Scaling of adult body weight to height across sex and race/ethnic groups: relevance to BMI[1–4]

Steven B Heymsfield, Courtney M Peterson, Diana M Thomas, Moonseong Heo, John M Schuna Jr., Sangmo Hong, and Woong Choi

ABSTRACT

Background: Body mass index (BMI) is formulated on the assumption that body weight (BW) scales to height with a power of 2 (BW $\propto$ height^2), independent of sex and race-ethnicity. Powers differing from 2 are observed in studies of selected samples, thus raising the question if BMI is a generalizable metric that makes BW independent of height across populations.

Objectives: The objectives were to test the hypothesis that adult BW scales to height with a power of 2 independent of sex and race-ethnicity and to advance an understanding of BMI as a measure of shape by extending allometric analyses to waist circumference (WC).

Design: We conducted cross-sectional subject evaluations, including body composition, from the NHANES and the Korean NHANES (KNHANES). Variations of the allometric model ($Y = \alpha X^{\beta}$) were used to establish height scaling powers ($\beta \pm$ SE) across non-Hispanic white and black, Mexican American, and Korean men and women.

Results: Exploratory analyses in population samples established age and adiposity as important independent determinants of height scaling powers (i.e., β). After age and adiposity in the next series of analyses were controlled for, BW scaling powers were nonsignificantly different between race/ethnic groups within each sex group; WC findings were similar in women, whereas small but significant between-race differences were observed in the men. Sex differences in β values were nonsignificant except for BW in non-Hispanic blacks and WC in Koreans ($P < 0.05$). Nationally representative powers for BW were (NHANES/KNHANES) 2.12 $\pm$ 0.05/2.11 $\pm$ 0.06 for men and 2.02 $\pm$ 0.04/1.99 $\pm$ 0.06 for women and for WC were 0.66 $\pm$ 0.03/0.67 $\pm$ 0.05 for men and 0.61 $\pm$ 0.04/0.56 $\pm$ 0.05 for women.

Conclusions: Adult BW scales to height with a power of $\sim$2 across the 8 sex and race/ethnic groups, an observation that makes BMI a generalizable height-independent measure of shape across most populations. WC also follows generalizable scaling rules, a finding that has implications for defining body shape in populations who differ in stature. *Am J Clin Nutr* 2014;100:1455–61.

Keywords adiposity, allometric analysis, body composition, body shape, nutritional assessment

INTRODUCTION

The increasing global prevalence of obesity requires an easy-to-use phenotypic measure of adiposity that can be applied to the general population. Both the WHO and the U.S. NIH have long embraced BMI as the central measure of human adiposity from birth onward (1, 2).

BMI, body weight (BW)[5] divided by height squared (height^2), has for decades come under intense scrutiny, including with some criticism, as a marker of both excess adiposity and as a predictor of health status, morbidity, and mortality (3–11). Our focus in this report is on the applicability of BMI across populations varying in sex and race-ethnicity.

The primary question surrounding the use of BMI across different sex and racial-ethnic populations is whether BW/height^2 is a reliable marker of adiposity. This question can be divided into 2 parts: Does BW scale to height with a power of 2 (i.e., BW $\propto$ height^2), as widely assumed across groups differing in sex and race-ethnicity? If BW does scale as height^2, does BMI reliably predict adiposity across sex and race/ethnic groups? Many studies have explored these 2 questions (3–9, 12–14), but few had carefully evaluated large samples applying the same measurement methods across a range of race/ethnic groups, including Asians, that firmly answer prevailing concerns surrounding the generalizability of BMI.

The 1999–2006 NHANES (15, 16) and the 2008–2010 Korean NHANES (KNHANES) (17, 18) provide a new opportunity to explore these 2 questions in large-population samples that include men and women in 4 main race/ethnic groups: non-Hispanic (NH) whites, NH blacks, Mexican Americans, and Asian Koreans. The protocols used in NHANES and KNHANES are identical to the extent possible and thus provide a unique opportunity to examine scaling relations across 4 major race/ethnic groups without concern for between-study measure-

[1] From the Pennington Biomedical Research Center, LSU System, Baton Rouge, LA (SBH, CMP, and JMS); Montclair State University, Montclair, NJ (DMT); Albert Einstein College of Medicine, Bronx, NY (MH); and Hanyang University, Seoul, Republic of Korea (SH and WC).

[2] CMP is funded by a Roadmap Scholars Fellowship from the Louisiana Clinical and Translational Science (LA CaTS) Center; LA CaTS was supported by NIH grant U54 GM104940.

[3] Supplemental Tables 1–3 and Supplemental Material are available from the "Supplemental data" link in the online posting of the article and from the same link in the online table of contents at http://ajcn.nutrition.org.

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

[5] Abbreviations used: BW, body weight; DXA, dual-energy X-ray absorptiometry; FM, fat mass; KNHANES, Korean NHANES; NH, non-Hispanic; WC, waist circumference.

