APPLIED SCIENCES

How *Should* Adult Handgrip Strength Be Normalized? Allometry Reveals New Insights and Associated Reference Curves

ALAN M. NEVILL[1], GRANT R. TOMKINSON[2,3], JUSTIN J. LANG[4,5], WYATT WUTZ[2], and TONY D. MYERS[6]

[1]Faculty of Education, Health and Wellbeing, University of Wolverhampton, Walsall Campus, Walsall, UNITED KINGDOM; [2]Department of Education, Health and Behavior Studies, University of North Dakota, Grand Forks, ND; [3]Alliance for Research in Exercise, Nutrition and Activity (ARENA), Allied Health and Human Performance, University of South Australia, Adelaide, SA, AUSTRALIA; [4]Centre for Surveillance and Applied Research, Public Health Agency of Canada, Ottawa, ON, CANADA; [5]School of Mathematics and Statistics, Faculty of Science, Carleton University, Ottawa, ON, CANADA; and [6]Sport and Health, Newman University, Birmingham, UNITED KINGDOM

ABSTRACT

NEVILL, A. M., G. R. TOMKINSON, J. J. LANG, W. WUTZ, and T. D. MYERS. How *Should* Adult Handgrip Strength Be Normalized? Allometry Reveals New Insights and Associated Reference Curves. *Med. Sci. Sports Exerc.*, Vol. 54, No. 1, pp. 162–168, 2022. **Introduction:** Handgrip strength (HGS) is an important indicator of health. Because HGS is strongly associated with body size, most investigators normalize HGS for some measure of body size as a more sensitive indicator of strength within a population. We aimed to 1) identify the optimal body size dimension to remove (normalize) HGS for differences in body size among adults and 2) generate norm-referenced centiles for HGS using the identified body size dimension. **Methods:** Data were from the National Health and Nutrition Examination Survey, a representative sample of the US noninstitutionalized civilian population. Exclusions resulted in a final sample of 8690 adults 20 yr and older. HGS was measured using handheld dynamometry. Body size dimensions included body mass, height, and waist circumference. The most appropriate dimension(s) associated with HGS is identified using allometry. We fitted centile curves for normalized HGS using the generalized additive model for location, scale, and shape. **Results:** Findings suggest that neither body mass nor body mass index is appropriate to normalize HGS. Incorporating all three body size dimensions of body mass, height, and waist circumference, or the reduced subsets of body mass and height, or height alone, suggests that the most appropriate normalizing (body size) dimension associated with HGS should be a cross-sectional or surface area measure of an individual's body size (i.e., L^2, where L is a linear dimension of body size). Given that height was also identified as the signally best body size dimension associated with HGS, we recommend HGS be normalized by height^2 (i.e., HGS/HT^2). Centile curves for HGS/HT^2 by age group and gender were therefore provided. **Conclusions:** Scaling adult HGS by height^2 may help normalize strength for population-based research. **Key Words:** HAND STRENGTH, BODY SIZE, ADULT, NUTRITION SURVEYS, CROSS-SECTIONAL STUDIES, WAIST CIRCUMFERENCE

Muscle strength, assessed by handgrip strength (HGS) using isometric dynamometry, is considered a powerful marker of current and future health (1–5). Low adult HGS is significantly associated with an increased risk of all-cause, cardiovascular, and noncardiovascular mortality (3,6), stroke (3), several cancers (including colorectal, lung, and breast cancer) (6), chronic obstructive pulmonary disease (6), type 2 diabetes (7), fractures (8), cognitive declines (including dementia) (8), and functional disability (9). Low HGS is also part of decision algorithms and assessment criteria for determining sarcopenia (10), dynapenia (11), and frailty (12). HGS is easy, affordable, and safe to assess (13); has moderate-to-high construct validity with total body and knee extensor strength (14); and has high-to-very-high test–retest reliability (15). It is for these reasons why HGS is widely used to determine strength capacity in clinical and epidemiological settings and for population health surveillance (16).

However, HGS is strongly and positively associated with body size, with taller and/or heavier individuals having greater HGS. For this reason, most investigators report HGS both in absolute units (usually kilograms) and normalized for some measure of body size, as a more sensitive indication of strength capacity within a population where subgroups are known to vary in body size (e.g., gender, race). Various normalizing methods have been used to adjust HGS for differences in body size. Most investigators have normalized HGS to body mass (17–24), some have normalized to body mass index (BMI) (23–26), whereas few have normalized to other measures of body size (e.g., height) (22,23). The process of normalizing variables such as HGS per body mass (an index known as a ratio standard) has come under strong criticism in the past, a point originally made by Tanner (27) and subsequently

Address for correspondence: Grant R. Tomkinson, Ph.D., Department of Education, Health and Behavior Studies, University of North Dakota, 2751 2nd Avenue North, Stop 8235 Grand Forks, ND 58202; E-mail: grant.tomkinson@und.edu.
Submitted for publication June 2021.
Accepted for publication August 2021.

0195-9131/21/5401-0162/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000002771

by Nevill et al. (28). Indeed, focusing on scaling HGS specifically, Külkamp et al. (29) confirmed that HGS should not be normalized by dividing HGS by the entire body mass in both judo athletes and nonathletes. Nevertheless, such ratio standards, using HGS per body mass or HGS per BMI to normalize HGS data, have been used to develop nationally representative norm-referenced centiles (21,25) and criterion-referenced health-related cut points (17,23). This inconsistency in normalization approaches prompts the obvious research question, "How should HGS be normalized for differences in body size?"

