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Allometric scaling of isometric biceps strength in adult females and the effect of body mass index

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Abstract

The purposes of this study were to (1) derive and test allometric scaling models of biceps isometric strength using body mass (BM) and muscle cross-sectional area (CSA) as the scaling variables, (2) assess the influence of body mass index (BMI) by separating the cohort by BMI (normal <25 kg/m² vs. overweight/obese ≥25 kg/m²) and repeating step 1, and (3) assess the effect of BMI on isometric strength allometrically adjusted for differences in CSA by comparing scaled strength between normal weight versus overweight/obese women. The participants were 183 women (18–39 years old) who reported no strength training in the prior year. Isometric strength and CSA of the biceps were assessed on the non-dominant arm. The CSA allometric model met all statistical criteria and produced a scaling exponent of 0.44. The BM model did not meet these criteria until the entire cohort was separated by BMI. The scaling exponents for normal weight and overweight/obese women were 1.48 and 0.35, respectively. These data suggest that BMI exerted

an influence on the relationship between BM and allometrically scaled isometric strength and may be explained by previous studies demonstrating greater contribution of fat mass (FM) versus fat-free mass (FFM) to BMI in overweight/obese women. As such, allometric scaling models of isometric strength, especially in populations that are heterogeneous with regard to body composition, must be carefully tested and examined across the range of BMI. Isometric strength relative to CSA was not significantly different between groups. However, allometrically scaled strength, using CSA as the criterion variable, was significantly greater in overweight/obese women compared to those of normal weight. These data suggest that isometric strength in women is not completely determined by CSA and other factors such as intramuscular fat and muscle fiber type may be confounding or contributing factors.

Keywords

Allometric scaling; Muscle strength; Muscle cross-sectional area; Body mass index

Introduction

Muscle strength testing is commonly used to evaluate, assess, and compare data regarding muscle function in athletic, clinical, and rehabilitation settings. The ability to compare muscle strength between and within groups is important in research as well. Results from strength testing are commonly confounded by body size, and inconsistencies can arise when strength data are non-normalized for body size or normalized using inappropriate methods (Jaric 2002, 2003). Absolute methods of strength testing tend to yield a bias toward larger individuals (Vanderburgh et al. 1995) while ratio methods [i.e., strength relative to body mass (BM)] tend to yield a bias toward smaller individuals (Atkins 2004). Normalizing strength relative to muscle cross-sectional area (CSA) has been proposed as the gold standard within fusiform muscle groups (i.e., biceps) (Klein et al. 2001). However, we recently showed that CSA did not demonstrate the expected relationship with isometric strength in a large cohort of adult males (Zoeller et al. 2007). Allometric scaling models, typically using BM or fat-free mass (FFM), have been proposed as an alternative approach to control for differences in body size and/or muscle mass (Jaric 2002).

Allometric scaling is based on the theory of geometric similarity, which holds that all humans have the same shape and differ only in size (Astrand and Rodahl 1986; Jaric et al. 2005). More specifically, limb lengths are proportional to body height (L), and all areas (e.g., CSA) are proportional to L^2 , whereas all volumes and volume-associated indices, such as body mass, are proportional to L^3 . As such, muscle CSA is proportional to $BM^{2/3}$. Alternatively, any muscle CSA is directly proportional to the strength/force produced by that muscle. However, these assumptions may be confounded by other factors such as body composition, fiber type distribution, muscle fiber pennation angle, distances of the tendon insertion from the center of rotation of the joint, and limitations inherent in measures of CSA compared with muscle volume. The issues identified above have been extensively reviewed by Bruce et al. (1997).

Allometric scaling models use log-linear or other regression models to remove the potential confounders of differences in BM, FFM or CSA. However, allometric scaling models must be carefully evaluated for appropriateness of fit using regression diagnostics (Batterham and George 1997; Nevill and Holder 1995).

