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ORIGINAL ARTICLE

Allometric scaling of strength measurements to body size

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Abstract For comparative purposes, normalisation of strength measures to body size using allometric scaling is recommended. A wide range of scaling exponents have been suggested, typically utilising body mass, although a comprehensive evaluation of different body size variables has not been documented. Differences between force (*F*) and torque (*T*) measurements of strength, and the velocity of measurement might also explain some of the variability in the scaling exponents proposed. Knee extensor strength of 86 young men was assessed with measurement of torque at four velocities (0–4.19 rad s^{-1}) and force measured isometrically. Body size variables included body mass, height and fat-free mass. Scaling exponents for torque were consistently higher than for force, but the velocity of torque measurement had no influence. As the confounding effects of fat mass were restricted, scaling exponents and the strength of the power-function relationships progressively increased. Fat-free mass determined a surprisingly high proportion of the variance in measured strength (*F*, 31%; *T*, 52–58%). Absolute force and torque measurements, and even torque normalised for body mass, were significantly influenced by height, although strength measures normalised to fat-free mass were not. To normalise strength measurements to body mass, for relatively homogenous lean populations (body fat <20%), exponents of 0.66 (*F*) and 1.0 (*T*) are appropriate. For more adipose populations (body fat >20%) lower body mass exponents appear more suitable (*F*, 0.45; *T*, 0.68). Nevertheless, fat-free mass is the recommended index for scaling strength to body size, and higher exponents (*F*, 0.76; *T*, 1.12) are advocated in this case.

Keywords Muscle strength · Force · Torque · Body mass · Fat-free mass · Height

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Introduction

Muscle strength is a parameter of physical fitness and muscle function that is commonly evaluated in exercise, sport and medical science. One issue in comparing the strength measured in large populations is allowing for the effect of body size. Body size is a factor well known to exert a substantial influence on muscle strength, but how strength measurements should be normalised for differences in body size remains the subject of some debate (Jaric 2002). Hence this topic has practical application when comparing the strength values of large groups or populations of variable body size. Furthermore, the question of how strength changes with body size is also of interest, and may enhance our understanding of the determinants of muscle strength.

Ratio standards, where strength is divided by body mass or an alternative index of body size, have frequently been used in an attempt to remove the effect of the body size variable (Nevill et al. 1992). This simplistic approach assumes that strength is directly proportional to the body size variable (i.e. body mass). Allometric scaling, has been widely recommended (Davies and Dalsky 1997; Jaric 2002) and is based on the principle of geometric similarity. Specifically, dividing strength by the body size variable raised to an appropriate power has been theorised to eliminate the effects of the body size variable (Sholl 1948) e.g. for absolute strength (*S*) and body mass (BM) values: Normalised strength = S/BM^b where *b* is the allometric power exponent that removes the influence of BM. This method is regarded as more appropriate for the scaling of strength to body size than ratio standards (Astrand and Rodahl 1986).

Studies examining the relationship between strength and body size have found allometric exponents that provide body mass-independent indices of strength that range from 0.36 to 1.39 (Nevill et al. 1998; Jaric et al. 2002a). Research on the influence of body size upon strength has often used a wide range of ages, including either children or an older population, where anthropometry may not be the only independent variable. More importantly, however, the method of strength measurement employed could be crucial, but has only been investigated in a single study to date (Jaric et al. 2002a). Jaric et al. (2002a) proposed that different body mass exponents should be used depending upon whether strength has been recorded as a force (*F*) or torque (*T*) measurement. These authors theorised that as body size changes the lever arms of the muscle and external resistance would change in proportion, and therefore force output (*F*) would be proportional to muscle force (Fm) i.e. $F \propto \mathrm{Fm}$. As Fm depends on the physiological cross-sectional area of the muscle, then $F \propto \mathrm{BM}^{2/3}$. In contrast, *T* depends upon Fm multiplied by the lever arm of the muscle (la), which as with any length will vary with $\mathrm{BM}^{1/3}$. Thus $T = \mathrm{Fm} \times \mathrm{la} \propto \mathrm{BM}^{2/3} \times \mathrm{BM}^{1/3} = \mathrm{BM}$, and theoretically an allometric exponent of 1 or a ratio standard may be fitting in this case. These authors went on to calculate the scaling exponents for force and torque measurements from six different exercises. Broadly their findings supported the theory, but with wide variation across the exercises (*F*, mean BM exponent 0.67, range 0.45–0.97; *T*, mean BM exponent 1.02, range 0.41–1.39) possibly due to the small number of subjects and broad age range (Jaric et al. 2002a).