Hence, the purposes of the current study are twofold. Using a nationally representative sample of Americans 20 yr and older, we aimed to 1) identify, using allometric scaling, which body size dimension is optimal to remove (adjust/normalize) HGS for differences in body size, and 2) to generate norm-referenced centile data for normalized HGS estimated using the generalized additive model for location, scale, and shape (GAMLSS) (30). We hypothesized that the most appropriate body size dimension associated with HGS was likely to be a cross-sectional area of body size such as body mass ($M^{0.67}$), see, for example, Külkamp et al. (29) when normalizing HGS and Nevill et al. (28) when normalizing maximal oxygen uptake for differences in body size.

METHODS

Participants. We used data from the 2011–12 and 2013–14 cycles of the National Health and Nutrition Examination Survey (NHANES) data set, which used a complex multistage probability design to assess the health and nutrition status of a representative sample of the US noninstitutionalized civilian population (31). These cycles of the NHANES were selected because they included measures of HGS. Written informed consent was provided by participants and the National Center for Health Statistics Research Ethics Review Board–approved NHANES protocols (Protocol No. 2011-17). We did not seek additional approval because the data used in this study were free from personal identifiers.

Although NHANES recruited participants 6 yr and older, we only used data on adults 20 yr and older (20–80+ yr, with adults 80 yr and older top-coded in the NHANES at 80 yr of age) in this study. Of the initial 19,931 participants, 10,988 were excluded because they (a) were younger than 20 yr ($n = 8602$), (b) were pregnant ($n = 174$), (c) performed the HGS assessment seated (due to physical limitations; $n = 386$), (d) were not assessed for HGS with both hands ($n = 1539$), or (e) had missing data (e.g., body mass, height, waist circumference; $n = 287$). In addition, following the procedures of Wang et al. (32), we excluded a further 253 participants as outliers because their bilateral HGS asymmetry was ≥30%. These exclusions resulted in a final sample of 8690 adults 20 yr and older.

Measures. The HGS and anthropometry protocols are described in detail elsewhere (33–36). HGS was measured using the Takei digital handgrip dynamometer (Model T.K.K.5401; Takei Scientific Instruments, Niigata City, Japan). Participants were randomly assigned to start the HGS test with their right or left hand, with the dynamometer adjusted for hand size by ensuring that the middle phalange of each participant's index finger was bent to 90° and rested flat atop of the handle. A submaximal effort practice trial was performed to ensure the dynamometer was properly adjusted for hand size and to confirm understanding of the HGS protocol. Participants stood upright (unless they were physically limited), with their feet hip width apart, their arm extended and hanging down away from their body, and squeezed the dynamometer with maximal effort. Three trials were performed for each hand, alternating hands between trials, with 60 s of rest between measures on the same hand. The coefficient of variation across the three trials was 8.2%, equivalent to a typical error of 2.8 kg. For this study, HGS was taken as the average of the maximum score attained for each hand.

Standing height was measured using a fixed stadiometer with an adjustable headboard. Body mass was measured using a Mettler Toledo digital weight scale (Mettler-Toledo, Columbus, OH). Waist circumference was measured at end-tidal expiration using a steel measuring tape placed directly on the skin at the level of the superior lateral border of the iliac crests. Participants self-reported their age and gender.

Statistical analyses. To obtain nationally representative estimates, analyses were conducted using NHANES sample weights (survey, strata, and cluster weights), which account for the complex survey design (including oversampling), survey nonresponse, and poststratification. To identify the most appropriate body size dimension(s) associated with HGS, we developed the following multiplicative model with allometric body size components, similar to that used to model the physical performance variables of Greek children (37), Peruvian children (38), and older adults (39).

$$\mathrm{HGS} = a\, M^{k_1} \times \mathrm{HT}^{k_2} \times \mathrm{WC}^{k_3}\, \varepsilon \qquad [1]$$

where a is the scaling constant and k_1, k_2, and k_3 are scaling exponents for the body mass (M), height (HT), and waist circumference (WC), respectively, and ε is the multiplicative error ratio (28). Note that the multiplicative error ratio ε assumes that the error will increase in proportion to body size, a characteristic in data known as heteroscedasticity that can be controlled by taking logarithms, as described hereinafter. Age and gender were incorporated into the model by allowing a to vary for either gender and each age group (age categories 20–29, 30–39, …, 80 yr and over) to accommodate the likelihood that HGS may rise and then peak sometime during middle age and decline thereafter. The model can be linearized with a log transformation, and multiple regression/ANCOVA can be used to estimate the body mass and height exponents for HGS having controlled for both age and gender (equation 2). In effect, log-transformed HGS becomes the dependent variable, with age and gender incorporated as fixed factors with log(M) and log(HT) entered as the covariates.

$$\log(\mathrm{HGS}) = \log(a) + k_1 \log(M) + k_2 \log(\mathrm{HT}) + k_3 \log(\mathrm{WC}) + \log(\varepsilon) \qquad [2]$$