Excess adiposity, as in overweight or obesity, represents a potential confound for allometric scaling when using BM or even CSA as the scaling variables, especially in females. Lafortuna et al. (2004) and Sartorio et al. (2004) both found that in obese males, greater BM was due to “similar contributions from fat and fat-free mass but mainly contributed by fat mass in female subjects” (Sartorio et al. (2004). Both of these studies showed BMI to be significantly and positively associated with muscular strength in males. In females, however, Lafortuna et al. (2004) found BMI to have no association with muscular strength while Sartorio et al. found a significant but very weak association. These data suggest that allometric scaling of muscular strength using BM as the scaling variable may be confounded by the relative contribution of fat mass (FM), especially in females.

Based on limited evidence, it has been suggested that increased adiposity may impair muscle function and strength. Several studies have shown that obese individuals demonstrate significantly lower muscle strength or power even after allometric scaling of strength/power measures using BM as the scaling variable (Pescatello et al. 2007; Duche et al. 2002; Hulens et al. 2001). However, each of those studies had methodological issues in terms of the development or application of the allometric models. Finally, we are not aware of any studies that have used allometric scaling with CSA as the scaling variable to evaluate the association between adiposity/BMI and muscular strength.

The data for this project were derived from a subset of participants from the Functional Single Nucleotide Polymorphisms Associated with Muscle Size and Strength (FAMuSS) study (Thompson et al. 2004). The FAMuSS study is a multi-site, controlled, unilateral biceps resistance exercise study assessing four specific variables: (1) baseline biceps muscle strength, (2) baseline biceps muscle CSA, (3) post-training biceps muscle strength, and (4) post-training muscle CSA. The goal of the study is to search for relationships between these muscle traits and specific genetic markers [single-nucleotide polymorphisms (SNP)].

The well-controlled design of the FAMuSS study also provided a unique opportunity to develop and evaluate allometric scaling models in a large cohort of previously untrained adult females and evaluate the influence of BMI. As such, the purposes of this study were to (1) derive allometric scaling models of baseline/pre-training biceps isometric strength of the non-dominant arm using pre-training BM and CSA as the independent or scaling variables, (2) test model appropriateness/fit using regression diagnostics and further assessing the models by cross-validation within the cohort, (3) assess the influence of BMI on allometric modeling of isometric strength, as appropriate, by separating the cohort by BMI (normal <25 kg m⁻²) vs. overweight/obese ≥ 25 kg m⁻²) and repeating steps 1 and 2 and, (4) assess the effect of BMI on isometric strength allometrically adjusted for differences in CSA by comparing allometrically scaled strength between individuals of normal BMI and those overweight/obese.

Methods

The methods for the FAMuSS project have been detailed previously by Thompson et al. (2004). However, a brief description is presented below:

Participants

This study used archival data from five of the eight FA-MuSS study institutions: Florida Atlantic University, University of Central Florida, Hartford Hospital, West Virginia University, and Dublin City University (Ireland). Data from 183 women who completed the FAMuSS study were analyzed. Before initiating the study, all participants were informed of all procedures and risks associated with the study and signed an informed consent in accordance with each institution's institutional review board for human subject experimentation. Further approval to use these archived data was obtained from the Florida Atlantic University institutional review board for human subjects experimentation.

Experimental measurements

Body mass—A body mass measurement (kilograms, kg) was performed with calibrated balance-beam scales before the initiation of all strength testing and training for all FAMuSS study participants.

Magnetic resonance imaging—Magnetic resonance imaging (MRI) was performed before exercise training to assess biceps brachialis anatomical CSA, as previously described (Thompson et al. 2004). The reproducibility of these data has also been previously described (Pescatello et al. 2007). Because of concerns that post-exertion swelling can spuriously increase MRI measurements, pre-training MRI were performed before testing isometric strength.

