they often include limited demographic descriptions of evaluated subjects (5,19–36). After removing these sample and methodology concerns, do race/ethnic differences in how BMI relates to %fat in fact remain present? If so, what is their magnitude? Answering this question provides a baseline for the analyses that follow.

In the current report, we derive US nationally representative %fat prediction equations for adult NH white, NH black and Mexican American subjects using the dual-energy X-ray absorptiometry (DXA) data from NHANES (Supplementary Table 3). An example of predicted values for %fat is presented in Fig. 1 for representative subjects with an age of 30 years and a BMI of 25 kg m^{-2} . We use a BMI of 25 kg m^{-2} throughout this report in examples as a useful threshold value for ‘overweight’ that is close to recent past and current US national averages (37). Across both men and women in a large carefully controlled study, NH blacks have the lowest %fat, followed next by NH whites, while Mexican Americans have the greatest %fat; in other words, we find the %fat sequence: NH blacks < NH whites < Mexican Americans. These findings, consistent with earlier reports (38,39), show young adults of the same BMI but differing in race and ethnic group do have significantly different levels of adiposity. The magnitude of these predicted group differences is relatively small, maximally a mean of about 3% percent fat units.

While the findings in this example are consistent with the prevailing literature (38,39), a much more complex set of anatomic relationships is present between these three race and ethnic groups. To begin with, our %fat prediction models are based on cross-sectional data and the evaluated groups were exposed to very different environments up until the time they were studied as part of NHANES. One measure that reflects these potential exposure differences is stature, as adult height is strongly influenced by developmental diet and health status (40,41). As shown in the left-hand panels of Fig. 2, in some cases, there are large stature differences between the three race and ethnic groups, and these differences vary across the adult lifespan. In addition to underlying genetic mechanisms, these height differences likely reflect distinct patterns of nutritional, economic and social exposures to the populations under study.

If these population differences in stature are indeed because of potentially differential environmental exposures, the question arises if the aforementioned between-group

differences in adiposity among young adults are stable across the adult lifespan. Using the same BMI (25 kg m^{-2}) across the three race/ethnic groups, predicted adiposity levels differ markedly within and between groups over the evaluated age-span, as shown in the right-hand panels of Fig. 2. Now NH white subjects have the highest predicted %fat levels at age 70 years while NH blacks continue to have the lowest levels of predicted %fat. These observations indicate that simple generalizations on race/ethnic differences in BMI–adiposity relations are not possible without delving further into an understanding of how stature, age and adiposity collectively relate to BMI. Similar BMI–adiposity patterns are observed at BMI levels above and below 25 kg m^{-2} using the NHANES %fat prediction equations shown in Supplementary Table 3 and Supplementary Fig. 1.

Body mass index and related mathematical constructs

While calculated tens of thousands of times every day, few of those applying BMI give much consideration to the complex mathematical and anatomical relations that are embodied in what has become the most widely used shape index on a global scale. Two seminal reports provide the modern foundation for BMI: Quetelet's 1842 observation that body weight increased across adults as height (42), and the findings of Keys *et al.* in 1972 (43) that BMI had the strongest association with %fat in comparison to several other weight-height indices available at the time.

Relationships to race/ethnicity

Body weight scaled to height

Quetelet's observation can easily be replicated today on any large database that includes measurements of adult body weight and height. The natural log ($\ln$) of body weight (Wt) is plotted against the natural log of height (Ht) and the slope of the resulting regression line (α in the equation $\ln(Wt) = \alpha \ln(Ht) + \ln(k)$) is the scaling exponent and k is the intercept. Written in the form of a typical allometric model, $Wt = kHt^\alpha$, α is the scaling exponent or power which Quetelet found to have a value of approximately 2. The calculated index, Wt/Ht^2 or BMI, is ideally highly correlated with adult body weight yet is independent of height (43,44).

One controversy arising related to BMI is that weight might scale to height with powers other than 2 (15,45,46). For example, if adults differing in height were simple magnifications of each other or 'isometric', then weight would scale as height³ (42,47). If this is the case, then adjusting weight for height² would lead to erroneous conclusions regarding adiposity comparisons across short and tall people (44). A short and a tall person with the identical weight/ Ht^2 would not have the same weight/ Ht^3 . Perhaps incorrectly adjusting weight for height² instead of height³ explains why Mexican Americans appear to differ in %fat from their taller but similar BMI NH white and black counterparts.

To test this hypothesis, we derived the height powers for NH white, NH black and Mexican NHANES participants in a previous report (17). However, there are at least two caveats regarding biological factors that may skew the scaling powers in a population sample. First, many adults gain weight as they age and older adults are also often shorter than their

younger counterparts because of secular effects and gradual vertebral bone loss (48). The α level may thus be influenced by older adults who are heavier with greater adiposity and yet shorter than those who are younger. Recall that the goal is to develop a value for α that reflects how body weight increases across adults as a function of height that is independent of age.

A second concern relates to the presence of significant correlations between adiposity and height in some population samples, even after taking age into consideration (17,18). Biological theories to explain this observation include accelerated growth in obese children with premature ossification of epiphyses leading to short adult stature (49); and MC4R-mediated influences on hypothalamic somatostatinergic tone leading to obesity and accelerated growth in children and obesity with tall adult stature (50). While a definitive mechanism or theoretical explanation for the %fat-height correlation observed in some groups has not been established, the important concern related to BMI is that again this effect may influence the slope of log body weight vs. log height. For example, a sample of young adults may be characterized by high levels of both adiposity and body weight present in short subjects, (17,18) and this effect will again influence the slope of log body weight vs. log height. A prevailing assumption, one important in developing static allometric models in the current context is that adiposity is biologically independent of height in the general population (17).

