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Allometric Scaling of Maximal Strength Performance in Physically Active College-Aged Males: Removing the Effects of Body Weight

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Abstract **Background**: Anytime a trend or correlation is observed between fitness scores and the size of the participating individuals, it is possible that body weight (BW) is confounding the performance. A common method employed to correct this bias is ratio scaling (i.e., dividing the score by BW). However, another method, allometric scaling, may be more accurate in partitioning out BW effects from performance scores. The purpose of this study was two-fold. First, to compare the results of ratio scaling and allometric scaling in removing the effects of BW from maximal strength scores. Second, to validate the scaled strength scores by examining their differences across groups of varying BW. **Methods**: A cross-sectional convenience sample of N = 80 traditional male college students ages 18 to 24 years was used in the analysis. Four different maximal strength tests were administered including hand grip strength (GS), 1RM bench press (BP), 1RM leg press (LP), and vertical jump (VJ). Body measures of height, BW, BMI, and WC were collected using standardized procedures. Scaling was performed using the following general calculation: MS/BW^b, where MS is the maximum strength score and *b* the scaling exponent for BW. An exponent of 1.0 was used for ratio scaling. The fit BW coefficients from log-log regression models supplied the exponents for allometric scaling. Pearson correlations were utilized to examine the relationships between body measures and scaled strength scores. ANOVA was used to examine differences in scaled strength scores across BW tertile groups. **Results**: Mean age of the sample was 20.5 ± 1.6 yr with mean BMI, GS, BP, LP, and VJ of 27.5 ± 4.7 kg/m^2, 54.2 ± 8.6 kg, 230.3 ± 63.8 lb, 582.4 ± 159.5 lb, and 23.7 ± 4.3 in, respectively. BW, BMI, and WC were significantly related to BP, LP, and VJ. Body measures were not related to GS. Ratio scaling increased the dependence between the body measures and maximal strength scores. Allometric scaling removed the effects of all body measures from maximal strength scores except for a weak association between height and LP. ANOVA models indicated no significant differences across BW tertile groups for the four allometric scaled maximum strength scores. **Conclusion**: Results from this study indicate that ratio scaling is a poor method for removing BW from maximal strength scores in traditional college-aged males. Allometric scaling for BW however adequately removed the effects of BW, BMI, and WC from maximal strength scores. Finally, GS does not appear to be dependent on body measures in this population.

Keywords: *allometry, scaling, measurement, evaluation, muscular strength*

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1. Introduction

Many human performance assessments are influenced by the participant’s body weight (BW) [1,2,3,4]. An extreme example is the performance difference in many fitness tests between children and adults [5]. A less obvious example is the negative relationship often seen between cardiorespiratory fitness and BW or body mass index (BMI) [6,7]. Similarly, positive relationships involving BW and lean mass are often observed with muscular strength tests [8].

From an absolute performance perspective, these BW-related differences are valid. That is, a larger individual deserves credit and should be ranked higher if they indeed outperform a smaller counterpart on a muscular strength test. However, from a fitness evaluation perspective, a smaller individual should not necessarily be ranked lower than a larger counterpart because of absolute strength differences. This is the case because when an exercise professional administers a fitness test, they intend to measure and evaluate a specific trait - not an unwanted body measure masked as a fitness trait. A simple analogy is a math test with only word problems where performance may favor students with superior reading skills. Therefore, removing the effect that BW has on a performance test will allow for an independent evaluation of that specific fitness trait.

The concept of removing body size effects from physical tests is called ‘scaling’ (or normalizing) and several different scaling techniques have been used on fitness scores [9]. One of the more commonly applied techniques is called ‘ratio scaling’ where a fitness score is simply divided by the participant’s BW. Relative measures of both maximal oxygen consumption ($VO2_{max}$, ml/kg/min) and one-repetition maximum lifts (1RM, lb/kg) are common in field, research, and labs [10,11]. Despite its widespread use, ratio scaling often lacks certain properties for scores to be valid. Specifically, the relationship between a fitness score of interest and BW must be perfectly linear, proportional, with a zero intercept [12,13,14]. That is, the fitness score divided by BW must always yield a constant proportion. Departures from this property will systematically lower a ratio-scaled fitness score for larger participants and systematically inflate scores for their smaller counterparts [9]. Furthermore, the new ratio scaled fitness variable often remains correlated with BW, defeating the initial scaling purpose.