Isometric strength—Isometric strength of the elbow flexor muscles of the non-dominant arm was measured using a specially constructed, modified preacher bench and strain gauge (model 32628CTL, Lafayette Instrument Company, Lafayette, IN). Baseline measures of isometric strength were assessed on three separate days spaced no more than 2 days apart to control for learning effect. On each of the testing days, three maximal isometric contractions were performed with each arm. Each contraction lasted 2 s, with 1 min of recovery allowed between contractions. The average of the peak force produced during the three contractions was used as the criterion score. To obtain three consistent peak force values, up to two more contractions were performed if a peak value deviated by more than 22 N (Newtons, N or 2.25 kg) from the other two peak values. The average of the results obtained on the second and third pre-training testing days was used as the baseline criterion measurement (intraclass correlation = 0.90).

Applied sciences

Construction and evaluation of allometric scaling models—Baseline/pre-training isometric strength (N) of the non-dominant arm served as the dependent variable. Baseline/pre-training CSA (cm^2) and BM (kg) served as the independent variables to construct two

separate regression models and identify scaling exponents. The following steps outline the procedures used to construct and then evaluate the appropriateness of each model:

1. Subjects were randomly sorted and split into two groups (A and B) for cross-validation. Independent t tests were used to identify any between-group differences with regard to age, height, weight, and pre-training isometric strength and CSA. Alpha was adjusted using Bonferoni correction. Allometric scaling models were first constructed and tested for appropriateness of fit for Group A and then cross-validated on Group B (Step 6).
2. Normality of the dependent variable (pre-training isometric strength of the non-dominant arm) was assessed in the entire cohort, as well as Groups A and B.
3. A log-linear regression analysis was performed on the independent and dependent variables for Group A where $\log(\text{isometric strength}) = \text{intercept} + [(\text{slope of regression line}) \times \log(\text{BM or CSA})]$. The slope of the regression line was used as the allometric scaling exponent. So, for example, if we are using BM as the scaling variable, and the slope of the regression line is 0.67, then isometric strength would be scaled as $\text{isometric strength}/\text{BM}^{0.67}$.
4. Distribution of residuals and the assumption of homoscedasticity were tested by the Anderson–Darling Normality Test, Breusch–Pagan/Cook–Weisberg Test, and visual inspection. The residual errors should demonstrate a constant variance (homoscedasticity) and a normal distribution indicating that the model fits all individuals across the entire range (Nevill and Holder 1995).
5. Independence of the power ratio (allometrically scaled strength) and independent variables were assessed. For an allometric model to be deemed appropriate, there should be no significant correlation between the allometrically scaled strength measurement and the independent variable.
6. Step 5 was repeated on Group B using the same criterion of appropriateness of fit. The newly derived scaling exponents were applied to Group B and evaluated as an “internal test” or cross-validation. Again, there should be no significant correlation between the allometrically scaled strength and the independent variable.
7. If either of the models did not meet all of the criteria, the entire cohort was divided by BMI (normal weight BMI $< 25 \text{ kg m}^{-2}$ vs. overweight/obese BMI $\geq 25 \text{ kg m}^{-2}$) and new models developed fit and tested to assess the influence of BMI.
8. To test the influence of excess adiposity on isometric muscular strength (and assuming the CSA model met all statistical criteria) the cohort was separated by BMI as in Step 7 and between-group difference in isometric strength assessed with an unpaired t test.
9. Significance levels were two-sided with $\alpha = 0.05$ for all analyses.

Results

The descriptive characteristics for groups A and B are presented in Table 1. Descriptive data are also presented for participants divided by BMI classification (normal weight vs. overweight/obese). Briefly, group A was taller and stronger than group B. Overweight/obese women were heavier, stronger, and had a larger CSA than women of normal weight. Anderson–Darling normality tests showed that the isometric strength values for the entire cohort, as well as all subgroups, were normally distributed ($P > 0.05$ for all).

Body mass as a scaling variable

Log-linear regression analysis using BM as the independent variable was applied to Group A resulting in a scaling exponent of 1.08 (Fig. 1). The Breusch–Pagan/Cook–Weisberg test for heteroscedasticity was performed, and the residual errors from the BM model in group A were found to be randomly distributed or homoscedastic ($P = 0.417$). The test of the independence of the power ratio (Fig. 2) was non-significant ($P = 0.491$). However, visual inspection of the residuals and the histogram of residuals revealed an apparently greater proportion of positive residuals. This was confirmed by the Anderson–Darling normality test of the residuals distribution ($P = 0.002$). As such, the use of BM as a scaling variable was unsuccessful; not meeting all of the statistical criteria.