Therefore, to effectively deal with both issues, we performed regressions using both age and %fat as covariates. Applying these two covariates to the NHANES sample, we found that in fact adult body weight empirically scaled to height with powers very close to 2 in all three NHANES race/ethnic groups with values slightly larger in men (2.02–2.29) than in women (1.94–1.99) (Table 1). Moreover, these covariates shrunk the size of the 95 % confidence levels containing the scaling powers, leading to greater confidence that the scaling exponent is not 3 and is close to 2. Moreover, the small within sex-group differences in scaling powers cannot explain the variable BMI–adiposity relations observed across the three NHANES race/ethnic groups. In sum, body weight empirically scaled to height across NH white, NH black and Mexican American men and women with powers of about 2, after controlling for adiposity and age.

Regional body mass scaled to height

But do these findings mean that all people with the same BMI have an identical shape, independent of height? Humans have a head, two arms, two legs and a central ‘trunk’ mass component. However, great heterogeneity exists in the body weight proportions of these different regions. Do these four body mass regions all scale to height similar to body weight (i.e. with a power of 2), particularly across race and ethnic groups? A region that scales with a height power different from 2 may not be the same proportion of body weight in tall vs. short subjects as explained in Supporting Information III.

To answer this question, we examined height scaling powers for the four body mass regions using DXA data provided by the 1999–2006 NHANES. The regional mass scaling powers were derived using the same modeling approach as for body weight. Our regional mass-body

composition DXA model described in this and in later sections is shown in Supplementary Fig. 2.

We found an identical pattern across the three NHANES race/ethnic groups in both the men and women. Head mass scaled with a low power of about 1, leg mass scaled with powers between about 2.3 and 2.5, and arm and trunk mass scaled to height with powers close to 2 (18). Because body weight scaled to height in these subjects with a power of about 2, this means that taller people had a larger fraction of their body weight as leg mass and a smaller fraction as head mass than did their shorter NHANES counterparts. Viewed from another perspective, tall people from the three race/ethnic groups had a different distribution of their body mass (smaller relative head mass and larger relative leg mass), in comparison to shorter people with an identical BMI. Variation in regional body mass proportions with height may be one reason the shorter, younger Mexican American men and women groups might differ in relative body shape from the taller NH white and black groups.

Fat-free tissues scaled to height

As with body weight, adult lean or fat-free mass (FFM) also scaled in the NHANES sample as height^2 with α values slightly larger in men than in women (Table 1) (18,51). A different scaling pattern emerges when we now extend these analyses to the three main FFM components: bone, skeletal muscle and residual mass in the NHANES sample. Residual mass includes all non-musculoskeletal lean tissues and organs (52). Across sex and race/ethnic groups, skeletal muscle and bone mass scale to height with very similar powers of about 2.3 to 2.5 (Table 1). Collectively, musculoskeletal mass (skeletal muscle plus bone) also scales to height with powers of about 2.3–2.5. By contrast, residual mass scales to height with powers of about 1.7–2.0.

These new observations indicate that skeletal muscle and bone maintain relatively stable relations to each other as a function of stature and that taller subjects have a larger fraction of their FFM and body weight as those two components than do shorter subjects of equivalent age and adiposity. Viewed from another perspective, and combining these findings with our earlier observations, taller people have a larger fraction of their body weight in their legs and a larger fraction as skeletal muscle and bone than do shorter people of the same BMI. Similarly, taller people have a smaller fraction of their body weight as residual mass, the component that includes all non-musculoskeletal lean tissues and organs. This observation is consistent with the finding that some organs and tissues that comprise residual mass scale to height with very low powers. For example, brain mass scales to height in both men and women with powers of one or less (53).

We thus see that even though two people may have the identical BMI and FFM index (FFM/Ht^2), they can have very different regional body mass characteristics depending on their height. Importantly, these scaling features are similar among adult NH white, NH black and Mexican American men and women NHANES participants.

Waist circumference scaled to height

Important critical discussions also focus on empirical relations between body circumferences, BMI, adiposity and race/ethnicity - such as why blacks have low visceral

adiposity once adjusted for BMI (54). Among body circumferences, waist circumference is the most useful to evaluate in research and clinical settings because it is used as a measure of total body fat, visceral fat and as a marker of metabolic risk (55).

From an anatomical perspective, waist circumference encircles adipose tissues, skeletal muscles, bones and visceral organs. If waist circumference increased isometrically with stature, taller people would have a much larger waist circumference than is actually observed. Isometric enlargement of the waist as a function of stature would be characterized by a height scaling power of one. As an example, if adult A was twice the height of adult B, their waist circumference would also be twice as large. However, waist circumference actually increases across adults approximately as $Ht^{0.5-0.7}$ (16–18,39,55,56). While scaling powers are somewhat variable across race/ethnic groups, we can generalize that waist circumference scales similarly to height across NH white, NH black and Mexican Americans approximately as $height^{0.5-0.7}$ (17,18). We can thus conclude that greater stature in men and women from all three race/ethnic groups is accompanied by similar relative changes in body shape and composition. Of note, we also found similar height scaling patterns in Korean Asians (17,18).

Body shape and composition

Race/ethnic group effects

From our review of earlier studies and new NHANES analyses, we found that height scaling relations are similar across the three evaluated NHANES race/ethnic groups and that %fat variably differs across the evaluated NHANES race/ethnic groups, even after controlling for BMI and age. Thus, the variation in height powers likely explains only part of the differing BMI–adiposity relations among race/ethnic groups.