Another scaling technique proposed for fitness scores is residualized scaling using regression [15]. With this technique, the fitness scores of interest are regressed onto BW and the differences between raw scores and predicted scores from the model serve as the new scaled score. Although this method is intuitive in that it does provide a new partialized fitness variable independent of BW, it also requires the assumptions of linear regression, creates obscure looking scores, and may not be a simple procedure for all fitness practitioners to employ.

Allometric scaling, however, is a technique that often satisfies the above-mentioned shortcomings [16]. In brief, allometric scaling is accomplished by the following steps: 1) log transform the fitness score and BW variables, 2) perform linear regression using the log fitness scores as the dependent variable and log BW as the predictor variable (i.e., linearize the relationship), 3) raise the raw BW variable to a power of the fit log BW coefficient (*b*) (i.e., define the power function), 4) finally divide the original fitness score by the power function (i.e., compute a power function ratio). This allometric scaling procedure provides a new scaled fitness score that better models a nonlinear association, satisfies the proportional relationship requirement, and, most importantly, removes the effect of BW [9,16].

Data examining scaled maximal strength scores in specific populations like college-aged males are sparse. The purpose of this study was two-fold. First, to compare results of ratio scaling and allometric scaling in removing the effects of BW from maximal strength scores. Second, to validate the scaled strength scores by examining their differences across groups of varying BW.

2. Methods

Study design

This study was a secondary analysis of a larger campus-based fitness dataset [17]. It included a convenience sample of college students that assessed across the five components health-related fitness. Participants were included in the current study if they were male of traditional college age (i.e., 18 to 24 years), had complete muscular strength and anthropometric data, and were generally physically active. Students were initially recruited using public flyers and word-of-mouth. The university system’s institutional review board (IRB) approved all study methods and procedures.

Scaling

Scaling was performed using the following general calculation: MS/BW^b, where MS is the maximum strength score and *b* the scaling exponent for BW. The fit BW coefficients from log-log regression models supplied the exponents for allometric scaling (MS_{AS}). The general log-log regression equation is as follows:

$$\ln MS = \ln a + b \times \ln BW \quad .$$

The power (allometric) function is then:

$$MS_{AS} = a \times BW^{b} \quad .$$

The constant *a* in the multiplicative power function describes the rate of change. i.e., the rate of increase or decrease of the curve. The *b* parameter in the power function describes the shape of the curve. When the *b* exponent is positive (‘+’) the curve is concave up and increasing and when negative (‘-‘) the curve is concave down and decreasing. When values of *b* are between 0 and 1 exclusive the curve is concave down and increasing and when between -1 and 0 exclusive the curve is concave up and decreasing. Finally, an exponent of 1.0 was used for ratio scaling (MS_{RS}). Note that an exponent of 0.0 is equivalent to a ratio-scaled denominator of 1.0. That is, no scaling of the MS score.

Maximal strength performance

Four different field-based fitness tests were administered for maximal strength performance. These tests included: hand grip strength (GS) [18], 1RM bench press (BP) [19], 1RM leg press (LP) [19], and vertical jump (VJ) [20]. Both BP and LP were measured in pounds (lb), GS measured in kilograms (kg), and VJ measured in inches (in). BP was assessed by the heaviest load successfully lifted. BP procedure included lowering and raising the bar slowly with a closed pronated grip wider than shoulder width while ensuring the 5-points of contact [18]. LP was assessed by the heaviest load successfully pushed. LP procedure included lowering the load on a seated leg press machine (hip sled) until thighs parallel to the foot platform and raising until the knees completely extended [18]. GS was assessed with subject squeezing as forcefully as possible using a hand grip dynamometer (Camry, Model: EH101). The dynamometer was placed in the participant’s dominant hand with elbow extended and arm to the side next to the hip [19]. VJ was assessed as the difference between two chalked finger marks on a wall. A standing mark was made with dominant arm raised upward and body to the side of a wall. A jumping mark was made after forcefully jumping upward without stepping [20]. VJ was considered a measure of maximal explosive strength in this study.