Received March 27, 2014. Accepted for publication September 9, 2014.
First published online October 8, 2014; doi: 10.3945/ajcn.114.088831.

ment calibration and quality issues. The main aim of the present study was to examine in-depth the first of these questions: to establish scaling relations of BW to height among these 8 sex and race/ethnic groups. The second question is the focus of a follow-up report now in preparation. Our aim in this initial study was to establish if BW scales as height^2, a requirement for BMI to serve as a height-independent measure of body shape (19, 20). As part of this analysis, we additionally evaluated the scaling of waist circumference (WC) to height in the NHANES and KNHANES samples as a means of expanding generalizable features of adult human shape. Our study extends earlier reports on this topic that were based on more limited and less generalizable samples (12, 19, 21–23).

METHODS

Study design and rationale

Scaling relations to height

BMI is founded on the empirical relation observed between BW and height as described by the following simple allometric model:

$$Y = \alpha X^{\beta}\varepsilon, \tag{1}$$

with Y the dependent variable (BW), X the predictor variable (height), β the scaling exponent or "power," α the proportionality constant, and ϵ the multiplicative error (19, 21). When expressed in the form of natural logarithms, the classic allometric equation becomes

$$\log_e Y = \log_e \alpha + \beta \log_e X + \log_e \varepsilon. \tag{2}$$

Most studies, including those by Quetelet et al. (24, 25), found that β (i.e., Equation *2* slope) is equal to ∼2 across adult samples varying in age and that BW/height^2 is largely independent of height (19–21). However, the critical height power value (i.e., β in Equations *1* and *2*) of 2 remains controversial and a wide range of other scaling exponents are reported (∼1.5–2.5) and suggested (9–11, 26, 27). The causes of variability in these scaling powers are not well understood.

The first phase of analyses were aimed at elucidating the basis of this previously observed variability in scaling powers, and the second phase of analyses focused on development of nationally representative scaling powers for BW and WC. The samples used in these analyses are summarized in **Supplemental Table 1**.

Potential influence of age and adiposity

One explanation for variable height powers, notably other than 2, is that age-related effects on BW and height may independently influence the scaling power (i.e., β) of weight on height. When exploring these relations across wide age ranges, there are likely secular and other effects present in the evaluated data sets that influence scaling relations. Older subjects in adult samples are typically heavier and shorter than their younger counterparts (28), an effect that will strongly influence β independent of the scaling relation between BW and height. We examined this possibility in the first phase of data analyses.

A second explanation for variable height powers, other than 2, is that adiposity may influence β independently of fat-free body mass. To gain insight into this potential effect, consider human body mass as consisting of 2 main components: a relatively stable core mass (e.g., skeleton, muscle, etc.) that is a function of height and a highly variable portion that reflects cumulative energy balance and consists mainly of adipose tissue (23, 29)

When examining how BW scales to height, the unstated assumption is that BW and fat mass (FM) both scale to height with the same power. The relevance of this assumption can be seen when writing the classic allometric model individually for FM and BW, both scaled to height:

$$FM = \alpha_1(\text{height})^{\beta 1} \tag{3}$$

and

$$BW = \alpha_2(\text{height})^{\beta 2} \tag{4}$$

Therefore,

$$FM/BW = \alpha_1/\alpha_2(\text{height})^{\beta 1-\beta 2} \tag{5}$$

When β_1 and β_2 are equal (i.e., when both FM and BW scale the same to height), the value of β_1–β_2 is 0 and a nonzero number raised to the power of zero equals 1. Thus, when $\beta_1 = \beta_2$, adiposity (i.e., %fat) is independent of height. However, if the difference observed between β_1 and β_2 is not zero, %fat will correlate either positively or negatively with height and weight scaled to height no longer solely represents the relation between stature and BW. This potential "bias" in scaling power could partly account for some of the variability observed between studies when BW is scaled to height without adjusting for adiposity (9, 26, 30–32). We therefore evaluated whether FM and BW scaled to height with similar exponents as part of the first phase of data analyses.

Sex and race/ethnic group effects

The next stage in the first data analysis phase involved a detailed examination of how BW scales to height across the 8 sex and race/ethnic groups. Values of β for each group were derived by using multiple regression models that included age and adiposity as potential covariates. Within-sex and race/ethnic group values for β were also calculated for subjects aged ≥18 and <30, 30–39, 40–49, 50–59, 60–69, and ≥70 y. The aim of these analyses was thus 2-fold: establishing how BW scales to height within and across adult NH white, NH black, Mexican American, and Korean Asian men and women and to determine whether the scaling coefficients (β) observed within each sex race/ethnic group are influenced by age group.

Scaling of WC

Simple geometric body shape models predict that body "circumference" should scale as height$^{0.5}$ (**Supplemental Material**) (22). To examine this hypothesis, we evaluated the scaling of WC to height, adjusting for age and adiposity, across the 8 sex and race/ethnic groups.

Nationally representative scaling powers

The second phase of analyses was aimed at deriving nationally representative U.S. and Korean BW and WC scaling powers.

Subjects

The sample included data from the NHANES and KNHANES (16–18). Subjects aged ≥18 y who participated in the cross-sectional NHANES 1999–2006 study who had dual X-ray absorptiometry (DXA) evaluations were included in the analyses. NHANES survey methodology and measurement protocols are provided elsewhere (15, 16, 33–35). The KNHANES program is a nationwide cross-sectional survey that assesses the health and nutritional status of Korean residents administered by the Ministry of Health and Welfare and the Korea Centers for Disease Control and Prevention. KNHANES IV was carried out between 2007 and 2009, and KNHANES V was carried out between 2010 and 2012. During KNHANES IV and V, DXA studies were conducted from June 2007 to July 2011. In this study we used data from 2008 to 2009 (KNHANES IV) and 2010 (KNHANES V) (17, 18).