The remaining question is: how do body shape and composition vary across race/ethnic and age groups that are similar in body weight and height, and so also BMI? In the descriptive analyses that follow we provide a demonstration of the complex body shape and composition relationships that underlie the observed race/ethnic differences in BMI–adiposity relations and how these relations vary across the adult lifespan.

We extracted a sample of NHANES participants from the full database including the three race/ethnic groups who had similar BMI ($24 < 26 \text{ kg m}^{-2}$) and height (men, $165 < 175 \text{ cm}$; women, $155 < 165 \text{ cm}$) and thus weight who were within two age groups, younger (ages 18–29 years) and older (age ≥ 70 years). The selection of this sample and related analysis methods are described in Supporting Information II (17,18). We then examined whether body shape (regional body mass proportions) and composition (skeletal muscle, bone, residual mass, FFM and fat mass) differs across the BMI and height-matched NH white, NH black and Mexican American subjects within each sex and age group.

Regional body mass and whole-body composition results for the demonstration sample are presented in Table 2 for men and Table 3 for women. The tables provide statistical comparisons between the groups, and for convenience, here we report only statistically significant differences in the text, unless otherwise noted.

Younger adults (ages 18–29 years)

In the sample of young men and women, adiposity has the ranking as observed earlier: NH blacks < NH whites < Mexican Americans. These differences arise from variation between the groups in relative body shape and aspects of body composition even though the groups for each sex are similar in age, BMI, height and weight.

Non-Hispanic black group—The NH black men and women at the designated mean BMI ($\sim 25 \text{ kg m}^{-2}$) and height ($\sim 170 \text{ cm}$) had relatively more of their body mass in their appendages and relatively less in their trunk, compared with the NH white and Mexican American groups. The NH black men and women also had greater musculoskeletal mass (mean, ~ 3 to 5% percent units), but less residual mass (~ 1 to 2%) than NH white and Mexican American men and women. These combined body composition differences (~ 3 to 5% and -1 to -2%) led to a larger FFM and smaller mean %fat in the NH blacks (~ 1 to 2%) than in the corresponding NH white and Mexican American groups; however, in men, the %FFM and %fat differences between NH blacks and whites were of borderline significance. Nonetheless, this pattern of body composition differences was the same in both NH black men and women: the larger FFM than NH white and Mexican American subjects reflects the net significant differences between greater musculoskeletal mass and smaller residual mass. The difference in musculoskeletal mass between NH blacks and both NH whites and Mexican Americans was almost twice the size of the differences in %fat among the groups. The NH black men and women also had smaller waist circumferences (mean, ~ 2 – 7 cm) than their similar BMI and height NH white and Mexican American counterparts, although the difference between the NH black and white women was non-significant.

Mexican American group—On average, Mexican American subjects had more of their body mass stored in the trunk region, with the exception that the differences between Mexican American men and NH white men were non-significant. The Mexican American subjects also had less appendicular mass, but statistical significance was present only for comparison to the NH blacks. The Mexican American men and women had less musculoskeletal muscle mass and the same or less residual mass as NH whites or NH blacks, respectively. These combined body composition differences (~ -2 to -6% and 0 to 1%) led to a smaller FFM and greater % fat (mean, ~ 3 to 5% percent fat units) in the Mexican American men and women than in the corresponding NH white and black groups. Waist circumference was also larger (mean, ~ 2 to 7 cm) in the Mexican American men and women compared with their similar BMI and height NH white and Mexican American counterparts.

Older adults (age 70 years)

Important anatomic changes occur as people age, with older and younger adults having different body shape and composition (57). These effects can be observed in our cross-sectional sample by comparing differences in body shape and composition (in % units) between the BMI and height-matched younger and older NH white groups of men and women (Fig. 3). Relative to the younger subjects, the older NH white subjects had less body mass in their legs and more in their trunk; small and inconsistent differences are present in head and arm mass. Likewise, older NH white men and women had relatively less

musculoskeletal mass (−7% to −8%) and more residual mass (1% to 2%) than their younger counterparts. The combination of reduced musculoskeletal mass and larger residual mass led to a net smaller FFM and thus larger % fat (5% to 6%) in the older subjects. These observations in general were similar for both men and women in all three NHANES race/ethnic groups (Tables 2 and 3).

Assuming these cross-sectional observations reflect to some extent longitudinal changes in body shape and composition over the adult lifespan, they are the same or even larger in magnitude than the mean differences observed between race/ethnic groups at a given age. For the NH white men, %fat was greater in the older men by ~7% percent fat units, which is double the maximum between-race/ethnic group differences observed in the younger men. For the women, %fat was greater in the older NH white women by ~6%, again almost double the maximum between-race/ethnic group differences observed in younger women.

The same pattern of age-related differences in adiposity was present when examined using the nationally-representative % fat prediction equations (Supplementary Fig. 3): between-race/ethnic group differences in adiposity at the same age and BMI are smaller than adiposity differences between younger (age 30 years) and older (age 70 years) subjects. At a BMI of 25 kgm^{−2}, older NH white men had ~5% greater predicted %fat units than younger NH white men, while younger NH black and Mexican American men had ~2% less and ~1% greater %fat units than younger NH white men, respectively. Similarly, older NH white women had ~3% greater predicted %fat units than younger NH white women, while younger NH black and Mexican American women had ~1.5% less and ~1% greater %fat units than younger NH white women, respectively.