CSA as a scaling variable

The independent variable CSA yielded a scaling coefficient of 0.44 for group A, based on log-linear regression analysis (Fig. 1). The group A CSA model was non-significant ($P = 0.168$) for the Breusch–Pagan/Cook–Weisberg test for heteroscedasticity and for the independence test of the power ratio (Fig. 2). Visual inspection of residuals showed no systematic variation, which was confirmed by the Anderson–Darling normality test indicating that the residuals were normally distributed ($P = 0.10$). Therefore, unlike the BM model, the CSA model met all statistical criteria in group A.

Cross-validation of the models

The newly derived scaling exponents were applied to Group B and evaluated using the independence of the power ratio as the criterion. Log-linear regression analysis demonstrated a significant correlation ($P = 0.023$) between Group B's BM variable and the newly scaled isometric strength (Fig. 3) indicating that the BM exponent derived from group A did not completely remove the influence of BM on isometric strength. It is important to remember that the BM model did not meet all statistical criteria for group A, either.

In contrast, the CSA model met all statistical criteria when applied to group B, with no correlation ($P = 0.195$) between group B's CSA variable and the newly scaled isometric strength (Fig. 3). Visual inspection of the residuals and the histogram of residuals revealed no systematic variation as well as a normal distribution of the residuals for the CSA model. The Anderson–Darling normality test also found the residuals of the group B CSA model to be normally distributed ($P = 0.80$).

Evaluating the influence of BMI on BM as a scaling variable

Body mass as a scaling variable was unsuccessful because it did not meet all statistical criteria (group A) nor did it completely remove the effect of body mass on isometric strength (group B). To evaluate the influence of BMI, a new allometric scaling model was developed and tested on the entire cohort. The model produced a scaling exponent of 0.91 (Fig. 4) which was similar to that developed from group A (1.08). However, this scaling exponent also failed to meet all statistical criteria, specifically the Anderson–Darling normality test ($P = 0.034$).

The entire cohort was then segregated by BMI [$<25 \text{ kg m}^{-2}$ ($n = 139$) vs. $\geq 25 \text{ kg m}^{-2}$ ($n = 44$)] and models developed for both groups. The models yielded scaling exponents of 1.48 and 0.35 for women with a BMI < 25 and $\geq 25 \text{ kg m}^{-2}$, respectively and, most importantly, both models passed all statistical tests.

Comparing isometric biceps strength of normal weight versus overweight/obese women

As indicated in Table 1, compared with women of normal weight, absolute isometric biceps strength of the non-dominant arm was significantly greater in those classified as overweight/obese. Cross-sectional area of the biceps of the non-dominant arm was also significantly greater in overweight/obese women. When expressed relative to CSA, isometric biceps strength was not significantly different between women of normal weight and those who were overweight/obese (mean peak force $\text{CSA}^{-1} \pm \text{SEM} = 24.5 \pm 0.69$ vs. $26.8 \pm 1.5 \text{ N cm}^{-2}$, $P = 0.163$). However, allometrically scaled isometric biceps strength, with CSA as the scaling variable, was significantly greater ($P = 0.010$) in overweight/obese women compared with normal weight women (mean $\pm \text{SEM} = 110.9 \pm 5.2$ and $96.0 \pm 2.2 \text{ N CSA}^{-0.44}$, respectively).

Discussion

The most striking findings of this study were that (1) BMI exerted an apparent influence on the relationship between BM and allometrically scaled isometric strength in women, (2) the contribution of BM to allometrically scaled strength, as determined from the slope of the regression lines, and therefore the scaling exponents, was greater in women of normal weight compared to those who were overweight/obese, and (3) isometric strength relative to CSA (N CSA^{-1}) was not significantly different between women of normal weight and those who were overweight/obese but, (4) allometrically scaled strength, using CSA as the criterion variable, was significantly greater in overweight/obese women compared to those of normal weight.