A detailed accounting of the evaluated NHANES and KNHANES samples is summarized in Supplemental Table 1. The samples evaluated for WC scaling are minimally reduced in size because measurements were not made on some subjects. All NHANES procedures were approved by the National Center for Health Statistics, CDC. The survey received human subjects approval. The KNHANES study protocol was approved by the Korea Centers for Disease Control and Prevention Institutional Review Board, with all subjects providing written informed consent.

Body composition assessment

The same anthropometric measurement and training protocols and DXA systems with manufacturer-specified calibrations were used in NHANES and KNHANES (Hologic QDR-4500A densitometer, later reported in KNHANES as a QDR Discovery Wi; Hologic) (15–18, 33–35). The NHANES and KNHANES data sets contained whole-body DXA estimates of total BW, FM, and %fat values that were investigated in the present study. For consistency, all scaling evaluations that used BW as a dependent variable were conducted by using the DXA total BW value. The CV reported for DXA-measured FM is ~3% and for fat-free mass is ~2%.

Statistical methods

The analyses overall were aimed at establishing BW and WC scaling relations to height that are generalizable to noninstitutionalized portions of the U.S. and Korean adult populations. Nationally representative estimates were derived by using procedures for sample survey data in SAS (version 9.3; SAS Institute) to account for the complex, multistage probability designs of NHANES and KNHANES. Sample weights were used to adjust for noncoverage, nonresponse, and oversampling of some groups. SEs were derived by using Taylor series linearization. Significance was defined as $P < 0.05$ (two-tailed).

Descriptive statistics were initially computed to characterize the analyzed sample. Data from a Korean man with a biologically implausible WC value of 798 cm were excluded from all WC-related analyses. We then conducted the first phase of analyses to examine BW and WC scaling relations to height as moderated by adiposity, age, sex, and race. Subject group characteristics and powers are presented as X $\pm$ SE (95% CI). To establish BW and WC scaling relations to height, separate sex-specific regression models were fitted with BW and WC as the dependent variable and height, age, and/or %fat as independent variables. All dependent and independent variables incorporated in the regression models were log-transformed. To account for the multiply imputed structure of NHANES body composition data measured by DXA, analyses were conducted separately for each of the 5 imputed data sets by using PROC SURVEYREG, and the resulting estimates were averaged together by using PROC MIANALYZE (SAS Institute). Analyses of KNHANES data were conducted by using a similar strategy as that described for NHANES; however, no imputed data were provided in the publicly available KNHANES data set. The scaling factor (β) and corresponding SE for height were extracted from each final model in the sex-specific regression analyses.

Between–race-ethnicity group differences (NH white compared with NH black compared with Mexican American compared with Korean) in baseline characteristics and scaling powers were evaluated separately for each sex by using Cochran's Q test for heterogeneity with 3 df. Pairwise comparisons (6 in total) were then conducted for significant omnibus analyses by computing Cochran's Q while using a Bonferroni correction ($P < 0.05/6 = 0.0083$) and evaluated for significance at 1 df. Between-sex differences in scaling powers were evaluated by using additional dummy-variable regression analyses. For NHANES analyses, 95% CIs for scaling factors and critical *t*-statistic values for testing differences between scaling factors were derived by using df calculated according to the method proposed by Barnard and Rubin (36). The complete-data df used in this determination was 59 (number of primary sampling units – number of sampling strata). For KNHANES analyses, 95% CIs for scaling factors and critical *t*-statistic values for testing differences between scaling factors were derived by using 243 df (number of primary sampling units – number of sampling strata). We analyzed the developed models with regression diagnostics and residual distributions appeared normal. A subtle curvilinear residual relation within some models was present but the inclusion of additional model terms corrected nonlinearity and had no measurable influence on observed powers.

RESULTS

Subjects

A total of 26,068 subjects were evaluated in the race-stratified analyses described herein—12,548 men and 13,520 women—across the 8 sex and race/ethnic groups (**Table 1**, Supplemental Table 1). Of these, 17,126 were analyzed from NHANES and 8942 from KNHANES. Group mean ($\pm$SE) age varied from 36.2 $\pm$ 0.5 y in Mexican American men to 47.1 $\pm$ 0.3 y in NH white women. Korean women had the smallest height (157.5 $\pm$ 0.1 cm), whereas NH white men had the greatest height (177.5 $\pm$ 0.1 cm). Korean men and women had both the lowest BMI and %fat within their respective sex groups, whereas values of BMI and %fat were substantially larger and variable among the remaining 3 race/ethnic groups. Between-group statistical comparisons for baseline characteristics are shown in Table 1.

Age and adiposity scaling effects

The scaling powers of height (i.e., $\beta \pm$ SE) derived for BW, FM, and WC are presented in **Table 2**.