Non-Hispanic black group—Body shape and composition observed in the three race/ethnic groups of older men and women are presented Tables 2 and 3. The most consistent finding is that the NH black men and women continued to have the largest relative musculoskeletal mass (mean , ~2% to 3% percent units). The larger musculoskeletal mass, however, was counterbalanced by a smaller residual mass of variable statistical significance, and this combination led to non-significant differences in FFM and %fat from the other two race/ethnic groups.

Mexican American group—The older NH white and Mexican American men and women differed in body shape and composition, although there was no definable pattern compared with that seen for the NH black subjects, and %fat was also similar across the two groups.

Concluding perspectives

The NHANES ‘race/ethnic’ group classification separates people into groups that differ in body shape and composition phenotype

Investigators comparing body shape and composition phenotypes across race and ethnic groups face a formidable challenge in separating out what might constitute inherited vs. environmental effects. On the inherited side, racial admixture is well established among the groups evaluated in NHANES, particularly the NH blacks and Mexican Americans (58,59).

Likewise, environmental differences between the evaluated groups are probably substantial. Importantly, developmental nutrition and health factors strongly influence adult stature, body shape and body composition (60,61).

Environmental and lifestyle factors working over long time periods may account for why race/ethnic differences in body shape and composition were less apparent in the older subjects evaluated in NHANES. We have tried to tease apart some of these factors in our analyses but interpretation of our findings requires consideration of the multiple complexities when reviewing potential biological mechanisms. Given these provisos, it is clear that the NHANES race/ethnic group classification separates people with different body shape and composition phenotypes. These differences are most consistent and apparent in younger adults but to some extent are present in older age.

Body weight scales similarly across adult race/ethnic groups as height⁻² and body mass index is independent of height

We confirm that body weight empirically scales as height⁻² across adults after controlling for adiposity and age. BMI in this context is thus a measure of adult shape that is independent of height. Moreover, we found that height scaling powers are similar across the three NHANES race/ethnic groups.

Our findings should be framed in the context of Burton's critical review of statistical approaches and their limitations in deriving height powers (i.e. α) that are the basis of BMI (15). Burton showed why values for α can vary and how statistical methods can distort perceived body mass-height relations. As Burton points out, the 'true' functional relationships between body mass and height have yet to be established (15).

Body component proportions are a function of adult height

We discovered that people who have the same BMI but who differ in height also differ in regional body mass and body composition proportions. Specifically, we found that taller adults who have the same BMI as shorter adults have a larger proportion of their body mass in their legs and as musculoskeletal mass and a smaller proportion in their head. We similarly observed that waist circumference increases with stature as $Ht^{0.5-0.7}$. Importantly, regional body mass, body composition and waist circumference show very similar height scaling patterns across NH white, NH black and Mexican American men and women. These observations suggest that race/ethnic-specific height scaling powers are not needed.

At the same body mass index and height, body component and regional body mass proportions differ across the adult age-span

Another observation, confirmatory of earlier studies (19,57,62), is that for the same BMI and height, older people have a different body shape and composition than younger people.

Our findings on the NHANES demonstration sample show that relative to younger people of the same BMI and height, older adults have a smaller appendicular and musculoskeletal mass and a corresponding larger trunk and residual mass. The net body composition effect was a smaller FFM and larger fat mass for the same BMI and height. This age-related body

shape/composition phenotype, consistent across men and women in our demonstration sample, likely reflects senescence-mediated hormonal changes, lowering of physical activity levels, reductions in trunk length with osteoporosis, and many other related mechanisms.

Our findings affirm the limitations of BMI as a measure of sarcopenia or age-related skeletal muscle loss (63). Even though younger and older adults had the same average BMI, substantially less skeletal muscle and bone were present in the older adults. We found in our demonstration sample that these body composition and shape changes with advancing age were generally similar between men and women in all three NHANES race/ethnic groups.

An important proviso is that even though we are comparing lean mass components across older and younger adults, at present we have no way to ascertain the quality of these differences. Specifically, with aging lean tissues proportionally increase in connective tissue and structural proteins and for skeletal muscle there are greater relative losses of type II vs. type I fibers (63). Thus, our observed anatomic differences between older and younger adults may not translate directly to age-related functional effects.

The larger relative trunk mass and waist circumference in older adults reveals that waist circumference and BMI are not perfectly coupled, the two often contrasted as measures of health risk (64). The larger trunk mass in older adults of the same BMI represents net differences from younger adults in total adipose tissue, skeletal muscle, bone and even the relatively larger total residual organ and tissue mass. Senescence is also accompanied by enlargement of visceral adipose tissue, and this small but metabolically important compartment also likely contributes to the greater waist circumference observed in older adults (65).

At the same body mass index and height, body component and regional body mass proportions differ across National Health and Nutrition Survey race/ethnic groups

The most consistent observation emerging from our nationally-representative %fat prediction models and from evaluation of our demonstration sample were the body shape and composition differences observed between NH black subjects and the other two race/ethnic groups. Compared with the matched NH white and Mexican American subjects, greater musculoskeletal mass and less residual mass combined to create a net same or larger FFM in all of the NH black groups. These body composition effects were accompanied by correspondingly greater leg mass and smaller trunk mass and waist circumference in NH blacks, with the one exception of a larger waist circumference in the older NH black women. Relative musculoskeletal mass differences between NH blacks and the other two race/ethnic groups were even larger and more consistent than those for adiposity.