Traditionally, R^2 is used to measure goodness of fit. However,

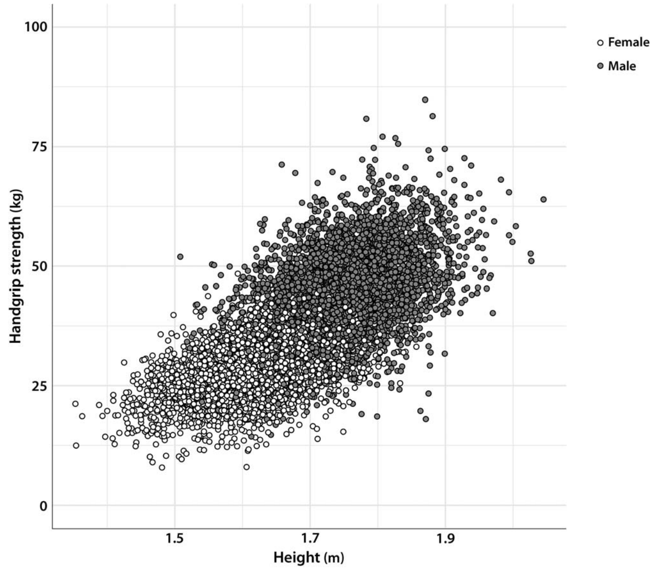

FIGURE 1—Association between HGS (in kilograms; average of the maximum score attained for each hand) and height (in meters) by gender.

higher R^2 values do not always indicate a better fit. Higher R^2 can indicate overfitting, and adding noise variables will also inflate R^2. Although R^2 is useful, it is not necessarily the best method of comparing competing models. An alternative method of model comparison is to use the Akaike information criterion (AIC) that can be conceptualized as a "distance" or error between the data and a model, with lower values indicating a better model. Unlike R^2, which rewards models for being more complex (i.e., having more noise variables) with a higher value being better, AIC penalizes models for being more complex, with a lower value being better. As a result, model comparison (goodness of fit) between the allometric models and the equivalent linear, additive models was assessed using the AIC. The difference between two AIC values was interpreted as negligible (<2), moderate (>2 and ≤6), strong (>6 and ≤10), or very strong (>10) evidence for the model, with the lower AIC value being better.

Methods for developing the centile curves. Using a group of models called GAMLSS (30), we fitted centile curves for the most appropriate normalized HGS ratio (to be identified in the Results section) by age and gender. Using this approach, we were able to fit different response distributions and different nonparametric smoothing functions (cubic splines, P-splines, and local polynomial regression). The response distributions fitted included the Box-Cox-*t*, Box-Cox Cole and Green, and Box-Cox Power Exponential. Each model included NHANES sample weights to adjust the dependent variable for oversampling and to better estimate population parameters. We selected the best-fitting models using scaled AIC values (40), which rank models according to their relative importance. The Box-Cox-*t* (μ, σ, ν, τ) power transformation produced the best fit for both males and females. This distribution, defined by Yv having a shifted truncated *t* distribution with τ degrees of freedom, is a four-parameter distribution, which includes μ (approximately the median, which controls the location), σ (approximately the coefficient of variation, which controls the scale), ν (approximately the skewness, which controls the asymmetry), and τ (approximately the kurtosis) (30).

The effects and covariates assessed using the ANCOVA were considered significant at $P < 0.05$. All statistical analyses were conducted in IBM SPSS Statistics (version 26; IBM, Chicago, IL), except for the centile curves, which were conducted in R (v4.0.2 (41)). We used the GAMLSS package to fit centile curves (30). Postestimation diagnostics for these models included standard QQ-plots, de-trended normal QQ-plots (worm plots (42)), and transformed Owen's plots, to check the age-conditional normality of the transformed data (43).

RESULTS

To illustrate the strong and positive association between HGS and body size ($r = 0.73$, $P < 0.001$), the HGS values of US men and women were plotted against height in Figure 1. This figure provides evidence that the errors increase with height, a characteristic in data known as heteroscedasticity that can be controlled by taking logarithms, as described previously in the Methods section.

The ANCOVA of log-transformed HGS identified the main effects of gender and age as significant (age and gender; both $P < 0.001$) but not the age–gender interaction ($P > 0.05$). The main effects of age and gender are shown in Figure 2.

The ANCOVA also revealed that all three body size covariates were significant (Table 1). Note that fitted body mass (*M*) and height (HT) exponents are both positive, but waist circumference (WC) is negative, confirming that greater body mass and height benefit HGS, but excess waist circumference is detrimental to HGS.

If waist circumference is unavailable, the reduced body mass and height allometric model covariates for HGS are given in Table 2.

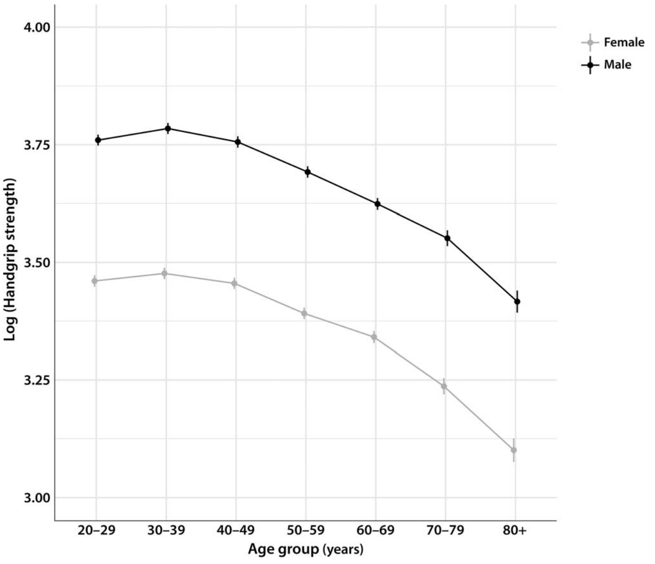

FIGURE 2—Means (±SE) of log-transformed HGS adjusted for log(*M*), log(HT), and log(WC) by age group and gender.

TABLE 1. The fitted parameters of the ANCOVA for all three body size covariates.