Age

When BW alone was scaled to height for the 8 study groups, the observed values for β in Equation *2* ranged widely, from

TABLE 1
Subject characteristics[1]

	Men				Women			
	NH white	NH black	MA	Korean	NH white	NH black	MA	Korean
n^2	4406 (4295)	2035 (1970)	2256 (2202)	3851 (3837)	4235 (4118)	2045 (1971)	2149 (2102)	5091 (5068)
Age, y	45.0 ± 0.3^a	40.9 ± 0.4^b	36.2 ± 0.5^c	42.7 ± 0.3^d	47.1 ± 0.3^a	42.7 ± 0.5^b	38.2 ± 0.6^c	44.7 ± 0.3^d
BW, kg	89.4 ± 0.4^a	89.1 ± 0.6^a	81.6 ± 0.6^b	69.4 ± 0.2^c	74.7 ± 0.4^a	83.9 ± 0.5^b	72.8 ± 0.6^a	56.6 ± 0.2^c
Height, cm	177.5 ± 0.1^a	177.1 ± 0.1^b	170.1 ± 0.2^c	170.9 ± 0.1^d	163.2 ± 0.1^a	163.0 ± 0.2^a	157.8 ± 0.2^b	157.5 ± 0.1^b
BMI, kg/m^2	28.3 ± 0.1^a	28.3 ± 0.2^a	28.1 ± 0.2^a	23.7 ± 0.1^b	28.0 ± 0.2^a	31.5 ± 0.2^b	29.2 ± 0.3^c	22.8 ± 0.1^d
Fat, %	28.2 ± 0.1^a	25.4 ± 0.1^b	27.8 ± 0.2^a	22.0 ± 0.2^c	39.5 ± 0.2^a	40.4 ± 0.2^b	40.6 ± 0.2^b	32.8 ± 0.2^c
WC, cm	100.6 ± 0.3^a	95.8 ± 0.4^b	96.6 ± 0.5^b	84.1 ± 0.5^c	92.6 ± 0.4^a	97.8 ± 0.4^b	93.8 ± 0.6^a	77.0 ± 0.2^c

[1]Values are means ± SEs. Values with different superscript letters are significantly different, $P < 0.05/6 = 0.0083$. Additional sample information can be found in Supplemental Table 1. Between–race-ethnicity comparisons were performed by using Cochran's Q test for heterogeneity. BW, body weight; MA, Mexican American; NH, non-Hispanic; WC, waist circumference.

[2]Values are total numbers of subjects; subjects with WC values are in parentheses.

a low of 1.19 ± 0.06 for Korean women to a high of 2.42 ± 0.12 for Mexican American men; the mean (SD) power for all 8 groups was 1.86 (0.41). When age was added to the model, the range of powers shifted upward (1.77 ± 0.10 to 2.50 ± 0.12) to a mean (SD) of 2.05 (0.29).

Adiposity

FM alone scaled to height across the 8 sex and race/ethnic groups, with values for β in Equation 2 also ranging widely from a low of 0.43 ± 0.13 for Korean women to a high of 2.84 ± 0.24 for Mexican American men. FM scaling to height strongly influenced the power of BW scaled to height. An example is for NH black and white women. BW and FM scaled similarly to height in NH black women (1.82 ± 0.15 and 1.66 ± 0.25, respectively; both $P < 0.001$) and their %fat was nonsignificantly correlated with height (P = NS). By contrast, FM scaled to height in the NH white women with a power of 1.04 ± 0.17 ($P < 0.001$) and the corresponding power for BW scaled to height was 1.57 ± 0.10 ($P < 0.001$). As expected, the large discordance between FM and weight scaling to height was accompanied by a significant correlation between %fat and height in NH white women ($P < 0.001$).

Age-adjusted powers for BW and FM scaling to height are presented in Table 2. Of the 8 sex and race-ethnicity groups, 6 (NH white men, Mexican American men, Korean men, NH white women, Mexican American women, and Korean women) showed significant correlations between %fat and height. Although the mean age- and %fat-adjusted power for the 8 groups (2.06) was similar to that of the powers adjusted for age alone (2.05), the variability in power estimates was reduced by more than one-half with %fat adjustment (SD: 0.12 compared with 0.29). We conclude from this series of analyses that age and adiposity effects strongly influence the powers observed when BW is scaled to height in adult samples.

Scaling of BW and WC to height

BW

The powers and 95% CIs observed for BW scaled to height, adjusted for age and adiposity, are summarized for the 8 sex-race/ethnic groups in Table 2. The age- and %fat-adjusted powers of

TABLE 2
Powers observed for BW, FM, and WC scaled to height[1]