It has been observed that rapid movements of either body limbs or of the entire body are unaffected by differences in body size (Astrand and Rodahl 1986). This might suggest use of a power function exponent of close to 0 for these tasks as no normalisation is required. If this were the case it might be expected that as joint angular velocity increases the influence of body size on torque would diminish. Alternatively, in the dynamic situation, as angular velocity increases above zero, torque is dependant on muscle power (Pm) multiplied by the lever arm of the muscle (la). As muscle power is the product of muscle force and velocity (*v*), it depends not only on the cross-sectional area (a geometric index of Fm, as above), but also the velocity of contraction. In geometric terms, the velocity of contraction is influenced by the length of the muscle i.e. $\mathrm{BM}^{1/3}$. In this dynamic situation, therefore, it is possible that $T = \mathrm{Pm} \times \mathrm{la} = \mathrm{Fm} \times v \times \mathrm{la} \propto \mathrm{BM}^{2/3} \times \mathrm{BM}^{1/3} \times \mathrm{BM}^{1/3} = \mathrm{BM}^{4/3}$, and body size could have a greater influence on *T* at high velocities than for isometric measurements.

Scaling strength values for differences in overall body mass, with either ratio standards or allometry, does not account for differences in body composition, which can be considerable. As adipose tissue does not contribute to force or torque production lean or fat-free mass (FFM) might be expected to be a stronger determinant of strength, and provide a more effective body size variable for normalisation of strength values. This issue has received little attention, however, and has not been considered in relation to force and torque normalisation. Another issue we have observed, albeit anecdotally, is that height (*H*) may influence strength performance. Whether this is simply a consequence of increasing body mass or an independent effect is unknown. The only evidence we are aware of suggests a low allometric exponent for height normalisation of force data (1.06–1.23, Nevill et al. 1998). As force is proportional to muscle cross-sectional area (CSA), it might be expected to be related to H^2, and as torque is related to muscle CSA multiplied by lever arm length, it might be expected to be related to H^3. It is possible therefore that height exerts a separate and distinct influence on force and torque, in addition to body mass, or due to the close association of height and body mass, this may not be the case.

This study had three aims: (1) to examine in more detail the body mass exponents for scaling *F* and *T* strength measurements, and whether the angular velocity at which torque was measured affected the influence of body mass on strength; (2) to explore the scaling exponents for *F* and *T* when fat-free mass was used as the criterion measure of body size; (3) to examine the influence of height on strength measured as *F* and *T*.

Methods

Participants

Eighty-six healthy young men aged 18–30 years (Mean ± SD: 20.1 ± 2.2 years) volunteered to participate in this study and provided written informed consent. The study had local ethics committee approval, and the participants were recruited from University students and staff. They had no history of strength training and were free from locomotor or neuromuscular disease. Participants were required to have a low or moderate level of physical activity (<4 sessions of exercise per week). This was assessed by having participants estimate their weekly time spent performing vigorous and moderate physical activity.

Anthropometric assessment

Participants' height was measured with a wall-mounted stadiometer (Holtain Ltd, Crymych, Wales). Body mass was measured with a beam balance scale (Avery Ltd, Fairmont, MN) with subjects wearing shorts and a T-shirt. Skinfold thickness was measured at four sites (biceps, triceps, iliac crest [termed 'suprailiac' by Durnin and Womersley (1974)] and subscapular) using Harpenden skinfold callipers (British Indicators Ltd, Wolverhampton, UK). All these measurements were done by the same investigator according to International Society for the Advancement of Kinanthropometry guidelines (Hawes and Martin 2001). From the sum of four skinfolds, body density was calculated using the formula for males aged 20–29 years of Durnin and Womersley (1974) and percentage body fat estimated using the Siri (1956) equation. Fat mass and fat-free mass (FFM) were derived from the percentage body fat and body mass values.