Measurement of isometric strength

As indicated previously, the intraclass correlation for the two measurement trials was calculated at 0.90. The absolute mean $\pm \text{SD}$ for trials 1 and 2 were 669.34 ± 204.13 and $683.06 \pm 200.60 \text{ N}$, respectively. Using the methodology of Nevill and Atkinson (1997), the mean difference $\pm \text{SD}$ between the two trials was calculated as $14.41 \pm 93.79 \text{ N}$ with a 95% “confidence interval” of -169.44 to 204.92 N . While this SD is relatively large, representing 13.9% of the mean of the two trials (675.22 N), it is well within the range presented by

Nevill and Atkinson. Specifically, of the 16 examples of “measurement agreement” involving measurements of muscular strength, the present data showed greater test–retest variability than ten, but lesser variability than six of these examples. Further, the variability shown presently (13.9% of the mean of the two trials) was lower than the weighted mean variability of 19.5% ($n = 266$) from the examples presented. Finally, the distribution of the difference scores was normal and random, indicating no measurement bias.

The influence of BMI on the relationship between BM and isometric strength

Allometric scaling of isometric biceps strength produced very different scaling exponents for normal weight women compared with those who were overweight/obese (1.48 vs. 0.35, respectively). These exponents are, by definition, the slope of the log-linear regression lines and indicate that as BM increased across the range of BMI, the contribution of BM to isometric strength was over four times greater for women of $\text{BMI} < 25 \text{ kg m}^{-2}$ compared with those with $\text{BMI} \geq 25 \text{ kg m}^{-2}$. The scaling exponent derived for normal weight females is much greater than that predicted by the theory of geometric similarity. To our knowledge, there are no studies that have examined the relationship between body mass and allometrically scaled strength in untrained women of normal weight. Therefore, it is not possible to discuss our results in light of previous work. These data, however, do suggest that other factors such as voluntary muscle activation/coactivation, as discussed below, may influence the relationship between muscle strength and body mass in this population. Regardless, these findings are consistent with the premise that the relative contribution of FM is greater than that of FFM in women who are overweight/obese.

Even in males, a very recent study found that adiposity influenced the allometric scaling of isometric knee extensor strength (Folland et al. 2008). Allometric scaling exponents using BM as the scaling variable were developed for 86 young men with no history of strength training. The cohort was split into two groups based on percent body fat measured by skinfolds. The percent body fat for the lean group ranged from 9.1 to 20.7% and 20.8 to 38.2% for the “adipose half”. Consistent with the present study, the scaling exponent for the lean group was considerably greater compared with the “adipose” group (0.68 vs. 0.45).

Lafortuna et al. (2004, 2005) examined gender differences in body composition, muscle strength and power in two similar but separate studies. In the first study, the relationship between body composition and muscular power was examined in 377 obese individuals. As BMI increased across the range in males, the contribution from FM and FFM was essentially equivalent (49 and 51%, respectively). In females, however, the contribution of FM was more than three times greater than that for FFM (76.8 vs. 23.3%, respectively). Further, there were gender differences in the trends in FM and FFM across the range of BMI. In males, the trends for FM and FFM, as indicated by the slope of the regression lines, were similar with slopes of 1.31 and 1.61, respectively. In females, however, the trends were very different with slopes of 2.23 for FM and 0.23 for FFM. In addition, while the relationship between BMI and FFM was statistically significant, it was very weak as indicated by an R^2 of 0.0495.

In a subsequent study (Lafortuna et al. 2005), this same group examined these relationships in 95 adults. Total volume of FFM was greater in obese versus non-obese participants for

both genders. In obese males, greater BM was due to “similar contributions from fat and fat-free mass but mainly contributed by FM in female subjects”. Specifically, as BM increased in males, the increase in was roughly 50/50 for FM and FFM. In females, the increase in BM was 75% FM and only 25% FFM. As BMI increased from 35 to 55 kg m⁻², the increase in the ratio of FM to FFM (FM/FFM) in the obese women was four times that observed for obese men.