	Men				Women			
Model covariate	NH white	NH black	MA	Korean	NH white	NH black	MA	Korean
BW	1.96 ± 0.09	2.35 ± 0.14	2.42 ± 0.12	2.01 ± 0.08	1.57 ± 0.10	1.82 ± 0.15	1.59 ± 0.14	1.19 ± 0.06
Age	2.10 ± 0.10	2.43 ± 0.14	2.50 ± 0.12	2.11 ± 0.08	1.77 ± 0.10	1.89 ± 0.15	1.78 ± 0.14	1.79 ± 0.07
%Fat	2.13 ± 0.06	2.39 ± 0.10	2.15 ± 0.07	2.13 ± 0.06	2.10 ± 0.06	1.99 ± 0.08	2.00 ± 0.09	1.62 ± 0.05
Age, %fat	2.02 ± 0.06	2.29 ± 0.09	2.14 ± 0.07	2.11 ± 0.06	1.97 ± 0.06	1.94 ± 0.08	1.99 ± 0.09	1.99 ± 0.06
95% CI	1.91, 2.14	2.10, 2.48	2.01, 2.27	1.99, 2.23	1.85, 2.09	1.77, 2.10	1.82, 2.17	1.87, 2.10
FM	1.70 ± 0.18	2.28 ± 0.32	2.84 ± 0.24	1.62 ± 0.21	1.04 ± 0.17	1.66 ± 0.25	1.21 ± 0.22	0.43 ± 0.13
Age	2.22 ± 0.18^2	2.67 ± 0.31	3.04 ± 0.25^2	2.13 ± 0.22^2	1.58 ± 0.17^2	1.86 ± 0.25	1.59 ± 0.22^2	1.42 ± 0.15^2
WC	0.42 ± 0.07	0.74 ± 0.11	0.78 ± 0.09	0.31 ± 0.08	0.17 ± 0.08	0.50 ± 0.11	0.18 ± 0.08	−0.44 ± 0.05
Age	0.65 ± 0.07	0.93 ± 0.11	0.89 ± 0.09	0.70 ± 0.07	0.45 ± 0.07	0.59 ± 0.11	0.38 ± 0.08	0.41 ± 0.06
%Fat	0.56 ± 0.03	0.79 ± 0.05	0.58 ± 0.05	0.42 ± 0.06	0.55 ± 0.05	0.62 ± 0.07	0.47 ± 0.06	−0.09 ± 0.05
Age, %fat	0.60 ± 0.03^a	0.82 ± 0.05^b	0.63 ± 0.05^a	$0.67 \pm 0.05^{a,b}$	0.59 ± 0.05	0.63 ± 0.07	0.52 ± 0.06	0.56 ± 0.05
95% CI	0.52, 0.67	0.72, 0.93	0.53, 0.72	0.59 0.80	0.49, 0.69	0.49, 0.77	0.41, 0.64	0.47, 0.66

[1]Values are β_{height} ± SEs unless otherwise indicated. Values with different superscript letters are significantly different, $P < 0.05/6 = 0.0083$. Additional sample information can be found in Supplemental Table 1. Between–race-ethnicity comparisons were performed by using Cochran's Q test for heterogeneity. BW, body weight; FM, fat mass; MA, Mexican American; NH, non-Hispanic; WC, waist circumference.

[2]Significant correlation between %fat and height, $P < 0.05$.

height ranged narrowly from a low of 1.94 ± 0.08 in NH black women to a high of 2.29 ± 0.09 in NH black men. There were no significant differences among these powers within each sex group, and only the powers for NH black and Mexican American men significantly differed from 2.

Powers of BW scaling to height for each sex, race, and age group are presented in **Supplemental Table 2**. Although height powers were generally stable across age groups for men, a small downward drift in β-values was present in women.

WC

The scaling of WC to height results for the 8 sex and race/ethnic groups are presented in Table 2. WC alone scaled to height across the 8 sex and race/ethnic groups, with values for β in Equation 2 ranging widely with a low of −0.44 ± 0.05 for Korean women to a high of 0.78 ± 0.09 for Mexican American men. Powers increased in all groups after adding age to the model with WC alone. After adjustment for age and adiposity, WC scaled to height with powers ranging from ∼0.52 to 0.82. There were no significant differences in WC scaling powers for women, whereas between-race/ethnic differences were present in the men. The smallest height power was present in NH white men (0.60 ± 0.06) and the largest height power was in the NH black men (0.82 ± 0.05).

Between-sex differences in scaling relations

The between-sex differences in powers for BW and WC scaled to height within each race/ethnic group are presented in **Supplemental Table 3**. The power differences did not differ significantly between men and women with the exception of NH black men and women for BW and Korean men and women for WC (both $P < 0.05$).

Nationally representative powers

After race-ethnicity (NH white, NH black, Mexican American, or other) across the entire NHANES sample was controlled for, the respective powers for BW and WC scaled to height were 2.12 ± 0.05 and 0.66 ± 0.03 for men and 2.02 ± 0.04 and 0.61 ± 0.04 for women. For KNHANES, the respective nationally representative powers for BW and WC scaled to height were 2.11 ± 0.06 and 0.67 ± 0.05 for men and 1.99 ± 0.06 and 0.56 ± 0.05 for women.

DISCUSSION

The primary focus of the present investigation was to establish if powers of height applied as part of calculating BMI are appropriate across sex and race/ethnic groups. A secondary aim was to evaluate how WC scales to height across the 8 evaluated groups. The availability of NHANES and KNHANES data sets collected with the same methods and protocols provided a unique opportunity to conduct an in-depth exploration of these 2 related study questions. These analyses extend earlier studies that were conducted in more limited and less generalizable samples (12, 19, 21–23).

The primary findings of the current study were 3-fold: within and across the evaluated samples, variation in age and adiposity had a major influence on the strength and nature of observed stature scaling relations; scaling patterns for BW and WC were generally similar across sex, age, and race/ethnic groups; and at the population level, BW and WC scaled to height with respective powers of ∼2 and 0.5–0.8, with values nonsignificantly larger in men than in women except for the sex differences in BW scaling among NH blacks and in WC scaling among Koreans.