Body measures

Body measures for this study were assessed on the same lab visit with two measurements recorded for each in rotational order and then averaged, unless large differences noted. Height was assessed using a wall mounted stadiometer (Seca, Model: 216) to the nearest 0.5 cm. BW was assessed with a digital floor scale (Seca, Model: 803) to the nearest 0.1 kg. BMI (kg/m^2) was computed as a calculation of weight (kg) divided by height in meters (m) squared (m^2) [21]. Waist circumference (WC) was assessed to the nearest 0.5 cm using an elastic tape and measuring the narrowest point between the participant's umbilicus and xiphoid process [22].

Statistical analyses

Descriptive statistics were computed to describe the sample and study variables. Histograms were inspected to judge normality and identify outliers. Pearson correlations (r) were utilized to examine the relationships of body measures with unscaled and scaled strength scores. Since the sample size was the same for all analyses, $N = 80$, a critical value of r was obtained where $|r| > r_{cv}$ of .220 was considered significant at a two-tailed α of .05.

Least squares linear regression was used on log transformed variables (i.e., log-log regression) with the strength scores as the dependent variable and BW as the predictor. The fit BW coefficients from the regression models supplied the exponents for allometric scaling. Standard errors (SE) and confidence intervals (CI) were used to examine the significance of the power exponents as well as indirectly test the exponents for unscaled and ratio-scaled scenarios.

Finally, to validate the strength scores, analysis of variance (ANOVA) was used to examine differences in unscaled and scaled means across BW groups. ANOVA models used strength scores that were first converted to T-scores (i.e., *Mean* = 50, *SD* = 10) to aid interpretation and comparison. Additionally, BW tertile groups were created where the 1st BW tertile contained the lightest males and the 3rd BW tertile contained the heaviest males. All p-values were reported as two-sided and statistical significance set at $p < 0.05$.

3. Results

Table 1. Descriptive statistics for the study sample

Variable	*Mean*	*Median*	*SD*	*Min*	*Max*
Age (yr)	20.5	20.0	1.6	18.0	24.0
Height (cm)	180.6	180.0	9.1	159.0	208.5
BW (kg)	89.9	86.1	17.4	62.0	152.7
BMI (kg/m^2)	27.5	26.7	4.7	20.8	41.6
WC (cm)	86.2	84.0	9.4	71.5	122.0
GS (kg)	54.2	52.4	8.6	32.0	77.5
BP (lb)	230.3	225.0	63.8	31.5	450.0
LP (lb)	582.4	540.0	159.5	270.0	900.0
VJ (in)	23.7	23.8	4.3	13.0	36.5

Note. N = 80. BW is body weight. BMI is body mass index. WC is waist circumference. VJ is vertical jump. GS is grip strength. BP is bench press. LP is leg press. All variables had approximate bell-shaped distributions with slight right skewness in BW, BMI, and WC.

Table 1 contains descriptive statistics for the sample. Mean age of the participants was 20.5 ± 1.6 yr with mean BMI, GS, BP, LP, and VJ of 27.5 ± 4.7 kg/m2, 54.2 ± 8.6 kg, 230.3 ± 63.8 lb, 582.4 ± 159.5 lb, and 23.7 ± 4.3 in, respectively. All variables had approximate bell-shaped distributions with slight right skewness for BW, BMI, and WC. One participant had a sample Z-score typically considered an outlier (i.e., $|Z| > +3.00$) for BW (152.7 kg, $Z = 3.61$), BMI (41.6 kg/m2, $Z = 3.01$), and WC (122.0 cm, $Z = 3.79$). Since these body measure values were checked for accuracy, did not excessively skew the distributions, did not alter the results when removed, and subjectively seem reasonable in this population, the participant remained in the analysis.