Parameter Estimates						
Dependent Variable: Log(HGS)						
					95% Confidence Interval	
Parameter	*B*	SE	*t*	Sig.	Lower Bound	Upper Bound
Intercept	3.290	0.080	41.028	<0.001	3.132	3.447
Log(*M*)	0.577	0.024	24.341	<0.001	0.531	0.624
Log(HT)	0.968	0.049	19.672	<0.001	0.871	1.064
Log(WC)	−0.619	0.034	−18.474	<0.001	−0.685	−0.553
Female	−0.372	0.020	−18.994	<0.001	−0.411	−0.334

R^2 = 0.752 (adjusted R^2 = 0.752).

Finally, examining the log-transformed body size covariates in Table 2, the height covariate log(HT) seems to be the dominant body size dimension associated with HGS (*t* score is nearly twice as large as that associated with body mass). For this reason, we reran the ANCOVA using a simplified/reduced allometric model (equation 2), excluding log(*M*) and log(WC). The follow-up analysis revealed the height covariate was highly significant (Table 3), but the fitted height (HT) exponent was very close to 2 (i.e., HT^2), suggesting that if we were to use height alone, HGS should be normalized by dividing HGS by HT^2.

Note that the simplified ANCOVA of log-transformed HGS also confirmed very similar age and gender main effects to those reported Figure 2, with main effects for both age and gender being significant ($P < 0.001$) but not the age–gender interaction ($P > 0.05$; Fig. 3).

To assess the benefit of using allometric scaling to determine the appropriate body size dimension to normalize HGS as independent of body size, we calculated the AIC for the above log model 3 and compared it with the AIC obtained from fitting the equivalent linear, additive models using height and height^2 as covariates. The AIC for the allometric (log-linear) model 3 was 57,256. When we fitted the equivalent linear, additive model to predict HGS (using the fixed factors gender and age group plus the gender–age group interaction) but allowing height or height^2 as the covariates, the AIC values were 58,333 and 58,312, respectively. Clearly the AIC associated with allometric model 3 (AIC = 57,256) is vastly superior to the equivalent linear, additive models AIC = 58,333 and 58,312 (differences >1000), respectively, evidence for very strong differences.

The centile curves for the HGS/HT^2 by age are given for males and females separately in Figure 4.

These curves enable the reader to estimate an individual's normalized HGS (HGS/HT^2) using a nationally representative sample of American adults for comparative purposes. These centile curves provide a straightforward interpretation and add a valuable level of precision. For example, in the case of an individual's HGS/HT^2 slope and age, if their estimate is on the 75th centile, it means that for every 100 individuals of the same age, 75 would have a lower HGS/HT^2 slope and 25 a higher HGS/HT^2 slope. Point-estimate centile tables by age for males and females are also given in Table 4.

TABLE 2. The fitted parameters of the ANCOVA adopting the log-transformed body mass and height body size covariates.

Parameter Estimates						
Dependent Variable: Log(HGS)						
					95% Confidence Interval	
Parameter	*B*	SE	*t*	Sig.	Lower Bound	Upper Bound
Intercept	1.972	0.037	52.828	<0.001	1.899	2.045
Log(*M*)	0.164	0.008	20.565	<0.001	0.148	0.179
Log(HT)	1.438	0.043	33.521	<0.001	1.354	1.522
Female	−0.355	0.020	−17.800	<0.001	−0.394	−0.316

R^2 = 0.742 (adjusted R^2 = 0.742).

TABLE 3. The fitted parameters of the ANCOVA adopting the log-transformed height body size covariate alone.

Parameter Estimates						
Dependent Variable: Log(HGS)						
					95% Confidence Interval	
Parameter	*B*	SE	*t*	Sig.	Lower Bound	Upper Bound
Intercept	2.516	0.027	93.261	<0.001	2.463	2.569
Log(HT)	1.752	0.041	42.678	<0.001	1.672	1.833
Female	−0.363	0.020	−17.781	<0.001	−0.403	−0.323

R^2 = 0.730 (adjusted R^2 = 0.729).

DISCUSSION

Our initial findings, obtained by fitting the multiplicative allometric model log transformed (equation 2) with all three body size terms, suggest that to obtain a normalized HGS_n independent of body mass, height, and waist circumference, we need to calculate the normalized ratio

$$HGS_n = HGS/\left(HT^{0.968} \times M^{0.577} \times WC^{-0.619}\right) \quad [3]$$

see the exponents reported in Table 1. Physiologically, this finding makes perfect sense. Taken together, the body mass and waist circumference terms ($M^{0.577} \times WC^{-0.619}$) suggest a body mass divided by WC ratio, where the latter is likely to reflect a measure of adiposity providing a ratio likely to be a proxy for lean body mass. The height term will reflect an advantage that a taller individual will be able to exert on

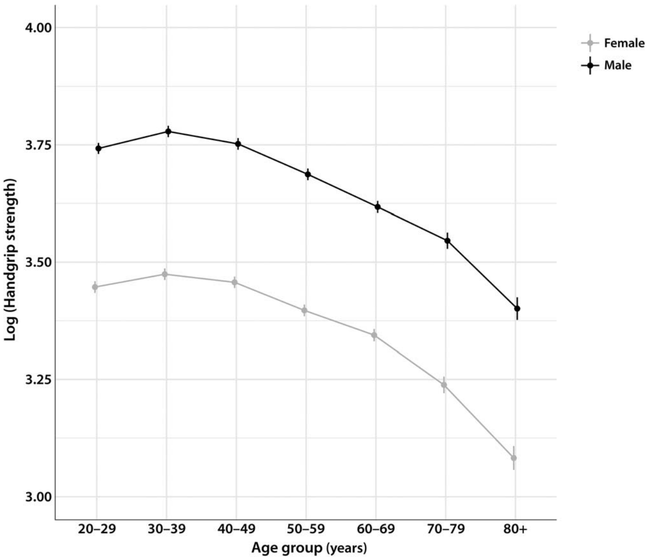

FIGURE 3—Means (±SE) of log-transformed HGS adjusted for log(HT) alone by age group and gender.