Age and adiposity effects

A main feature of BMI is that it provides a measure of body shape independent of height (20). Correlations between BMI and height can arise only if BW in a sample scales to height with powers differing from 2. Correlations between BMI and height have been observed many times in the past (10, 30–32, 37, 38). For example, the Diverse Populations Collaborative Group (37) reported the presence of small inverse correlations between stature and BMI in 25 samples (n = 385,232) of men (random effects average: −0.026; 95% CI: −0.041, −0.012) and women (random effects average: −0.119; −0.132, −0.106). The reasons for these discrepancies are largely unknown, but many have speculated on their mechanisms (9).

We hypothesized that the variable powers of weight scaled to height derive in part from a failure to control adequately for sample age and adiposity in developed regression models. The effects of age on scaling relations across a wide age range of adults can likely be ascribed to nonrandom variation in BW and height across the adult life span. Older subjects in most cohorts tend to be heavier and shorter than their younger counterparts. Effects such as these could have an important outcome on the slope (i.e., β) of log BW regressed on log height as in Equation *2*.

We found that age can affect the scaling relation between BW and height, an effect that appeared to have a larger influence on the scaling exponent than did adiposity. However, this observation mainly applied to women. We hypothesize that age may influence the scaling exponent for women but not for men because of the loss of height and the weight gain that frequently accompanies menopause in women. Second, age appeared to skew the scaling exponent in certain race/ethnic groups of women more than others, an effect most apparent for Korean women. One explanation for this finding is that there may be generational differences in nutrition that are greater in Koreans than in the American race/ethnic groups.

Adiposity may also influence the observed scaling exponent but appears to have less of an effect than age alone. As noted earlier, BW can be viewed as consisting of a stature-dependent component and an energy balance–dependent component, the latter composed mainly of body fat. We can only speculate, as is often assumed, that the stature-dependent portion of BW has a stable proportion of body fat across people differing in height. On the other hand, the portion of BW sensitive to energy balance can be influenced by a number of genetic and environmental factors that are unrelated to stature.

Combinations of factors such as socioeconomic status, nutrition, health status, and smoking history are the likely basis for the observed correlations across subjects between adiposity and stature. The important question remains why population stature-BMI correlations are so pervasive in previously reported studies. Whatever the mechanisms, our findings clearly show that 2 factors, across-population variation in age and adiposity, have the potential for obscuring the "true" empirical relations between

BW and height. These effects are particularly important when exploring BMI–body composition differences across race/ethnic groups that vary widely in age, height, and BW such as those reported in the current study.

BW and circumference scaling relations

Our primary focus was on how BW scales to height within and across sex and race/ethnic groups and similarly how WC scales to height. Analysis of each group indicated that, in general, BW scaled to height with powers centered around 2. Analyses allowing for generalization to noninstitutionalized NH whites, NH blacks, Mexican Americans, and Korean Asians showed small nonsignificant differences in height powers between men and women with the exception of NH blacks. This finding has been emphasized in the past by Burton (9) and by the Diverse Populations Collaborative Group (37), and our large data set supports these earlier observations. As one potential mechanism explaining these small sex differences in scaling powers, men likely have a greater BW for their height because of anabolic effects appearing during puberty that lead to greater stature and skeletal muscle mass than are present in women (39).

The finding that WC scales to height with powers of ∼0.5–0.8 is consistent with earlier observations (22). Assuming that the human body has a cylindrical shape, a density of unity, and that weight scales as height^2, then body "circumference" will scale as height$^{0.5}$. This is an oversimplified geometric model (Supplemental Material), and future studies are needed to refine shape predictions and to establish their biomechanical and metabolic basis. Although at present it is unknown how WC relates to an integrated mean whole-body circumference value, we can assume that this anthropometric trunk dimension captures general features of body size. We found small and, in some cases, significant scaling differences across race groups in men, the origin of which is uncertain. As for BW, WC scaled to height with larger powers in the men than in the women and in one case this difference reached significance (i.e., Korean Asians).

Height-adjusted WC indexes are increasingly being reported in the medical literature as a comparable metric to BMI (40–42). Our findings show clearly that the appropriate powers for adjusting WC for differences in stature are ∼0.5–0.8 and not 1.0 (22). As for BMI, the use of an incorrect sample denominator will lead to an undesirable correlation between the height-adjusted circumference and height. Optimally, the circumference ratio should be independent of height and ideally reflect underlying pathophysiology.

Conclusions and implications

The present study findings identify 2 factors, age and adiposity, as a main basis for the large range of powers observed when BW is scaled to height across sex and race/ethnic groups. We show that failure to control for age and adiposity, especially in women, may lead to incorrect scaling exponents when evaluating the effects of body size as defined by height on BW. Powers of height observed after adjustments for age and adiposity in regression models had a narrow range of ∼2 for BW and ∼0.5–0.8 for WC, with some small but significant differences across sex and race/ethnic groups, the mechanisms of which need further study. Although differences in height powers were generally small and likely of little clinical significance, the possibility always exists to apply population-specific powers in a weight-height index as suggested in 1971 by Benn (43). Such measures may be appropriate in groups, such as Pacific Islanders, who were not evaluated in the current report. With that option as a proviso, we conclude that BMI, BW/height^2, is a reasonable stature-independent metric for across-sex and race/ethnic comparisons of body shape and composition.