Merz *et al.* (22) and Trotter *et al.* beginning in the 1950s (30–32) described greater relative extremity lengths and bone mass measured in black compared with white skeletons. Since then a number of studies have confirmed and extended these observations in living humans (41,66,67), allowing us to develop a composite phenotype with new findings from the present report. We surmise that NH black NHANES participants at the same age, BMI, body weight and height have relatively longer extremities and greater musculoskeletal mass and smaller trunk and residual mass than the other two evaluated groups. This combination of

anatomic features led to a larger FFM and thus when body weight and BMI serve as the reference across race/ethnic groups, NH black Americans have a smaller fat mass and %fat.

What mechanisms underlie the race/ethnic differences in body shape and composition? Separate from the environmental exposures mentioned previously, the early-life appearance of skeletal differences between blacks and whites suggests morphogenesis mechanisms are involved (60,66,68). In addition, black-white hormone level differences are recognized that relate to bone, skeletal muscle and fat mass development and maintenance (69–71). Genetic mechanisms are also now recognized that conjointly regulate both adipose tissue and skeletal muscle mass (72). These observations raise the possibility that race/ethnic differences in adiposity may be linked directly to the same or similar mechanisms accounting for the kinds of lean mass differences found in the current report.

A related earlier observation made by Norgan in 1994 was that long-legged Australian Aborigines with a low sitting height/stature ratio (SHR) had very low BMIs even though they did not appear to be malnourished (73). Bogin and Beydoun confirmed and extended Norgan's observations in 2007 (74) showing with data from NHANES III that people with a low SHR and longer relative leg length have a lower BMI than those with a higher SHR ratio. Burton *et al.* in 2012 (75) reported the presence of a negative correlation between leg length and leg cross-sectional area. These findings taken together suggest that race/ethnic groups who have relatively longer legs for their height have a lower BMI than their shorter-legged race/ethnic counterparts. An important remaining question is if adding a measure such as SHR to BMI improves prediction of health outcomes or clarifies why some race/ethnic groups appear to have greater morbidity or mortality than others when framed in the context of solely BMI.

Our findings in the younger Mexican American men and women were almost the inverse of those in the NH black subjects: relatively smaller appendicular and larger trunk mass; less musculoskeletal mass with similar or larger residual mass; smaller FFM and greater %fat; and larger waist circumference. This body shape and composition phenotype was consistent in the younger demonstration group but became less so in the older sample and as also predicted from our nationally-representative body fat prediction equations. As with the earlier literature on detailed body composition in blacks (4), similar reports on Mexican Americans tend to include small samples with even more limited anatomic measurements. We cannot thus clearly ascertain in the Mexican American group whether, for example, the smaller musculoskeletal mass than observed in the other younger demonstration groups is because of shorter extremities or relatively less bone and skeletal muscle per unit limb length. This information gap needs to be filled in future studies and serves as an example of the thorough phenotyping that should be carried out when evaluating BMI–adiposity associations across race/ethnic groups. As suggested by Bogin and Beydoun (74), environmental factors, including early life nutrition, strongly influence adult relative leg length and perhaps this observation in-part accounts for the body shape and stature findings of the Mexican Americans, many of whom immigrated from low-income regions of Mexico to the United States. Comprehensive studies of Mexican American infants and children born in the United States would help to establish if a distinct body shape-composition phenotype appears early in life and the extent to which this phenotype is related to socioeconomic

status. Not only would this information fill an important knowledge gap, but a fuller understanding of how these phenotypes relate to health outcomes would emerge.

Waist circumferences also differed between the BMI-equivalent race/ethnic groups in our demonstration sample, largely mirroring variation in trunk mass. The smaller trunk mass and waist circumference in younger NH blacks compared with NH whites and Mexican Americans is also consistent with the presence of less visceral adipose tissue mass reported in African American men and women (76).

As the largest global race/ethnic group, Asians share many of the same phenotypic features as reported here for Mexican Americans: shorter stature, higher %fat and relatively larger trunk adiposity and waist circumference relative to Caucasians of similar age and BMI (10,20). Most of these comparative studies have measurement limitations similar to those noted earlier, such as differences in the software algorithms that compute body composition, and so the magnitude of Asian-Caucasian relative body shape and composition differences, for example, have yet to be established with the certitude offered by a data set such as NHANES. There are even small between-DXA system and software version differences that are in the range of NHANES race/ethnicity adiposity differences (77). Comparisons of race/ethnic groups across nations and continents with the use of multiple DXA systems require meticulous attention to instrument calibrations.

While BMI is the primary focus of our report, race/ethnicity differences in body shape and composition are also relevant to other widely used models in the clinical nutrition field. In particular, Forbes's FFM-fat equation (78) is incorporated into several important dynamic energy balance models (79) and the findings reported herein are consistent with and expand on those of Thomas *et al.* (80) and Broyles *et al.* (81) that critically examine race/ethnic factors in Forbes' model development and application.

The collective stature, age and race/ethnic factors combine to make BMI highly heterogeneous with respect to regional body mass and body composition proportions

The collective findings of our in-depth review reveal a remarkable heterogeneity in regional body mass and body composition proportions encompassed within the same level of BMI across groups differing in race/ethnicity and age. We can now give a quantitative estimate to the statement that BMI is 'a fairly reliable indicator of body fatness (12)' when applied across differing NHANES race/ethnic and age groups. As an extreme example, a NH black man at the age of 30 years with a BMI of 25 kg m^{-2} is predicted using our nationally-representative equations to have an adiposity level of 22.4% fat whereas a comparable BMI NH white man at the age of 70 years has a predicted adiposity level of 28.1%, a difference of almost 6% percent fat units. Reversing the calculation, at an adiposity of 22.4% as in the younger NH black subject, an equivalent adiposity in the older NH white subject would be accompanied by a predicted BMI of 20.7 kg m^{-2} , a difference of over 4 BMI units. Even the difference in adiposity across the adult age span of four decades within the NH white men is relatively large, almost 4% percent fat units. The corresponding relative differences for musculoskeletal mass are even larger, as observed in our demonstration sample analyses.