Table 2. Pearson correlations for body measures and raw unscaled maximum strength scores

Variable	VJ	GS	BP	LP
Height (cm)	.012	.158	.025	-.020
BW (kg)	**-.308**	.092	**.297**	**.423**
BMI (kg/m^2)	**-.356**	.017	**.332**	**.505**
WC (cm)	**-.424**	.054	**.241**	**.545**

Note. N = 80. Values of $|r| > r_{cv}$ of .220 are significant, $p < .05$ (in bold). BW is body weight. BMI is body mass index. WC is waist circumference. VJ is vertical jump. GS is grip strength. BP is bench press. LP is leg press.

Table 2 contains the Pearson correlations for body measures and raw unscaled maximum strength scores. BW, BMI, and WC were each significantly and positively related to BP and LP (r_s .241 to .545). Conversely, BW, BMI, and WC were each significantly and negatively related to VJ (r_s -.308 to -.424). Body measures were not related to GS and height was not related to any strength score. Table 3 contains the Pearson correlations for body measures and ratio-scaled maximum strength scores. Most noteworthy is that all correlations in this analysis were negative and the majority significant. The exceptions were BMI with BP and LP as well as WC with LP ($p > .05$).

Table 3. Pearson correlations for body measures and ratio-scaled maximum strength scores

Variable	VJ$_{RS}$	GS$_{RS}$	BP$_{RS}$	LP$_{RS}$
Height (cm)	**-.303**	**-.263**	**-.266**	**-.335**
BW (kg)	**-.778**	**-.702**	**-.309**	**-.231**
BMI (kg/m^2)	**-.710**	**-.640**	-.187	-.050
WC (cm)	**-.754**	**-.607**	**-.261**	-.007

Note. N = 80. Values of $|r| > r_{cv}$ of .220 are significant, $p < .05$ (in bold). VJ$_{RS}$ is vertical jump divided by body mass. GS$_{RS}$ is grip strength divided by body mass. BP$_{RS}$ is bench press divided by body mass. LP$_{RS}$ is leg press divided by body mass.

Table 4. Power function exponents for allometric-scaled maximum strength scores using body weight

Variable	ln VJ	ln GS	ln BP	ln LP
b	-0.31651	0.08674	0.51289	0.6764
SE	0.1116	0.0972	0.1990	0.1518
Model p	.0058	.3751	.0118	<.0001
RMSE	.181	.158	.324	.247
H_0: $b = 1.0$	reject	reject	reject	reject
H_0: $b = 0.0$	reject	fail	reject	reject

Note. N = 80. b is BW exponent of the power (allometric) function. ln VJ is the natural log of vertical jump. ln GS is the natural log of grip strength. ln BP is the natural log of bench press. ln LP is the natural log of leg press. RMSE is root mean square error. H_0: b = 1.0 is testing against ratio scaling where exponent is 1.0. H_0: b = 0.0 is testing against no scaling where exponent is 0.0.

Table 4 displays the power function exponents for BW and associated statistics for allometric scaled maximum strength scores. Power exponents were significantly different from 0.0 for VJ, BP, and LP but not GS. This indicates that GS statistically does not require BW scaling. Power exponents were significantly different from 1.0 for all strength scores, indicating that ratio-scaled strength scores are not statistically useful in removing the effects of BW. Table 5 contains the Pearson correlations for body measures and allometric scaled maximum strength scores. Most noteworthy, no correlations in this table were significant, less height and LP_{AS} (*r* = -.239), which was considered weak. This indicates that allometric scaling not only removed the effects of BW from the maximal strength scores but also the effects of BMI and WC.

Table 6 contains the comparison of unscaled maximum strength T-scores across BW tertiles. Significant differences were observed for VJ_T, BP_T, and LP_T across BW tertile groups. Additionally, linear trend tests indicated a positive trend for BP_T and LP_T and negative trend for VJ_T. As expected, no differences were observed for GS_T across BW tertile groups. Table 7 contains the same ANOVA summary statistics for ratio-scaled strength scores. Significant differences were observed for $VJ_{RS.T}$, $GS_{RS.T}$, and $LP_{RS.T}$ across BW tertile groups. Additionally, all ratio-scaled strength measures trended toward negative associations with BW tertile groups. Table 8, finally, contains the same ANOVA summary statistics for the allometric-scaled strength scores. No significant differences were observed nor significant linear trends found across BW tertile groups in this table.