We thank Emily F Mire for help with database acquisition and development and Kevin E Wilson at Hologic Inc., who facilitated investigator collaborations.

The authors' responsibilities were as follows—SBH, CMP, DMT, and SH: designed research; SH and WC: conducted research and provided essential materials; SBH, CMP, DMT, MH, and JMS: analyzed data; and SBH, CMP, DMT, MH, JMS, SH, and WC: wrote the manuscript and had primary responsibility for final content. None of the authors declared a conflict of interest.

REFERENCES

1. WHO. Obesity: preventing and managing the global epidemic. Report of a WHO Consultation. Geneva (Switzerland): World Health Organization; 2000. WHO Technical Report Series 894.
2. National Institutes of Health. Clinical guidelines on the identification, evaluation, and treatment of overweight and obesity in adults: the evidence report. Obes Res 1998;6(Suppl 2):51S–209S. Erratum in: Obes Res 1998;6(6):464.
3. Jensen MD, Ryan DH, Apovian CM, Loria CM, Ard JD, Millen BE, Comuzzie AG, Nonas CA, Donato KA, Pi-Sunyer FX, et al. 2013 AHA/ACC/TOS guideline for the management of overweight and obesity in adults: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and The Obesity Society. J Am Coll Cardiol 2014;63(25 Pt B):2985–3023. Erratum in: J Am Coll Cardiol 2014;63(25 Pt B):3029-30.
4. Berrington de Gonzalez A, Hartge P, Cerhan JR, Flint AJ, Hannan L, MacInnis RJ, Moore SC, Tobias GS, Anton-Culver H, Freeman LB, et al. Body-mass index and mortality among 1.46 million white adults. N Engl J Med 2010;363:2211–9.
5. Romero-Corral A, Somers VK, Sierra-Johnson J, Thomas RJ, Collazo-Clavell ML, Korinek J, Allison TG, Batsis JA, Sert-Kuniyoshi FH, Lopez-Jimenez F. Accuracy of body mass index in diagnosing obesity in the adult general population. Int J Obes (Lond) 2008;32:959–66.
6. Okorodudu DO, Jumean MF, Montori VM, Romero-Corral A, Somers VK, Erwin PJ, Lopez-Jimenez F. Diagnostic performance of body mass index to identify obesity as defined by body adiposity: a systematic review and meta-analysis. Int J Obes (Lond) 2010;34:791–9.
7. Green DJ. Is body mass index really the best measure of obesity in individuals? J Am Coll Cardiol 2009;53:526; author reply 7–8.
8. Gallagher D, Visser M, Sepulveda D, Pierson RN, Harris T, Heymsfield SB. How useful is body mass index for comparison of body fatness across age, sex, and ethnic groups? Am J Epidemiol 1996;143:228–39.
9. Burton RF. Why is the body mass index calculated as mass/height2, not as mass/height3? Ann Hum Biol 2007;34:656–63.
10. Garn SM, Leonard WR, Hawthorne VM. Three limitations of the body mass index. Am J Clin Nutr 1986;44:996–7.
11. Samaras T, editor. Human body size and the laws of scaling: physiological, performance, growth, longevity and ecological ramifications. New York: Nova Science Publishers; 2007.
12. Heo M, Kabat GC, Gallagher D, Heymsfield SB, Rohan TE. Optimal scaling of weight and waist circumference to height for maximal association with DXA-measured total body fat mass by sex, age and race/ethnicity. Int J Obes (Lond) 2013;37:1154–60.
13. Keys A, Fidanza F, Karvonen MJ, Kimura N, Taylor HL. Indices of relative weight and obesity. J Chronic Dis 1972;25:329–43.
14. He W, Zhang S, Song A, Yang M, Jiao J, Allison DB, Heymsfield SB, Zhu S. Greater abdominal fat accumulation is associated with higher metabolic risk in Chinese than in white people: an ethnicity study. PLoS ONE 2013;8:e58688.
15. National Center for Health Statistics. Documentation, codebook, and frequencies: dual-energy X-ray absortiometry. National Health and