Recognizing this relative body shape and composition heterogeneity would appear essential when applying BMI as a measure of adiposity. While broadly viewed, BMI and %fat are very well-correlated within sex, race/ethnic and age groups (82), adiposity comparisons across groups without consideration for findings such as those reported herein pose the risk of ‘overweight’ and ‘obesity’ misclassification. Setting race/ethnic specific BMI cut points based solely on adiposity would appear to be overly complex and likely would defeat the public health goal of setting BMI as a health risk indicator with simple memorable ‘thresholds’ for additional actions at specific levels. Nonetheless, it is important for public knowledge that the body shape and composition heterogeneity across race/ethnic groups and age-span are widely known and embraced.

In the context of BMI as a public health measure, the setting of action ‘thresholds’ is usually based not solely on BMI-adiposity associations but on morbidity and mortality outcomes (4–6,83,84). Viewed in that context, BMI correlates not only with adiposity but other body components, notably muscularity and trunk fat, that associate with several clinical outcomes (85–87). Broadening the view of BMI as one global measure of health with less concentration on direct linkages solely with adiposity would help to alleviate the ongoing intense debate about this simple index’s value as an ‘alternative for direct measures of %fat (12)’. Moving beyond using BMI alone to estimate meaningful clinical outcomes would appear to be a clinically more relevant focus than the more circuitous concept of BMI as a good proxy of adiposity and that, in turn, inadequate or excess body fat leads to adverse clinical outcomes.

Our findings also relate to waist circumference as a measure of visceral fat and thus to adverse cardiometabolic health outcomes. We show that waist circumference, like BMI, varies with subject height, age, and race/ethnicity and these relations were similar for total trunk mass. Waist circumference thus appears to be a phenotypic measure beyond that solely of visceral fat and may even reflect the mass of large organs within the trunk such as liver (88).

Conclusions

In sum, body weight empirically scales as height² across adult NH whites, NH blacks and Mexican Americans, and BMI in this context is a height-independent measure of body shape. When BMI and height are held constant, however, regional mass and body composition proportions differ across the three NHANES race/ethnic groups to a variable extent. Similarly, regional body mass and body composition proportions also differ within the same sex and race/ethnic group across the adult age-span because of presumably both secular and age-related biological mechanisms. BMI thresholds used to predict clinical outcomes have public health value, and here we conclude that there is little to be gained by introducing race/ethnic specific BMI cut points using solely adiposity as the reference. In particular, BMI reflects more than individual differences in adiposity and other components of body composition (e.g. musculoskeletal mass) also impact health outcomes (85,87). More in-depth studies are needed to elaborate race/ethnic differences in body shape and composition and how these differences relate to clinically meaningful risks. Lastly, a need

exists for practical phenotypic measures beyond BMI, and even circumferences, that can further refine estimates of body shape and proportions at the population and individual level.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors extend their appreciation to Emily F. Mire, MS, for her assistance with NHANES data acquisition.

Funding sources

CMP is supported in part by 1 U54 GM104940 from the National Institute of General Medical Sciences of the National Institutes of Health, which funds the Louisiana Clinical and Translational Science Center. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Abbreviations

BMI	body mass index
BMC	bone mineral content
CI	confidence interval
df	degrees of freedom
DXA	dual-energy x-ray absorptiometry
FFM	fat-free mass
FM	fat mass
Ht	height
Mex Am	Mexican American
MSk	musculoskeletal
NH	non-Hispanic
NHANES	National Health and Nutrition Survey
RM	residual mass
SD	standard deviation
SkM	skeletal muscle
SE	standard error
WC	waist circumference
Wt	body weight

%fat percentage body fat

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Figure 1.

Percent (%; $\bar{X} \pm \text{SE}$) fat observed in NHANES men (upper panel) and women (lower panel) across the three evaluated race/ethnic groups. Prediction models derived from the full sample (Supplementary Table 3, lower portion) were used to predict % fat levels for representative subjects age 30 years with a body mass index (BMI) of 25 kg m⁻². NH non-Hispanic; Mex Am, Mexican American.

Figure 2.

Height vs. age in NHANES men and women participants across the three evaluated race/ethnic groups (left hand panels) and predicted %fat vs. age for men and women NHANES participants (right hand panels). Percent fat values at each decade of age were derived using the nationally-representative equations summarized in the lower portion of Supplementary Table 3 at a BMI of 25 kg m^{-2} . NH, non-Hispanic; Mex Am, Mexican American.

Figure 3.

Patterns of between-age group differences in regional body mass and composition with younger NH white men and women as the referent groups. The Δ s in % units were calculated as: percentage (%) of body weight for the component of interest observed in the older NH white group minus the corresponding results in the younger NH white group. Positive or negative values indicate, respectively, larger or smaller relative amounts of regional mass, bone, skeletal muscle (SM), residual mass (RM), fat-free mass (FFM) or fat mass present in the older NH white group compared with the corresponding younger NH white groups. †Between-age group difference for nine within-sex group comparisons significant at a two-sided $p < 0.05/9$, or $p < 0.006$.