Table 5. Pearson correlations for body measures and allometric-scaled maximum strength scores

Variable	VJ_{AS}	GS_{AS}	BP_{AS}	LP_{AS}
Height (cm)	.166	.113	-.126	**-.239**
BW (kg)	-.018	-.005	-.013	-.015
BMI (kg/m^2)	-.118	-.067	.068	.140
WC (cm)	-.194	-.029	-.016	.185

Note. N = 80. Values of $|r| > r_{cv}$ of .220 are significant, $p < .05$ (in bold). BW is body weight. BMI is body mass index. WC is waist circumference. VJ_{AS} is vertical jump divided by allometric adjusted body mass. GS_{AS} is grip strength divided by allometric-adjusted body mass. BP_{AS} is bench press divided by allometric adjusted body mass. LP_{AS} is leg press divided by allometric adjusted body mass.

Table 6. Comparison of unscaled maximum strength T-scores across body weight tertiles

	1st BW Tertile		2nd BW Tertile		3rd BW Tertile		ANOVA	
Variable	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	p^a	p^b
VJ_T	51.43	6.64	52.76	11.98	45.86	9.50	.0250	.0392
GS_T	47.59	9.09	52.66	10.68	49.66	9.85	.1796	.4503
BP_T	44.71	5.70	51.90	11.94	53.20	9.36	.0031	.0015
LP_T	43.88	5.79	51.03	11.46	54.86	8.78	.0001	<.0001

Note. N = 80. The 1st BW tertile contains the lightest males and the 3rd BW tertile contains the heaviest males. [a]One-way ANOVA testing for differences in group means. [b]Linear trend test. VJ_T is raw vertical jump scores converted to T-scores. GS_T is raw grip strength scores converted to T-scores. BP_T is raw bench press scores converted to T-scores. LP_T is raw leg press scores converted to T-scores.

Table 7. Comparison of ratio-scaled maximum strength T-scores across body weight tertiles

	1st BW Tertile		2nd BW Tertile		3rd BW Tertile		ANOVA	
Variable	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	p^a	p^b
$VJ_{RS.T}$	57.83	6.22	51.72	7.96	40.75	7.07	<.0001	<.0001
$GS_{RS.T}$	56.81	8.17	52.31	7.55	41.14	7.01	<.0001	<.0001
$BP_{RS.T}$	51.17	6.89	52.79	12.33	46.08	8.99	.0348	.0600
$LP_{RS.T}$	50.42	7.34	52.24	12.90	47.36	8.55	.1941	.2649

Note. N = 80. The 1st BW tertile contains the lightest males and the 3rd BW tertile contains the heaviest males. [a]One-way ANOVA testing for differences in group means. [b]Linear trend test. $VJ_{RS.T}$ is ratio scaled vertical jump scores converted to T-scores. $GS_{RS.T}$ is ratio scaled grip strength scores converted to T-scores. $BP_{RS.T}$ is ratio scaled bench press scores converted to T-scores. $LP_{RS.T}$ is ratio scaled leg press scores converted to T-scores.

Table 8. Comparison of allometric-scaled maximum strength T-scores across body weight tertiles

	1st BW Tertile		2nd BW Tertile		3rd BW Tertile		ANOVA	
Variable	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	p^a	p^b
$VJ_{AS.T}$	48.21	6.67	52.59	12.52	49.13	9.67	.2432	.7380
$GS_{AS.T}$	48.59	9.26	52.80	10.71	48.56	9.72	.2041	.9913
$BP_{AS.T}$	47.78	6.46	52.60	12.72	49.54	9.47	.2078	.5224
$LP_{AS.T}$	48.02	7.03	52.05	13.04	49.85	8.83	.3442	.5078

Note. N = 80. The 1st BW tertile contains the lightest males and the 3rd BW tertile contains the heaviest males. [a]One-way ANOVA testing for differences in group means. [b]Linear trend test. $VJ_{AS.T}$ is allometric scaled vertical jump scores converted to T-scores. $GS_{AS.T}$ is allometric scaled grip strength scores converted to T-scores. $BP_{AS.T}$ is allometric scaled bench press scores converted to T-scores. $LP_{AS.T}$ is allometric scaled leg press scores converted to T-scores.