Nutrition Examination Survey 2003-2004 [cited 2014 Jun 15]. Available from: http://www.cdcgov/nchs/data/nhanes/dxa/dxx.pdf.
16. Kelly TL, Wilson KE, Heymsfield SB. Dual energy X-ray absorptiometry body composition reference values from NHANES. PLoS ONE 2009;4:e7038.
17. Kim HJ, Kim Y, Cho Y, Jun B, Oh KW. Trends in the prevalence of major cardiovascular disease risk factors among Korean adults: results from the Korean National Health and Nutrition Examination Survey, 1998–2012. Int J Cardiol 2014;174(1):64–72.
18. Hong S, Oh HJ, Choi H, Kim JG, Lim SK, Kim EK, Pyo EY, Oh K, Kim YT, Wilson K, et al. Characteristics of body fat, body fat percentage and other body composition for Koreans from KNHANES IV. J Korean Med Sci 2011;26:1599–605.
19. Heymsfield SB, Gallagher D, Mayer L, Beetsch J, Pietrobelli A. Scaling of human body composition to stature: new insights into body mass index. Am J Clin Nutr 2007;86:82–91.
20. Cole T. Weight-stature indices to measure underweight, overweight, and obesity. In: Himes JE, editor. Anthropometric assessment of nutritional status. Hoboken (NJ): Wiley-Liss; 1991. p. 83–111.
21. Heymsfield SB, Heo M, Thomas D, Pietrobelli A. Scaling of body composition to height: relevance to height-normalized indexes. Am J Clin Nutr 2011;93:736–40.
22. Heymsfield SB, Martin-Nguyen A, Fong TM, Gallagher D, Pietrobelli A. Body circumferences: clinical implications emerging from a new geometric model. Nutr Metab (Lond) 2008;5:24.
23. Heymsfield SB, Gonzalez MC, Shen W, Redman L, Thomas D. Weight loss composition is one-fourth fat-free mass: a critical review and critique of this widely cited rule. Obes Rev 2014;15(4):310–21.
24. Quetelet A, Downes OG. Letters addressed to H. R. H. the Grand Duke of Saxe Coburg and Gotha, on the theory of probabilities, as applied to the moral and political sciences. London: Charles & Edwin Layton; 1849.
25. Quetelet LAJ, Knox R, Smibert T. A treatise on man and the development of his faculties, tr. (under the superintendence of R. Knox). In: Smibert T, editor. People's ed; 1842. p.63–7.
26. Trefethen LN [Internet]. Available from: http://people.maths.ox.ac.uk/trefethen/bmi.html.
27. Larsson I, Henning B, Lindroos AK, Naslund I, Sjostrom CD, Sjostrom L. Optimized predictions of absolute and relative amounts of body fat from weight, height, other anthropometric predictors, and age 1. Am J Clin Nutr 2006;83:252–9.
28. Ogden CF, Carrol C, Flegal KM. Mean body weight, height, and body mass index, United States 1960–2002 [cited 2013 Mar 5]. Available from: http://wwwcdcgov/nchs/data/ad/ad347pdf.
29. Grande F. Nutrition and energy balance in body composition studies. In: Brozek J HA, editors. Techniques for measuring body composition. Washington: National Academy of Sciences, National Research Council; 1961.
30. Bosy-Westphal A, Plachta-Danielzik S, Dorhofer RP, Muller MJ. Short stature and obesity: positive association in adults but inverse association in children and adolescents. Br J Nutr 2009;102:453–61.
31. Smalley KJ, Knerr AN, Kendrick ZV, Colliver JA, Owen OE. Reassessment of body mass indices. Am J Clin Nutr 1990;52:405–8.
32. Bogin B, Varela-Silva MI. Fatness biases the use of estimated leg length as an epidemiological marker for adults in the NHANES III sample. Int J Epidemiol 2008;37:201–9.
33. Schenker N, Borrud LG, Burt VL, Curtin LR, Flegal KM, Hughes J, Johnson CL, Looker AC, Mirel L. Multiple imputation of missing dual-energy X-ray absorptiometry data in the National Health and Nutrition Examination Survey. Stat Med 2011;30:260–76.
34. National Center for Health Statistics. Technical documentation for the 1999-2004 dual energy X-ray absorptiometry (DXA) multiple imputation data files. National Health and Nutrition Examination Survey [cited 2011 Nov 30]. Available from: http://wwwcdcgov/nchs/data/nhanes/dxa/dxa_techdocpdf.
35. Schoeller DA, Tylavsky FA, Baer DJ, Chumlea WC, Earthman CP, Fuerst T, Harris TB, Heymsfield SB, Horlick M, Lohman TG, et al. QDR 4500A dual-energy X-ray absorptiometer underestimates fat mass in comparison with criterion methods in adults. Am J Clin Nutr 2005;81:1018–25.
36. Barnard J, Rubin D. Miscellanea: small-sample degrees of freedom with multiple imputation. Biometrika 1999;86:948–55.
37. Diverse Populations Collaborative Group. Weight-height relationships and body mass index: some observations from the Diverse Populations Collaboration. Am J Phys Anthropol 2005;128:220–9.
38. Micozzi MS, Albanes D, Jones DY, Chumlea WC. Correlations of body mass indices with weight, stature, and body composition in men and women in NHANES I and II. Am J Clin Nutr 1986;44:725–31.
39. Rogol AD. Growth, body composition and hormonal axes in children and adolescents. J Endocrinol Invest 2003;26:855–60.
40. Lee CM, Huxley RR, Wildman RP, Woodward M. Indices of abdominal obesity are better discriminators of cardiovascular risk factors than BMI: a meta-analysis. J Clin Epidemiol 2008;61:646–53.
41. Mørkedal B, Romundstad PR, Vatten LJ. Informativeness of indices of blood pressure, obesity and serum lipids in relation to ischaemic heart disease mortality: the HUNT-II study. Eur J Epidemiol 2011;26:457–61.
42. Schneider HJ, Friedrich N, Klotsche J, Pieper L, Nauck M, John U, Dorr M, Felix S, Lehnert H, Pittrow D, et al. The predictive value of different measures of obesity for incident cardiovascular events and mortality. J Clin Endocrinol Metab 2010;95:1777–85.
43. Benn RT. Some properties of weight-for-height indices when used as a measure of adiposity. Br J Prev Soc Med 1971;25:42–50.