Table 1
Nationally-representative scaling powers (α) observed in NHANES men and women

	Men			Women		
	NH White	NH Black	Mex Am	NH White	NH Black	Mex Am
N	4,406	2,035	2,256	4,235	2,045	2,149
Body weight	2.02 $\pm$ 0.06 ^a	2.29 $\pm$ 0.09 ^b	2.14 $\pm$ 0.07 ^{ab}	1.97 $\pm$ 0.06	1.94 $\pm$ 0.08	1.99 $\pm$ 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 mass	2.26 $\pm$ 0.05	2.40 $\pm$ 0.10	2.29 $\pm$ 0.08	2.32 $\pm$ 0.05 ^a	2.09 $\pm$ 0.06 ^b	2.37 $\pm$ 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
SM mass	2.31 $\pm$ 0.06	2.45 $\pm$ 0.11	2.41 $\pm$ 0.08	2.30 $\pm$ 0.07	2.25 $\pm$ 0.09	2.39 $\pm$ 0.11
	2.19–2.43	2.23–2.67	2.26–2.56	2.16–2.43	2.07–2.44	2.17–2.61
MSK mass	2.30 $\pm$ 0.06	2.44 $\pm$ 0.11	2.40 $\pm$ 0.07	2.30 $\pm$ 0.06	2.24 $\pm$ 0.08	2.39 $\pm$ 0.10
	2.19–2.42	2.23–2.65	2.25–2.55	2.17–2.43	2.06–2.41	2.19–2.59
Residual mass	1.77 $\pm$ 0.05 ^a	2.03 $\pm$ 0.08 ^b	1.80 $\pm$ 0.06 ^{ab}	1.69 $\pm$ 0.05	1.66 $\pm$ 0.08	1.65 $\pm$ 0.08
	1.66–1.87	1.87–2.20	1.67–1.92	1.59–1.79	1.49–1.83	1.48–1.82
FFM	2.05 $\pm$ 0.05	2.26 $\pm$ 0.09	2.12 $\pm$ 0.06	1.98 $\pm$ 0.05	1.97 $\pm$ 0.08	2.01 $\pm$ 0.09
	1.94–2.15	2.08–2.44	1.99–2.24	1.88–2.09	1.80–2.13	1.84–2.18

Powers are expressed as $\alpha \pm$ SE with 95% CI below. Abbreviations: FFM, fat-free mass; MSK, musculoskeletal; Mex Am, Mexican American; NH, non-Hispanic; SKM, skeletal muscle. Between-race/ethnicity comparisons performed using Cochran's Q Test for Heterogeneity. Values with different superscript letters are significantly different at $p < 0.05/3 = 0.0167$. Scaling powers are adjusted for %fat and age (17).

Table 2

Results of NHANES demonstration subgroup analyses for men

	Younger (ages 18–29 years)				Older (ages 70 years)			
	NH White	NH Black	Mexican Am		NH White	NH Black	Mexican Am	
N	33	37	86		66	14	28	
Age (years)	22.5±3.9 ^a	21.3±3.6 ^a	22.3±3.8 ^a		78.9 ± 5.5 ^a	76.8±5.0 ^{ab}	75.6±3.7 ^b	
Height (cm)	171.0±3.0 ^a	170.6 ± 2.7 ^a	169.7 ± 2.9 ^a		170.4±2.9 ^a	170.6±2.6 ^a	169.4±3.1 ^a	
Weight (kg)	73.1 ± 3.0 ^a	73.6±3.6 ^a	73.1 ± 3.7 ^a		72.7±3.1 ^a	74.4 ± 3.6 ^a	73.9±3.8 ^a	
BMI (kg m ⁻²)	25.0±0.7 ^a	25.2±1.0 ^a	25.4 ± 2.8 ^a		25.0±0.6 ^a	25.6±0.9 ^a	25.7±0.8 ^a	
WC (cm)	84.1 ± 4.2 ^a	80.6±4.9 ^b	87.9±4.2 ^c		97.0 ± 4.5 ^a	95.9±4.2 ^{at††}	99.7±5.0 ^b	
Regional mass (%)								
Head	6.7±0.05 ^a	7.0±0.5 ^b	6.8±0.5 ^a		6.5±0.5 ^a	6.6±0.4 ^a	6.7±0.7 ^a	
Trunk	46.8±1.6 ^a	43.7±2.0 ^b	47.6±1.7 ^a		51.1 ± 2.2 ^a	47.7±2.5 ^b	51.8±1.4 ^a	
Arms	12.9±0.9 ^a	13.1 ± 0.9 ^a	12.5±0.7 ^a		12.0±0.9 ^a	12.5±1.0 ^a	11.9±0.6 ^a	
Legs	33.5±1.5 ^a	36.2±2.1 ^b	33.1 ± 1.7 ^a		30.4±1.9 ^a	33.2±2.2 ^b	29.5±1.6 ^a	
Appendicular	46.4±1.6 ^a	49.3±2.0 ^b	45.6±1.8 ^a		42.4 ± 2.1 ^a	45.7±2.5 ^b	41.4±1.6 ^a	
Body comp. (%)								
Bone	6.5±0.6 ^a	7.1 ± 0.9 ^a	6.2±0.6 ^a		6.0±0.7 ^a	6.1 ± 1.0 ^a	5.9±0.7 ^a	
SM	39.2±2.3 ^a	42.2±3.4 ^b	37.3±2.5 ^c		31.6±2.6 ^a	34.0±2.2 ^b	31.4±1.7 ^a	
MSk	45.7 ± 2.6 ^a	49.3±4.0 ^b	43.4±2.9 ^c		37.6±2.8 ^a	40.1 ± 2.6 ^b	37.3±1.8 ^a	
RM	31.7 ± 1.7 ^a	30.0±1.8 ^b	31.2±1.6 ^a		33.1 ± 1.7 ^a	30.4±1.7 ^b	33.8±1.9 ^a	
FFM	77.4±3.1 ^{a††}	79.3±4.3 ^b	74.6±3.4 ^c		70.7±3.1 ^a	70.6±2.2 ^a	71.1 ± 2.6 ^a	
Fat	22.6 ± 3.0 ^{a††}	20.7±4.3 ^b	25.4±3.4 ^c		29.3±3.1 ^a	29.4±2.2 ^a	28.9±2.6 ^a	