Sartorio et al. (2004) explored the influence of gender, age and BMI on lower limb muscular power output in a relatively large population of obese men and women. As BM increased, the contribution from FM and FFM was 50/50 for males but was 79/21 for females. The authors observed that for the same amount of FFM, women have a greater total body weight and BMI.

These studies, in conjunction with the findings of the present investigation, suggest that allometric scaling of isometric strength using BM is influenced by the greater relative contribution of FM with increasing BMI, especially in women. As such, allometric scaling models of isometric strength, especially in populations that are heterogeneous with regard to body composition, must be carefully tested and examined across the range of BMI.

Allometric scaling as a means to explore the influence of BMI on muscular strength with emphasis on CSA

Based on limited and primarily anecdotal evidence, it has been suggested that increased adiposity may impair muscle function and strength. In general, absolute strength is greater in overweight or obese individuals while lower when expressed relative to BM (Blimkie et al. 1990; Maffiuletti et al. 2007; Pescatello et al. 2007). When strength is expressed relative to FFM, several studies have shown no strength differences between individuals of normal weight versus those who are overweight or obese (Lafortuna et al. 2005; Maffiuletti et al. 2007). Strength relative to CSA, especially as impacted by adiposity in females, has not been extensively investigated. In addition, very few studies have employed an allometric approach to this question.

Presently, absolute isometric strength was greater in overweight/obese women compared with those of normal weight ($P < 0.05$). Relative to BM, values for isometric strength were lower for obese/overweight women compared to those who were of normal weight ($P < 0.05$). However there was no group difference in isometric strength relative to CSA ($P > 0.05$). Finally, allometrically scaled isometric strength, using CSA as the scaling variable, was actually greater in overweight/obese women compared with those of normal weight.

The relationship between CSA and absolute isometric strength in the present investigation, while significant, was admittedly not strong, with an $R^2 = 0.0779$. Previously, we reported a much stronger relationship between CSA and isometric biceps strength in a subset of males from the FAMuSS study ($n = 136$, $R^2 = 0.33$, $P < 0.05$) (Zoeller et al. 2007). Hulens et al. (2001) reported weak but significant associations between FFM and isometric handgrip strength in 173 obese and 80 lean women with R^2 values of 0.078 and 0.12, respectively. These very limited data suggest that the relationship between CSA and/or FFM and

isometric strength in women may not be as strong as that for men. However, it is not possible to draw any conclusions at this time.

Pescatello et al. (2007) used another subset of FAMuSS participants to examine the impact of adiposity as assessed by BMI on the muscle size and strength changes resulting from 12 weeks of unilateral biceps resistance training. Baseline/pre-training measures of isometric biceps muscle strength and CSA were not reported by gender but for the entire cohort. As demonstrated in the present investigation, absolute isometric biceps strength was significantly greater in individuals who were overweight/obese compared to those of normal weight. Relative to BM, however, muscular strength was significantly lower for the overweight/obese group. Allometric scaling of isometric strength using BM as the scaling variable was also applied. However, rather than develop and test an allometric model as in the present investigation, a scaling exponent of 0.67 (based on the theory of geometric similarity) was applied but not tested. As such, it is difficult to draw any conclusions from these data.

In that same study, CSA was also greater in the overweight/obese group but there was no difference between the normal weight and overweight/obese groups when isometric strength was normalized for CSA; all of which is consistent with the present study. Unfortunately, there was no attempt to generate an allometric scaling model using CSA as the scaling variable nor was the association between CSA and isometric biceps strength reported.