Strength measurements

Before strength was measured, participants performed a warm-up of 5 min duration on a cycle ergometer (Monark 818E) at 50 W. All measurements took place between 1400 and 1800 hours and participants were asked to refrain from strenuous exercise in the 36 h before the test. Both legs of each participant were tested, and this was done unilaterally for maximum isometric force and peak torque at a range of velocities [0 (isometric), 0.52, 1.57 and 4.19 rad s^{-1} (30, 90 and 240° s^{-1})]. Biofeedback and loud verbal encouragement were provided throughout all strength measurements. The full range of measurements were repeated on two occasions ~7 days apart.

Isometric force measurements of the knee extensors were made using a conventional strength-testing chair (Parker et al. 1990) with participants seated in an upright position with the back supported. Hip and knee angles were 1.73 rad (100°) and 1.57 rad (90°), respectively. Participants were firmly secured with straps around the waist and shoulders, and their lower leg strapped to a calibrated U-shaped aluminium strain gauge (Jones and Parker 1989) with a linear response up to 850 N. The strain gauge was positioned directly perpendicular to the tibia. The strain gauge signal was sampled at 2,000 Hz with an analogue to digital converter (Micro 1401, Cambridge Electronic Design, Cambridge, UK) and recorded by PC with Spike 2 software (Cambridge Electronic Design, Cambridge, UK). Following some progressive sub-maximal contractions, maximum isometric force was determined by having participants perform three or four maximum voluntary contractions of the knee extensors, each of ~3 s duration and with 30 s between each contraction. The coefficient of variation (CV) for maximum isometric force over repeated test occasions was 3.3%.

For torque measurements, participants were seated in a Cybex Norm Isokinetic Dynamometer (Lumex Inc, NY, USA) with the axis of the knee joint aligned with the centre of rotation of the dynamometer arm, and the lower leg strapped to the lever arm just proximal to the ankle. Participants were restrained at the waist, shoulders and the distal part of the thigh, and the backrest was set at 1.73 rad (100°) from the horizontal base of the seat. Peak torque was assessed isometrically at 1.27 rad (73°) of knee flexion (the angle of peak torque) and isokinetically at 0.52, 1.57 and 4.19 rad s^{-1} (30, 90 and 240° s^{-1}). For isometric measurement, there were three practice contractions at 50% effort followed by three maximum voluntary contractions. For the isokinetic measurements, participants performed three practice trials of sub-maximal knee extension at each angular velocity, before at least three maximum contractions. For the repeated maximum contractions, the highest value was used as the representative figure for that occasion. There was at least 30 s rest between the practice and maximum contractions, and ~60 s between velocities. The range of motion for the isokinetic measurements was from 2.09 to 0.26 rad (120° to 15°) of knee flexion. Knee extensor torque was corrected for gravitational torque and contractions at the highest velocity (4.19 rad s^{-1}) were isovelocity for at least the range 1.57–0.52 rad (90°–30°). The CV for the measurement of torque at different velocities over repeated test occasions ranged from 5.3 to 6.3%.

Data analysis

Strength values from both legs measured on each occasion were averaged to provide representative values for each individual. The normality of this individual data was assessed by calculating skewness and kurtosis, and application of the Shapiro–Wilk test. The relationship between a strength measure (x) and a body size variable (y) was analysed using the standard allometric technique. Briefly, by applying linear regression to the logarithmic transformation of both x and y:

$$\ln(y) = \ln(a) + b \times \ln(x)$$

where $\ln(a)$ is the intercept and the slope b is equal to the exponent of the power function $y = ax^b$. The appropriateness of the model was evaluated. First for homoscedasticity and normal distribution, by visual inspection of the residuals, calculation of their skewness and kurtosis and a Shapiro–Wilk test of the normality of their distribution. Second, the independence of the power ratio (allometrically scaled strength) from the independent variable (i.e. BM, *H* or FFM) was assessed by correlation, with a lack of significance indicating linear independence. Data were analysed using SPSS v13 and expressed as mean ± SD. Significance was accepted at the level $P < 0.05$.