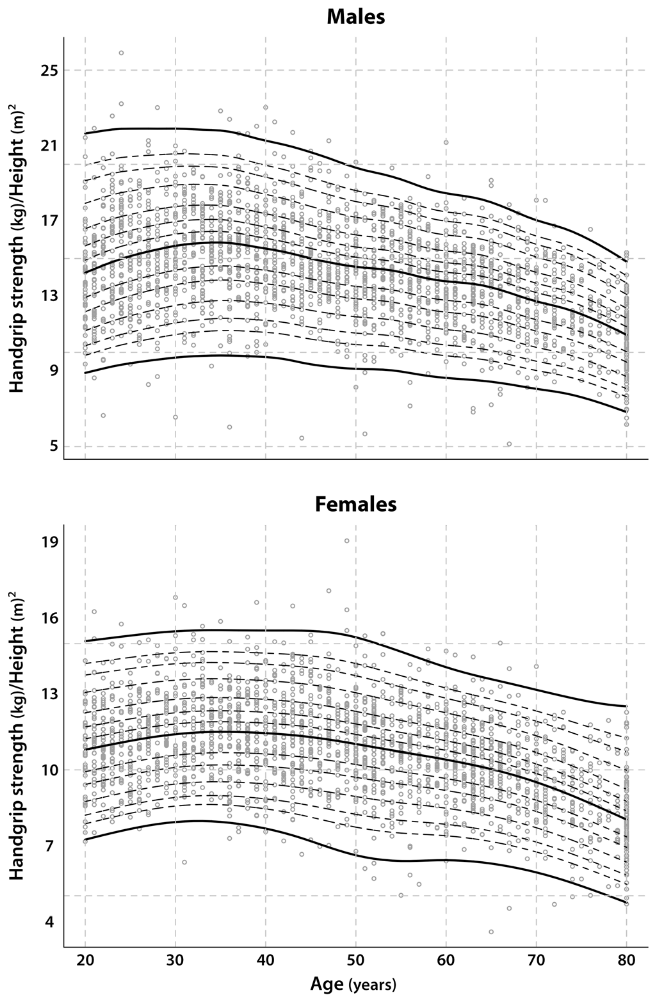

FIGURE 4—Centile curves for normalized HGS (HGS in kilograms divided by height in meters squared) by age and gender.

the handheld dynamometer, probably because of the mechanical advantage of having longer levers.

The fitted exponents in the model (Table 1) are also entirely compatible from dimensional considerations, as anticipated by Åstrand and Rodahl (44). In their chapter on body dimensions and muscular exercise, Åstrand and Rodahl (44) reported that force should scale to the physiological dimension of L^2, where L is a linear dimension of body size. Using L as the common linear body size dimension (e.g., body mass, $M = L^3$), the HGS denominator becomes ($HT^{0.968} \times M^{0.577} \times WC^{-0.619}$) = $L^{0.968}(L^3)^{0.577}\ L^{-0.619} = L^{0.968}L^{1.731}L^{-0.619} = L^{2.086}$, or approximately L^2. This is equivalent to a body surface or cross-sectional area, suggesting that HGS is associated with, or proportional to, muscle cross-sectional area. Many muscle physiologists might well have anticipated and approved of this dimensional interpretation.

Based on the reduced body mass and height allometric model (Table 2), to obtain a normalized HGS_n independent of body mass and height, we need to calculate the normalized ratio

$$HGS_n = HGS/\left(HT^{1.438} \times M^{0.164}\right) \quad [4]$$

The fitted exponents from the reduced-model covariates can also be interpreted from the aforementioned dimensional considerations. The body mass and height exponents are ($HT^{1.438} \times M^{0.164}$) $= L^{1.438}(L^3)^{0.164} = L^{1.438}L^{0.492} = L^{1.93}$, again approximately L^2.

Finally, using the simplified/reduced allometric model (equation 2), incorporating only log-transformed height log (HT) (excluding log(M) and log(WC)), the fitted height (HT) exponent was 1.752 (see the parameters in Table 3), again close to 2, suggesting that if we were to use height alone, HGS should be normalized to $HT^{1.752}$ as follows:

$$HGS_n = HGS/\left(HT^{1.752}\right) \quad [5]$$

a finding that is remarkably similar to the result reported by Maranhao Neto et al. (22), who recommended that HGS of older adults should be normalized using absolute HGS divided by height$^{1.84}$.

These results, using allometric models, suggest that the most appropriate body size components that will optimally remove the effect of body size when normalizing HGS should include all three terms body mass, height, and waist circumference, as given by equation 3. These results also suggest that investigators who normalize HGS using either body mass (17–24) and/or BMI (23–26) are probably using inappropriate normalizing body size terms. Clearly, if body mass and height are to be used, they should be combined by multiplying the M and HT terms together ($HT^{1.438} \times M^{0.164}$), see equation 4, not dividing body mass (M) by height (HT^2) as is the case when using BMI (in kilograms per meter squared) to normalize HGS. Furthermore, if only one body size component were to be used to normalize HGS, height ($HT^{1.752}$) would be considerably more successful than body mass (M) at removing the body size/dimensional effect when normalizing HGS.