Hulens et al. (2001) employed an allometric approach to study differences in isometric handgrip strength of lean versus obese women. Absolute handgrip strength was not significantly different between groups but was significantly lower in the obese women when expressed relative to BM. After allometrically correcting for FFM, handgrip strength was 10–16% lower in obese women compared with their lean counterparts ($P < 0.05$). However, the scaling exponents derived for obese and non-obese women were 1.07 and 0.36, respectively. These exponents indicate that as BM and FM increased, the contribution of FFM to handgrip strength also increased. This is not only in contradiction with the present study but with the findings of Lafortuna et al. (2005) and Sartorio et al. (2004), which were discussed earlier. Further, it is not clear if the authors tested their models for appropriateness of fit.

Blimkie et al. (1990) investigated group differences in voluntary strength (isometric knee extension) between 10 obese and 11 non-obese adolescent males who were matched for age, level of maturity, FFM and height. Strength measurements were normalized for BM and the product of muscle CSA and height (ht). Allometric scaling was not used in this study. Absolute isometric knee extensor strength was not different between groups but lower for obese adolescents when normalized for BM. When normalized for $\text{CSA} \times \text{ht}$, there was again no difference between groups in isometric strength. It is important to note that there was also no group difference in quadriceps CSA, which could be misleading. The muscle fibers of the knee extensors/quadriceps muscles are pennate in their structural arrangement and, as such, pennation angle may confound the apparent relationship between force, CSA and force CSA^{-1} (Ikegawa et al. 2008).

Arguably the most unique finding of the present study was that isometric biceps strength was greater in overweight/obese women compared with those who were of normal weight after allometrically controlling for CSA. While it is beyond the scope of this study to identify the mechanisms for this apparently greater muscle strength, there are several potential factors which may have played a role. It has been previously demonstrated that gross measures of CSA do not account for levels of intramuscular fat associated with overweight and obesity. Newham et al. (1998) examined isometric knee extensor strength, contractile properties (force/frequency, relaxation rate, fatigability), and quadriceps muscle fat content before and 1 year after gastrectomy (mean weight lost = 38.6 kg). Fat content of the quadriceps as well as CSA were reduced 1 year after surgery but with no change in strength or contractile properties. While CSA was significantly reduced after gastrectomy, it was due almost entirely to loss of intramuscular fat and not contractile tissue. The authors concluded that intramuscular fat associated with obesity may confound the relationship between CSA and measured muscular strength. As such, a simple measure of CSA, as used in the present investigation, may not be representative of the CSA of contractile tissue, especially in women who are obese.

Another important variable that may, at least in part, provide some explanation for greater strength in overweight/obese women after controlling for CSA is muscle fiber composition. A number of investigations have reported a positive association between percent or CSA of type 2 muscle fibers and adiposity in both humans and animals (He et al. 1995; Heige et al. 1999; Hickey et al. 1995; Kriketos et al. 1997; Wade et al. 1990). Again, a simple measure of CSA does not account for the type or relative CSA of skeletal muscle fibers.

Other factors that may have contributed to these findings were possible differences in percent voluntary muscle activation level and/or coactivation during the isometric strength assessments (Allen et al. 1995). For example, Allen et al. (1995) reported that during a maximal voluntary contraction (MVC), voluntary activation ranged from 70 to 100% for the forearm flexors. Given the purpose of our study, to simply explore the influence of BMI on allometric scaling of isometric biceps strength using a statistical model, there was no attempt to measure muscle activation and so we can only speculate about its impact. These measurements are typically obtained with the use of surface electromyography (EMG) and the twitch interpolation technique. However, it has been documented that the increased subcutaneous fat associated with overweight/obesity may confound the relation between EMG amplitude and force (Farina et al. 2004). Future studies exploring the impact of increased adiposity on muscle function should seek to measure voluntary activation/coactivation and other neural contributions to muscle force while controlling for differing levels of subcutaneous fat.

Finally, while the muscles of the upper limbs are sometimes referred to as “non-weight-bearing”, it is possible that chronically transporting and moving the excess subcutaneous fat (and therefore weight) of the arms associated with overweight/obesity may have resulted in a greater strength independent of muscle CSA.