Results

On average participants were 1.79 ± 0.06 m tall (range 1.64–1.95 m), had a body mass of 75.3 ± 10.8 kg (50.5–113.4 kg) including 58.1 ± 6.3 kg FFM (40.8–70.8 kg) and 22.2 ± 5.3% body fat (9.1–38.2%). Participants typically performed 2.0 ± 1.3 h of vigourous physical activity per week, with no relationship between physical activity and body size, composition or strength measurements. Maximum isometric knee extension force was 615 ± 90 N and peak knee extension torques were 250 ± 41 Nm (isometric), 203 ± 32 Nm (0.52 rad s^{-1}), 171 ± 26 Nm (1.57 rad s^{-1}), 119 ± 19 Nm (4.19 rad s^{-1}). The dependent variables (strength measures) were normally distributed for the whole sample and both adipose and lean sub-samples (Shapiro–Wilk, $P > 0.09$).

Body mass as a scaling variable

There was a significant power function relationship between body mass and isometric force ($R^2 = 0.09$, $P = 0.004$) with an exponent of 0.33 (Table 1). All measures of torque showed stronger power function relationships with body mass ($R^2 = 0.31$–0.38, all $P < 0.001$) that were similar, irrespective of the angular velocity at which torque was measured, with a mean exponent for the torque measurements of 0.69 (range 0.66–0.75). In fact, the relationships (and power function exponents) between the different torque measurements and each of the anthropometric variables were consistent, and showed no clear pattern with increasing velocity.

Each of these power function models were appropriate with homoscedastic residuals that showed no skewness or kurtosis and were normally distributed (Shapiro–Wilk, $P > 0.45$). In addition, independence tests of these power functions were not significant ($P > 0.68$).

Scaling for body mass with the sample divided into lean and adipose halves

For the whole group, the proportion of fat mass ranged from 9.1 to 38.2% (6.4–43.3 kg). When strength data for only the leaner half of the participants ($n = 43$; 9.1–20.7% body fat) was related to body mass, higher exponents were found for force (0.68, $R^2 = 0.22$, $P = 0.003$) and torque (mean 0.98; range 0.88–1.16; $R^2 = 0.32$–0.44, all $P < 0.001$) compared to the whole sample. When strength data for only the more adipose half of the participants ($n = 43$; 20.7–38.2% body fat) was related to body mass, however, exponents for force (0.45, $R^2 = 0.17$, $P < 0.01$) and particularly torque (mean 0.68; range 0.65–0.73; all $P < 0.001$) were similar to that of the whole sample. The power function models for both sub-samples (lean and adipose halves) were appropriate with homoscedastic residuals that were normally distributed (no skewness or kurtosis; Shapiro–Wilk, $P > 0.08$), and independence tests of these power functions that were non-significant ($P > 0.78$).

Scaling for fat-free mass

Use of fat-free mass as the body size variable produced even higher exponents for force (0.76; $R^2 = 0.31$, $P < 0.001$) and torque (mean 1.12; range 1.08–1.16; $R^2 = 0.52$–0.58, all $P < 0.001$). Hence, fat-free mass determined on average

Table 1 Allometric power function exponents for different measures of body size, with coefficients of determination (R^2) in parentheses

Body size variable	Force Isometric	Torque				
		Isometric	Isokinetic 0.52 rad s^{-1}	Isokinetic 1.57 rad s^{-1}	Isokinetic 4.19 rad s^{-1}	Mean
BM, $n = 86$	**0.33 (0.09)**	0.68 (0.31)	0.66 (0.32)	0.66 (0.36)	0.75 (0.38)	**0.69**
BM, adipose half of sample, $n = 43$	**0.45 (0.17)**	0.65 (0.30)	0.66 (0.34)	0.66 (0.37)	0.73 (0.35)	**0.68**
BM, lean half of sample, $n = 43$	**0.68 (0.22)**	1.16 (0.44)	0.88 (0.32)	0.90 (0.39)	0.97 (0.40)	**0.98**
FFM, $n = 86$	**0.76 (0.31)**	1.15 (0.53)	1.08 (0.52)	1.09 (0.58)	1.16 (0.55)	**1.12**
Height, $n = 86$	**0.92 (0.05)**	2.68 (0.31)	2.65 (0.34)	2.54[a] (0.34)	2.60[a] (0.30)	**2.62**

BM body mass (kg), *FFM* fat-free mass (kg), *H* height (m)

[a] Appropriateness of the power function calculated was questionable, due to non-normal distribution of the residuals

54% of the variation in knee extensor torque. These power function models were appropriate, with no significant skewness or kurtosis, normal distribution of the residuals (Shapiro–Wilk, $P > 0.08$) and independence of the power ratio ($P > 0.78$).