We recognize that these fitted exponents adopted in the normalizing equations 3, 4, and 5 mentioned previously are all "sample specific." That is, they are likely to work well for American adults, and even though they are both physiologically and dimensionally sound, they are unlikely to be equally successful with, and generalizable to, other populations. This was illustrated perfectly when we compare the fitted denominator exponent $HT^{1.752}$ reported in equation 5, with the same model adopted by Maranhao Neto et al. (22) for older Brazilian adults, given as $HT^{1.84}$.

However, when normalizing HGS, we need a *simple* methodology that is likely to be "generalizable" to all populations. The one consistent and robust finding from the aforementioned allometric models, was that the normalizing (body size) dimension associated with HGS was given by L^2 (a cross-sectional or surface area). Furthermore, given that we were able to confirm that height (HT^2) was the single best body size dimension associated with HGS, we recommend, in response to the question posed in the title, that HGS should be normalized by dividing HGS by height (HT^2).

Our findings have several implications. First, several studies investigating the associations between HGS and health

TABLE 4. Normalized HGS (HGS in kilograms divided by height in meters squared) centiles by age group and gender for a national sample of Americans 20 yr and older.

Age	C1	C3	C5	C10	C20	C30	C50	C60	C70	C80	C90	C95	C97	C99
Male														
20	8.4	9.5	10.0	10.9	12.0	12.7	14.1	14.7	15.5	16.4	18.3	19.0	19.8	21.6
25	8.9	10.2	10.8	11.7	12.9	13.7	15.0	15.7	16.4	17.3	18.5	19.6	20.4	21.9
30	9.2	10.6	11.2	12.2	13.4	14.2	15.5	16.1	16.8	17.6	18.6	19.7	20.4	21.8
35	9.4	10.8	11.5	12.5	13.6	14.4	15.6	16.2	16.9	17.6	18.6	19.7	20.4	21.7
40	9.5	10.8	11.5	12.4	13.5	14.2	15.4	16.0	16.6	17.3	18.4	19.4	20.0	21.5
45	9.3	10.6	11.2	12.1	13.2	13.9	15.0	15.5	16.1	16.8	17.9	18.8	19.5	20.9
50	8.9	10.2	10.8	11.7	12.7	13.4	14.5	15.0	15.5	16.2	17.4	18.1	18.7	20.0
55	8.7	10.0	10.6	11.5	12.5	13.2	14.3	14.8	15.4	16.0	16.9	17.8	18.4	19.6
60	8.0	9.4	10.1	11.0	12.0	12.7	13.8	14.3	14.8	15.5	16.5	17.3	17.8	19.0
65	6.7	8.5	9.3	10.4	11.5	12.3	13.4	13.9	14.4	15.1	16.0	17.0	17.7	19.1
70	5.7	7.7	8.6	9.8	11.0	11.7	12.9	13.4	14.0	14.7	15.3	16.8	17.6	19.4
75	4.8	6.9	7.8	9.0	10.2	11.0	12.1	12.6	13.1	13.8	14.3	16.1	16.9	19.1
80	3.8	5.8	6.8	8.0	9.1	9.8	10.9	11.3	11.9	12.6	13.3	14.8	15.7	18.1
Female														
20	7.4	8.0	8.4	8.9	9.5	10.0	10.8	11.2	11.7	12.2	13.0	13.7	14.2	15.1
25	7.7	8.3	8.6	9.2	9.8	10.3	11.2	11.6	12.0	12.6	13.4	14.1	14.5	15.4
30	7.8	8.5	8.8	9.4	10.1	10.6	11.4	11.9	12.3	12.9	13.7	14.4	14.8	15.8
35	7.7	8.5	8.9	9.5	10.2	10.7	11.5	12.0	12.4	13.0	13.8	14.5	14.9	15.9
40	7.4	8.3	8.7	9.4	10.1	10.6	11.5	11.9	12.4	12.9	13.7	14.4	14.9	15.9
45	7.0	8.0	8.5	9.2	10.0	10.5	11.4	11.8	12.2	12.8	13.6	14.3	14.8	15.9
50	6.5	7.7	8.2	8.9	9.7	10.3	11.1	11.5	12.0	12.5	13.3	14.1	14.6	15.8
55	6.2	7.4	7.9	8.7	9.5	10.0	10.9	11.3	11.7	12.2	13.0	13.7	14.3	15.4
60	6.0	7.2	7.7	8.4	9.2	9.7	10.6	11.0	11.4	11.9	12.6	13.3	13.8	14.9
65	5.8	6.9	7.4	8.1	8.8	9.4	10.2	10.6	11.0	11.5	12.2	12.9	13.4	14.5
70	5.4	6.4	6.9	7.6	8.3	8.8	9.6	10.0	10.4	10.9	11.6	12.3	12.8	13.9
75	5.0	5.9	6.3	6.9	7.6	8.1	8.9	9.2	9.6	10.1	10.9	11.6	12.2	13.3
80	4.5	5.3	5.7	6.2	6.9	7.3	8.0	8.4	8.8	9.3	10.1	10.9	11.5	12.8

have used scaling approaches that are not optimal. There is a need for future research to determine if using HT^2 to normalize HGS impacts these associations. Second, to improve comparability throughout the literature, we also recommend reporting raw HGS values (i.e., in the measured units) in addition to normalized HGS values, when possible. Last, we recommend using a quintile framework to facilitate the interpretation of these HGS centiles, similar to previous studies (e.g., [45]). For instance, adults below the 20th centile can be considered as having "very low" HGS; between the 20th and 40th centiles, "low" HGS; between the 40th and 60th centiles, "moderate" HGS; between the 60^{th} and 80^{th} centiles, "high" HGS; and above the 80^{th} centile, "very high" HGS.