The use of biceps brachii: advantages and disadvantages

It is important to note that the present study developed allometric scaling models and evaluated the influence of BMI on allometrically scaled isometric strength using a small, fusiform muscle mass. While the authors concede that this may limit the generalizability of these results, we also believe that it may also have a number of inherent advantages. As discussed above, the upper limbs are often classified as non-weight-bearing. Compared to the larger weight-bearing muscles of the lower limbs, it was anticipated that the biceps would not be as susceptible to the potential confound (i.e., training effect) of carrying excess body/fat mass as BMI increases across the range. The biceps brachii are fusiform in structure and, as such, may allow for a more valid assessment of the relationship between isometric strength and anatomical CSA compared with large, pennate muscles such as the knee extensors as discussed above (Bruce et al. 1997; Ikegawa et al. 2008).

Summary

Allometric scaling models of isometric biceps strength were developed, tested, and cross-validated in a cohort of 183 untrained adult females (aged 18–39 years) using BM and CSA as the scaling variables. The CSA model met all statistical criteria and produced a scaling exponent of 0.44. The BM model did not meet these criteria until the entire cohort was separated by BMI. The scaling exponents for the normal weight women and those who were overweight/obese were 1.48 and 0.35, respectively. Additionally, the contribution of BM to allometrically scaled strength was greater in women of normal weight compared to those who were overweight/obese. The results of previous studies suggest that these findings can be explained by the greater contribution of FM to BMI in overweight and especially obese women. These data suggest that BMI exerted an apparent influence on the relationship between BM and allometrically scaled isometric strength. As such, allometric scaling models of isometric strength, especially in populations that are heterogeneous with regard to body composition, must be carefully tested and examined across the range of BMI.

Isometric strength relative to CSA ($N \text{ CSA}^{-1}$) was not significantly different between women of normal weight and those who were overweight/obese. However, allometrically scaled strength, using CSA as the criterion variable, was significantly greater in overweight/obese women compared to those of normal weight. These data suggest that isometric strength in women is not completely determined by CSA and that other factors such as intramuscular fat and muscle fiber type may be confounding or contributing factors.

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Fig. 1. Log-linear regression analysis of Group A isometric biceps strength (N) using BM (kg, *top panel*) and CSA (cm², *bottom panel*) as independent variables

Fig. 2.
Test of the independence of the power ratio for Group A BM (*top panel*) and CSA (*bottom panel*) models

Fig. 3. Test of the independence of the power ratio for Group B BM (*top panel*) and CSA (*bottom panel*) after applying scaling exponents derived from Group A

Fig. 4.

Log-linear regression analysis of isometric biceps strength (N) using BM (kg) for the entire cohort (*top panel*), normal weight women (*center panel*), and overweight/obese women (*bottom panel*)

Table 1

Descriptive characteristics for groups A ($n = 92$), B ($n = 91$), normal weight group ($\text{BMI} < 25 \text{ kg m}^{-2}$, $n = 139$), and overweight/obese group ($\text{BMI} \geq 25 \text{ kg m}^{-2}$, $n = 44$)

	Group A	Group B	BMI < 25	BMI ≥ 25
Age (years)	24.5 ± 0.6	24.3 ± 0.6	23.9 ± 0.5	26.1 ± 1.1
Body mass (kg)	63.7 ± 1.0	62.4 ± 1.2	58.6 ± 0.5	$77.1 \pm 1.4^*$
Height (cm)	166.0 ± 0.7	$163.4 \pm 0.6^\#$	164.9 ± 0.5	163.0 ± 1.0
ND isometric strength (N)	318.5 ± 9.8	284.2 ± 7.8	287.1 ± 6.9	$346.9 \pm 15.7^*$
ND biceps CSA (cm^2)	12.4 ± 0.3	12.6 ± 0.3	12.1 ± 0.2	$13.7 \pm 0.5^*$

Values are means $\pm$ SEM

ND non dominant arm

* Significant difference ($P < 0.05$) between BMI <25 and BMI ≥ 25

[#] Significant difference ($P < 0.05$) between Group A and B