Scaling for height

There were significant power function relationships between height and isometric force with an exponent of 0.92 ($R^2 = 0.05$; $P = 0.04$), and height and torque measures with a mean exponent of 2.62 (range 2.54–2.68; $R^2 = 0.30$–0.34; $P < 0.001$). Although these models all showed independence of the calculated power ratio ($P > 0.67$), for isokinetic torque at 1.57 and 4.19 rad s^{-1} the residuals were not normally distributed (Z-skewness >2; Shapiro–Wilk $P < 0.05$) and hence the appropriateness of the models in these two cases was questionable.

When force measurements were normalised for body mass, there was no relationship with height ($R^2 = 0.004$, $P = 0.54$). However, for measurements of torque scaled to body mass there remained a significant influence of height ($R^2 = 0.09$–0.13; $P < 0.05$). In contrast, when either force or torque were scaled to fat-free mass there was no significant influence of height ($P = 0.11$–0.47).

Discussion

This study examined the relationship between, and the allometric scaling of, strength indicies (isometric force and torque at four velocities) with anthropometric variables (body mass, fat-free mass and height). The results revealed four main findings. First, allometric scaling exponents were substantially lower for the measurement of force than for torque, in accordance with previous findings (Jaric et al. 2002a). Second, the relationships between torque and body size variables (body mass, fat-free mass and height) was not influenced by knee joint angular velocity (similar exponents and coefficients of determination). Third, allometric scaling of strength to body mass, for a non-athletic population with a wide range of body composition, produced lower exponents (*F*, 0.33; mean of *T*, 0.69) than has been theorised (*F*, 0.66; *T*, 1.0). This appears to be due to heterogeneity in body composition and fat mass as power exponents for the adipose half of the sample (*F*, 0.45; *T*, 0.68) were lower than for the lean half of the sample (*F*, 0.68; *T*, 0.98), with the latter being similar to those expected. The most effective means of removing the influence of fat mass would seem to be scaling strength measures to FFM, and this produced even higher exponents (*F*, 0.76; *T*, 1.12). Fourth, absolute force and torque measurements, and even torque normalised for body mass, were significantly influenced by height, although strength measures normalised to fat-free mass were not.

The strength values recorded in this experiment were equivalent to previous reports of untrained healthy young men (Folland et al. 2000, 2005). Every effort was made to ensure that the participants made genuinely maximal contractions, and the reliability of the measurements was high (CV: 3.3% for force and 5.3–6.3% for torque). We deliberately attempted to avoid the potentially confounding effects of age, gender and chronic physical training in order to highlight the influence of body size upon strength. Therefore we recruited young male volunteers with no history of strength training and low to moderate levels of overall physical activity, which likely explained the wide variation in body composition. The range of activity levels that were included in this study were unrelated to body composition or muscular strength, suggesting physical activity did not confound the body size–strength relationships studied.

In agreement with the proposed theory and findings of Jaric et al. (2002a), the allometric power exponents when relating measurements of force to body mass were lower than for measurements of torque. The exponent values we found (*F*, 0.33; *T* mean 0.69), however, are substantially lower than 0.67 and 1.02 reported by Jaric et al. (2002a). In that study, the 16 participants are described as 'physically active' and likely had a more homogenous body composition, compared to the range of body fat values of our sample (9.1–38.2%). As fat mass makes no contribution to muscle function and strength this variation would be expected to confound the relationship between body mass and strength. It is not surprising, therefore, that when only the leaner 43 participants were considered we found stronger relationships between strength and body mass (higher R^2 values) with higher exponents (*F*, 0.68; *T* mean 0.98) that were very similar to the proposed theory and findings of Jaric et al. (2002a). The exponent for force we found with the leaner participants is also similar to those reported for a range of muscle groups with elite athletes (0.61, Jaric et al. 2002b) and the handgrip strength of young men (0.54, Vanderburgh et al. 1995), but distinct from that found with children aged between 8 and 17 years where age was a likely confounder (0.36–0.38, Nevill et al. 1998).