CONCLUSIONS

HGS is considered an important indicator of health. However, because HGS is strongly associated with body size, most investigators report HGS normalized for some measure of body size as a more sensitive indication of strength capacity of individual within a population. Some investigators choose to normalize HGS per unit of body mass (in kilograms), whereas others normalize per unit BMI (in kilograms per meter squared). The current study suggests that neither body mass nor BMI is appropriate to normalize adult HGS. Incorporating all three body size dimensions of body mass, height and waist circumference, or the reduced subsets of body mass and height, or height alone, suggests that the most appropriate normalizing (body size) dimension associated with HGS should be a cross-sectional or surface area measure of body size (i.e., L^2, where L is a linear dimension of body size). Given that height was also identified as the signally best body size dimension associated with HGS, we recommend HGS be normalized by dividing HGS by height^2 (HGS/HT^2). For this reason, the centile curves for the HGS/HT^2 by age (20–29, 30–39, …, 80 yr and over) are given separately for males and females in the study. Future research should confirm these results in other countries, preferably using nationally representative data.

The authors declare no conflicts of interest or external funding or sponsorship related to this study. The results of this study do not constitute an endorsement by the American College of Sports Medicine. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

REFERENCES

1. Cruz-Jentoft AJ, Bahat G, Bauer J, et al. Sarcopenia: revised European consensus on definition and diagnosis. *Age Ageing*. 2019;48(1):16–31.
2. García-Hermoso A, Ramírez-Campillo R, Izquierdo M. Is muscular fitness associated with future health benefits in children and adolescents? A systematic review and meta-analysis of longitudinal studies. *Sports Med*. 2019;49(7):1079–94.
3. Leong DP, Teo KK, Rangarajan S, et al. Prognostic value of grip strength: findings from the Prospective Urban Rural Epidemiology (PURE) study. *Lancet*. 2015;386(9990):266–73.
4. McGrath RP, Kraemer WJ, Snih SA, Peterson MD. Handgrip strength and health in aging adults. *Sports Med*. 2018;48(9):1993–2000.
5. Ortega FB, Silventoinen K, Tynelius P, Rasmussen F. Muscular strength in male adolescents and premature death: cohort study of one million participants. *BMJ*. 2012;345:e7279.
6. Celis-Morales CA, Welsh P, Lyall DM, et al. Associations of grip strength with cardiovascular, respiratory, and cancer outcomes and all cause mortality: prospective cohort study of half a million UK Biobank participants. *BMJ*. 2018;361:k1651.