4. Discussion

The primary purpose of this study was to compare the results of ratio scaling and allometric scaling in removing the effects of BW from maximal strength scores. Results showed that ratio scaling overall was a poor method for removing these effects. In fact, BW not only remained correlated with ratio-scaled strength scores but changed the direction of associations with BP_{RS} and LP_{RS}. Furthermore, ratio scaling created strong negative correlations between GS_{RS} and all four body measures, which were absent with the raw unscaled GS scores. Finally, ratio scaling of BW created negative correlations with height and each of the four maximal strength tests, which also were absent with the raw scores. In sum then, results from this study confirm that ratio scaling does not remove the effects of BW from maximal strength scores in college-aged males [9]. Moreover, these findings indicate that ratio scaling may result in new strength variables that are more biased than the original unscaled scores.

On the other hand, allometric scaling proved robust in removing the effects of BW from maximal strength scores. Specifically, BW was not significantly correlated with any of the four allometric-scaled strength scores. Additionally, allometric scaling of BW removed the effects of both BMI and WC from the strength scores, which were present in unscaled and ratio-scaled variables. These results underscore the use of allometric scaling as an efficacious means of removing BW bias from maximal strength scores.

Two final notes regarding the primary purpose of this study. The first is that GS was not correlated with BW or any body measure in this population of college-aged males. This was the case with raw unscaled GS as well as allometric-scaled GS_{AS}. This discovery contradicts findings from others [23,24]. Thus, further research may be needed to explore the reasoning behind this lack of association. Nonetheless intuition may suggest that BW is simply not a factor in GS among a relatively physically active and physically fit population of delimited age (i.e., 18 to 24 years). The second is the finding that height became weakly correlated with allometric-scaled LP_{AS}. Although this was the only significant allometric-scaled correlation, there is some theoretical justification. That is, once BW is statistically removed from the allometric-scaled LP_{AS}, some of its remaining variation could be explained by participant height and lower leg length [25,26,27]. Said differently, with BW held constant, those with longer legs might suffer a mechanical disadvantage in LP performance. Even though, the correlation between height and LP_{AS} was weak to the extent of likely causing nominal bias in LP evaluation.

A secondary purpose of this study was to validate the scaled strength scores by examining their differences across groups of varying BW. The logic behind this part of the study was to statistically test if BW-related bias remained in group means from scaled strength scores (i.e., unscaled, ratio-scaled, allometric-scaled). Results from these analyses confirmed previous correlational findings. That is, group means from unscaled and ratio-scaled strength scores suffer from BW-related bias. Additionally, the effects of BW appear to be removed from group means of allometric-scaled strength scores. Once again, BW was not related to unadjusted GS means in college-aged males.

A strength regarding this study is its use of four different maximal strength tests. Having multiple tests should be considered an attribute because, as in psychometric theory, multiple tests are more likely to target the full trait range than single tests [28]. In so doing, different findings were indeed observed for GS that may not otherwise have been found. Another strength regarding this study is the relatively large sample size and delimited population of traditional college-aged males. Having a homogenous sample allows for generalizations tailored to a specific and important population subgroup. Again, the findings regarding GS dispute what many other studies have reported – a finding that may not have otherwise been noticed.

The most important limitation in this study is its use of field tests for the maximal strength scores. Although laboratory tests may have added an improved degree of control over the assessment procedures, the strength tests used in this study are commonly administered and considered valid [29]. A final limitation of this study is the use of BW, as opposed to lean body mass, to adjust for size differences in strength scores. While a measure of lean mass might more accurately remove size differentials, BW is a convenient measure assessed and strongly correlated with lean body mass [30].

5. Conclusions

Results from this study indicate that ratio scaling is a poor method for removing BW from maximal strength scores. In fact, ratio-scaling was found to increase bias in strength scores above that seen from raw unscaled scores. Results also found that allometric scaling for BW adequately removes the effects of BW, BMI, and WC from BP, LP, and VJ scores. The nonlinear power function of allometric scaling also removes BW-related bias from strength score group means. Finally, GS does not appear to be dependent on body measures in traditional college-aged males.

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