Further confirmation of the influence of adiposity on these relationships is provided by the data from the more adipose half of the participants (20.7–38.2% body fat), where exponents for force (0.45) and particularly torque (mean 0.68) are similar to that of the whole sample. It appears that some of the lower exponents in the literature might have been the product of variable body composition. Thus, when allometrically scaling force and torque strength recordings to body mass, exponents of 0.66 and 1.0, respectively, appear appropriate for relatively homogenous lean populations (body fat <20%), but for groups with a high proportion of fat mass (body fat >20%) lower exponents (F, 0.45; T, 0.68) are recommended.

As fat mass will always confound to some extent, it appears more meaningful to scale strength to fat-free mass. In this case, when the influence of fat mass was entirely excluded the relationships between the body size variable (fat-free mass) and strength became stronger (higher R^2 values) with larger exponents (F, 0.76; T, 1.12). We are aware of only two previous studies that examined the allometric scaling of strength to fat-free mass, both measured torque and reported similar exponents to those we found (0.94–1.31, Weir et al. 1999; 1.20, Davies and Dalsky 1997).

In the current study, fat-free mass accounted for more than half (54%) the variation in knee extensor torque, irrespective of velocity ($R^2 > 0.50$), and $\sim$30% of the variation in isometric force ($R^2 = 0.31$). In terms of isometric force, the strength of this relationship with fat-free mass is similar to findings in young men ($R^2 = 0.25$, Maughan et al. 1983; older men $R^2 = 0.25$, Bunout et al. 2004). Perhaps due to decline in function with age, or simply the variability in the age of their participants, a previous report did not find such high coefficients of determination for fat-free mass and knee extensor torque ($R^2 = 0.28$, Hulens et al. 2001). The coefficients of determination we found for torque from the relatively crude and non-specific measurement of fat-free mass were surprisingly high ($R^2 = 0.52$–0.58), and similar to those reported for specific muscle size indicies (e.g. CSA, volume) revealed by MRI ($R^2 = 0.44$–0.50, Holmback et al. 2003; Kanehisa et al. 1994). The strong relationship between torque and fat-free mass supports the hypothesis that torque is proportional to mass (m) ($T = \mathrm{Fm} \times \mathrm{la} \propto \mathrm{m}^{2/3} \times m^{1/3} = m$).

In this study, high velocity movements were influenced by differences in body size (body mass and fat-free mass) in a similar manner to isometric torque, with no suggestion that allometric exponents were declining as has been suggested for high velocity movements (Jaric 2003). During rapid isoinertial movements that require high angular accelerations, body size may not influence muscle function and performance as both muscle power ($\mathrm{Pm} = \mathrm{Fm} \times v \propto m^{2/3} \times m^{1/3} = m$) and the moment of inertia ($I \propto$ segment mass) change in proportion to BM. During isokinetic movements, however, this does not seem to be the case, although the hypothesised greater influence of body size at higher velocities (i.e dynamic $T \propto m^{4/3}$) was also not supported.

Strength measures (force and torque) were significantly related to height. The allometric exponent for force in relation to height was lower than expected (0.92), as it was hypothesised to be proportional to H^2 (i.e. muscle CSA), but similar to that found by previous research (1.06–1.23, Nevill et al. 1998). Why this exponent was less than half that expected is not known. With strength measured as a torque, the height exponent was 2.62 (range 2.54–2.68), and closer to the hypothesised value H^3, although no previous research has examined the allometric scaling exponent for torque measurement in relation to height. When force measurements were normalised for body mass, there was no relationship with height, but for torque measurements scaled to body mass there remained a significant influence of height. This discrepancy is likely because the measurement of torque in general is more strongly related to body size variables (body mass, fat-free mass and height), and the scaling for body mass (whole sample and relevant exponent) may not fully remove the influence of body size. This is supported by the fact that when strength (either force or torque) was normalised for fat-free mass there was no significant influence of height.

In conclusion, scaling exponents for torque were consistently higher than for force, but with no effect of the angular velocity at which torque was measured. There was a progressively greater influence of mass indicies on strength measurements as the confounding effects of body composition and fat mass were restricted. To normalise strength measurements to body mass for relatively homogenous lean populations (body fat <20%) exponents of 0.66 (F) and 1.0 (T) are appropriate. For more adipose populations (body fat >20%) lower body mass exponents appear more suitable (F, 0.45; T, 0.68). Nevertheless, fat-free mass is the recommended index for scaling strength to body size, and higher exponents (F, 0.76; T, 1.12) are advocated in this case.

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