7. Tarp J, Støle AP, Blond K, Grøntved A. Cardiorespiratory fitness, muscular strength and risk of type 2 diabetes: a systematic review and meta-analysis. *Diabetologia*. 2019;62(7):1129–42.
8. Cooper R, Kuh D, Cooper C, et al. Objective measures of physical capability and subsequent health: a systematic review. *Age Ageing*. 2011;40(1):14–3.
9. McGrath R, Johnson N, Klawitter L, et al. What are the association patterns between handgrip strength and adverse health conditions? A topical review. *SAGE Open Med*. 2020;8:2050312120910358.
10. Cruz-Jentoft AJ, Sayer AA. Sarcopenia. *Lancet*. 2019;393(10191): 2636–46.
11. Manini TM, Clark BC. Dynapenia and aging: an update. *J Gerontol A Biol Sci Med Sci*. 2012;67(1):28–40.
12. Fried LP, Tangen CM, Walston J, et al. Frailty in older adults: evidence for a phenotype. *J Gerontol A Biol Sci Med Sci*. 2001;56(3): M146–57.
13. Suni JH, Miilunpalo SI, Asikainen TM, et al. Safety and feasibility of a health-related fitness test battery for adults. *Phys Ther*. 1998; 78(2):134–48.
14. Bohannon RW, Magasi SR, Bubela DJ, Wang YC, Gershon RC. Grip and knee extension muscle strength reflect a common construct among adults. *Muscle Nerve*. 2012;46(4):555–8.
15. Bohannon RW, Bubela DJ, Magasi SR, Gershon RC. Relative reliability of three objective tests of limb muscle strength. *Isokinet Exerc Sci*. 2011;19(2):77–81.
16. Lang JJ, Smith J, Tomkinson GR. Global surveillance of cardiorespiratory and musculoskeletal fitness. In: Brusseau TA, Fairclough S, Lubans DR, editors. *The Routledge Handbook of Youth Physical Activity*. New York (NY): Routledge; 2020. pp. 47–68.
17. Brown EC, Buchan DS, Madi SA, Gordon BN, Drignei D. Grip strength cut points for diabetes risk among apparently healthy U.S. adults. *Am J Prev Med*. 2020;58(6):757–65.
18. Hu S, Gu Y, Lu Z, et al. Relationship between grip strength and prediabetes in a large-scale adult population. *Am J Prev Med*. 2019;56(6):844–51.
19. McGrath RP, Vincent BM, Snih SA, et al. The association between handgrip strength and diabetes on activities of daily living disability in older Mexican Americans. *J Aging Health*. 2018;30(8):1305–18.
20. Peterson MD, Duchowny K, Meng Q, Wang Y, Chen X, Zhao Y. Low normalized grip strength is a biomarker for cardiometabolic disease and physical disabilities among U.S. and Chinese adults. *J Gerontol A Biol Sci Med Sci*. 2017;72(11):1525–31.
21. Peterson MD, Krishnan C. Growth charts for muscular strength capacity with quantile regression. *Am J Prev Med*. 2015;49(6):935–8.
22. Maranhao Neto GA, Oliveira AJ, Pedreiro RC, et al. Normalizing handgrip strength in older adults: an allometric approach. *Arch Gerontol Geriatr*. 2017;70:230–4.
23. Manini TM, Patel SM, Newman AB, et al. Identification of sarcopenia components that discriminate slow walking speed: a pooled data analysis. *J Am Geriatr Soc*. 2020;68(7):1419–28.
24. Whitney DG, Peterson MD. The association between differing grip strength measures and mortality and cerebrovascular event in older adults: National Health and Aging Trends Study. *Front Physiol*. 2019;9:1871.
25. McGrath R, Hackney KJ, Ratamess NA, Vincent BM, Clark BC, Kraemer WJ. Absolute and body mass index normalized handgrip strength percentiles by gender, ethnicity, and hand dominance in Americans. *Adv Geriatr Med Res*. 2020;2(1):e200005.
26. McLean RR, Shardell MD, Alley DE, et al. Criteria for clinically relevant weakness and low lean mass and their longitudinal association with incident mobility impairment and mortality: the foundation for the National Institutes of Health (FNIH) sarcopenia project. *J Gerontol A Biol Sci Med Sci*. 2014;69(5):576–83.
27. Tanner JM. Fallacy of per-weight and per-surface area standards, and their relation to spurious correlation. *J Appl Physiol*. 1949;2(1):1–15.
28. Nevill AM, Ramsbottom R, Williams C. Scaling physiological measurements for individuals of different body size. *Eur J Appl Physiol Occup Physiol*. 1992;65(2):110–7.
29. Külkamp W, Ache-Dias J, Kons RL, Detanico D, Dal Pupo J. The ratio standard is not adequate for scaling handgrip strength in judo athletes and nonathletes. *J Exerc Rehabil*. 2020;16(2):175–82.
30. Stasinopoulos MD, Rigby RA, De Bastiani F. GAMLSS: a distributional regression approach. *Stat Model*. 2018;18(3–4):248–73.
31. Johnson CL, Dohrmann SM, Burt VL, Mohadjer LK. National Health and Nutrition Examination Survey: sample design, 2011–2014. *Vital Health Stat 2*. 2014;(162):1–33.
32. Wang YC, Bohannon RW, Li X, Yen SC, Sindhu B, Kapellusch J. Summary of grip strength measurements obtained in the 2011–2012 and 2013–2014 National Health and Nutrition Examination Surveys. *J Hand Ther*. 2019;32(4):489–96.
33. Centers for Disease Control and Prevention (CDC). National Health and Nutrition Examination Survey (NHANES): muscle strength procedures manual. Available from: https://wwwn.cdc.gov/nchs/data/nhanes/2011-2012/manuals/Muscle_Strength_Proc_Manual.pdf. Accessed June 10, 2021.
34. Centers for Disease Control and Prevention (CDC). National Health and Nutrition Examination Survey (NHANES): anthropometry procedures manual. Available from: https://wwwn.cdc.gov/nchs/data/nhanes/2011-2012/manuals/Anthropometry_Procedures_Manual.pdf. Accessed June 10, 2021.
35. Centers for Disease Control and Prevention (CDC). National Health and Nutrition Examination Survey (NHANES): muscle strength procedures manual. Available from: https://wwwn.cdc.gov/nchs/data/nhanes/2013-2014/manuals/Muscle_Strength_2013.pdf. Accessed June 10, 2021.
36. Centers for Disease Control and Prevention (CDC). National Health and Nutrition Examination Survey (NHANES): anthropometry procedures manual. Available from: https://www.cdc.gov/nchs/data/nhanes/nhanes_13_14/2013_Anthropometry.pdf. Accessed June 10, 2021.
37. Nevill A, Tsiotra G, Tsimeas P, Koutedakis Y. Allometric associations between body size, shape, and physical performance of Greek children. *Pediatr Exerc Sci*. 2009;21(2):220–32.
38. Bustamante Valdivia A, Maia J, Nevill A. Identifying the ideal body size and shape characteristics associated with children's physical performance tests in Peru. *Scand J Med Sci Sports*. 2015; 25(2):e155–65.
39. Nevill A, Duncan M, Cheung DS, Wong AS, Kwan RYC, Lai CK. The use of functional performance tests and simple anthropomorphic measures to screen for comorbidity in primary care. *Int J Older People Nurs*. 2020;15(4):e12333.
40. Burnham KP, Anderson DR. *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*. Basel (Switzerland: Springer; 2002.
41. R Core Team. *R: A Language and Environment for Statistical Computing*. Vienna (Austria): R Foundation for Statistical Computing; 2020.
42. van Buuren S, Fredriks M. Worm plot: a simple diagnostic device for modelling growth reference curves. *Stat Med*. 2001;20(8):1259–77.
43. Owen AB. Nonparametric likelihood confidence bands for a distribution function. *J Am Stat Assoc*. 1995;90(430):516–21.
44. Åstrand P-O, Rodahl K. *Textbook of Work Physiology*. 3rd ed. New York (NY): McGraw-Hill; 1986.
45. Tomkinson GR, Lang JJ, Tremblay MS, et al. International normative 20 m shuttle run values from 1 142 026 children and youth representing 50 countries. *Br J Sports Med*. 2017;51(21):1545–54.