Results are X±SD. Subjects selected had BMIs 24 < 26 kg m⁻², height 165 < 175 cm and were divided into younger (ages 18–29 years) and older (age 70 years) groups.

Abbreviations: Am, American; BMI, body mass index; FFM, fat-free mass; MSk, musculoskeletal; RM, residual mass; SM, skeletal muscle; WC, waist circumference.

^{a,b,c} values with different superscript letters are significantly different at $p < 0.05/3 = 0.0167$.

^{††} $p < 0.03$ for comparison to NH black group.

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 $p < 0.03$ for comparison to Mexican Am group.

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Table 3

Results of NHANES demonstration subgroup analyses for women

	Younger (age 18–29 years)				Older (age 70 years)		
	NH White	NH Black	Mexican Am		NH White	NH Black	Mexican Am
N	79	38	69		73	14	13
Age (years)	22.6±3.9 ^a	21.4±3.6 ^a	22.6±4.2 ^a		78.0 ± 4. ^a	75.6 ± 5.3 ^a	76.0±4.1 ^a
Height (cm)	160.9 ±2.8 ^a	160.1 ±2.9 ^a	160.1 ±2.9 ^a		159.7 ±3.0 ^a	160.4 ±2.4 ^a	158.7 ±2.9 ^a
Weight (kg)	65.3±3.1 ^a	65.0 ± 4.1 ^a	65.3±3.2 ^a		64.8±3.4 ^{ab}	66.9±3.5 ^a	63.2±1.9 ^{ab}
BMI (kgm ⁻²)	25.2±0.9 ^a	25.3±1.0 ^a	25.5±0.9 ^a		25.4±0.9 ^a	26.0±1.0 ^a	25.1 ±0.6 ^a
WC (cm)	82.8±4.8 ^a	80.6 ± 5.7 ^a	84.9±4.8 ^b		91.7±6.0 ^a	96.1 ±5.8 ^a	91.9±7.0 ^a
Regional mass (%)							
Head	6.5±0.4 ^a	7.0±0.5 ^b	6.8±0.5 ^b		6.3±0.5 ^a	6.7±0.6 ^a	6.6±0.4 ^a
Trunk	47.0 ± 2.0 ^a	44.1 ±1.8 ^b	47.9±0.5 ^c		49.9±2.5 ^{ab}	48.5 ± 2.4 ^a	51.3±3.0 ^b
Arms	11.0±0.7 ^a	11.3±0.7 ^a	11.0±0.7 ^a		10.9±0.8 ^a	11.4±0.9 ^a	11.7±1.0 ^a
Legs	35.6±2.2 ^a	37.5±1.8 ^b	34.2±2.3 ^c		32.9±2.5 ^a	33.3±2.4 ^a	30.4±2.7 ^b
Appendicular	46.6±2.2 ^a	48.8±1.8 ^b	45.2 ± 2.2 ^a		43.8±2.5 ^a	44.7 ± 2.4 ^a	42.1 ±3.0 ^b
Body comp. (%)							
Bone	6.0±0.5 ^a	6.3±0.7 ^a	5.8±0.5 ^a		4.9±0.6 ^a	5.0±0.6 ^a	4.7±0.5 ^a
SM	30.1 ±2.1 ^a	32.8±2.0 ^b	28.8±2.5 ^c		24.6±2.2 ^a	26.8±2.3 ^b	24.3±2.8 ^a
MSk	36.1 ±2.3 ^a	39.1 ±2.4 ^b	34.6±2.6 ^c		29.5±2.3 ^a	31.8±2.3 ^b	29.0±3.0 ^a
RM	27.7±1.9 ^a	26.5±1.9 ^b	27.6±1.7 ^a		29.5±1.7 ^a	28.2±1.9 ^b	30.0±2.2 ^a
FFM	63.8±3.4 ^a	65.5±3.5 ^b	62.2±3.3 ^c		58.9±3.3 ^a	59.9±3.3 ^a	59.0 ± 4.2 ^a
Fat	36.2±3.4 ^a	34.5±3.5 ^b	37.8±3.3 ^c		41.1 ±3.3 ^a	40.1 ±3.3 ^a	41.0±4.2 ^a

Results are X ± SD. Subjects selected had BMIs 24 < 26 kg m⁻², height 155 < 165 cm and were divided into younger (ages 18–29 years) and older (age 70 years) groups

Abbreviations: Am, American; BMI, body mass index; FFM, fat-free mass; MSk, musculoskeletal; RM, residual mass; SM, skeletal muscle; WC, waist circumference.

^{a,b,c} values with different superscript letters are significantly different at $p < 0.05/3 = 0.0167$.