Gender- and height-related limits of muscle strength in world weightlifting champions

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Ford, Lincoln E., Alvin J. Detterline, Kevin K. Ho, and Wenyuan Cao. Gender- and height-related limits of muscle strength in world weightlifting champions. J Appl Physiol 89: 1061–1064, 2000.—To assess factors that limit human muscle strength and growth, we examined the relationship between performance and body dimensions in the world weightlifting champions of 1993–1997. Weight lifted varied almost exactly with height squared (Ht2.16), suggesting that muscle mass scaled almost exactly with height cubed (Ht3.16) and that muscle cross-sectional area was closely correlated with body height, possibly because height and the numbers of muscle fibers in cross section are determined by a common factor during maturation. Further height limitations of muscle strength were shown by only one male champion ≥183 cm and no female champions ≥175 cm. The ratio of weight lifted to mean body cross-sectional area was approximately constant for body-weight classes ≤83 kg for men and ≤64 kg for women and decreased abruptly for higher weight classes. These findings suggest a nearly constant fraction of body mass devoted to muscle in lighter lifters and a lesser fraction in heavier lifters. Analysis also suggests that contractile tissue comprises ~30% less body mass in female champions.

Among similarly conditioned athletes, those with thicker muscles will lift more weight; among minimally obese lifters, those with thicker muscles should have larger mean cross-sectional areas, defined as body weight divided by height. The ratio of weight lifted to mean cross-sectional area was therefore examined to determine the limits of muscle growth in the different body-weight classes.

Because body weights of individuals of different sizes but of the same body proportions vary in proportion to the cube of a linear dimension, such as height, the ratio of body weight to height cubed (W/Ht3), called weight-height index, is used here to estimate body thickness.

METHODS

The identities, body weights, and weight lifted for world champion weightlifters from 1993 to 1997 were obtained from the World Weightlifting Federation web site (10); two champions later disqualified for positive drug tests were replaced with the second-place finishers listed on the web site. The data are for 95 championships in 19 weight classes won by 68 athletes. The heights of 48 of these champions were obtained (by W. Cao) either by measurement or by questioning. Heights of the remaining 20 were kindly provided by L. Jones of USA Weightlifting and by P. Chang of the Chinese Taipei Weightlifting Association.

During 1993–1997, there were 10 body-weight classes for men (54, 59, 64, 70, 76, 83, 91, 99, 108, and 108+ kg) and 9 for women (46, 50, 54, 59, 64, 70, 76, 83, and 83+ kg). In 3 of these 19 classes, the championship was won by five different individuals; in 6, the championship was won by four individuals; in 9, the championship was won by three individuals; and in 1, the championship was won by two individuals. The presented data are the average for all five championships rather than for the lesser number of champions.

RESULTS

The object of weightlifting competition is to achieve the greatest sum of two weights lifted using two techniques: snatch and clean-and-jerk. The relationships among various body dimensions and sum of weights lifted are plotted in Fig. 1 for the men and women who won the World Weightlifting Championships from...
1993 to 1997. As shown in Fig. 1, A and C, heights and weights lifted for these champions approached plateaus for both men and women. Only one male champion was >183 cm (6 ft), and no female champion was >175 cm (5 ft, 9 in.). The plateau in weight lifted by women (Fig. 1C) is further indicated by the observation that in 4 of the 5 years, the unlimited-class champion lifted less weight than the heaviest limited-class champion. The approach to a plateau for men is shown by the unlimited-class champions lifting only 6% more weight, despite being 61% heavier than the heaviest limited-class champions.

The weight-height index (Fig. 1B), indicating body thickness, was approximately constant for lighter champions and increased in the heavier body-weight classes. Over the same range of lighter body weights, there was also a nearly constant ratio of weight lifted to mean body cross-sectional area (Fig. 1D), and this ratio declined at heavier body weights. The constant ratio implies that lateral muscle growth is related to height by a common factor. The decline in the ratio suggests that muscle makes up a lesser fraction of body composition in heavier lifters.

The decline in the ratio of weight lifted to cross-sectional area (Fig. 1D) appeared to match closely the increase in the weight-height index (Fig. 1B). To assess this correlation quantitatively, the ratio of weight lifted to cross-sectional area was multiplied by the weight-height index, which is computationally the same as dividing weight lifted by height squared. This quotient was very nearly constant. A least-squares method determined that the exact exponent needed to minimize variation in the quotient was 2.16 ($Ht^{2.16}$). The separate ratios of weight lifted to $Ht^{2.16}$ for men and women (Fig. 1E) were nearly constant over the entire range of body weights, including those of the unlimited-class champions. The plots in Fig. 1E indicate that weight lifted can be calculated as $120 \cdot Ht^{2.16}$ for men and $77.5 \cdot Ht^{2.16}$ for women. The ratio of these coefficients for men and women is 0.65.

The constant ratios in Fig. 1E imply that the cross-sectional area of contractile tissue in these champions was proportional to $Ht^{2.16}$ and that contractile tissue mass scales in proportion to $Ht^{3.16}$. The finding that the same relationship applied to the unlimited weight class champions further indicates an absolute upper limit to lateral muscle growth at a height of about 183 cm in men and 175 cm in women.

There were discernible transitions between the nearly constant weight-height indexes (Fig. 1B) and ratio of weight lifted to cross-sectional area (Fig. 1D) at lighter body weights and their respective increase and decrease at higher body weights. These transitions occurred at body weights of 83 kg in men and 64 kg in women. (The corners in the curves preclude a close fit.

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Fig. 1. Average body dimensions and performance of winners of 5 world weightlifting championships from 1993 to 1997. Body weight plotted as abscissa is the weigh-in weight at the competition. All weights are in kg and heights in m. A: height. B: body weight/height cubed ($Ht^3$). C: weight lifted. Ordinate denominator in D (X-section) is mean body cross-sectional area, calculated as body weight/height. Dashed horizontal lines in E are coefficients of 120 for men and 77.5 for women. Error bars indicating SE have been eliminated when errors are less than size of symbol.
of any continuous allometric function of the type shown in Fig. 1E relating body mass to the parameters plotted in Fig. 1, C and D.) Together, these relationships suggest an abrupt increase in the fraction of noncontractile tissue contributing to body mass in heavier champions. For both men and women, the ratio decreased by \( \sim 10\% \) from the values at which it began to fall below the mean for lighter lifters and the value for the highest body-weight-limited class, whereas body weight increased by \( \sim 30\% \) over the same range, suggesting that approximately one-third of the increase in body weight was due to noncontractile tissue.

A question arises as to the proper comparison of the relative strengths of men and women. The constant 0.65 ratio of coefficients in the functions relating height to weight lifted in Fig. 1E gives an excellent size-independent description of the differences, but, because competition is based on body weight and not height, a weight-related parameter is needed. The ratios of weight lifted to cross-sectional area for women beginning at lighter body weights (Fig. 1D). The variation in the ratio for women vs. men is reduced threefold, and size dependence is eliminated when the values for women are divided by the values for men three body-weight classes higher, i.e., when values are shifted to make both the heaviest weight-limited classes and the transition points in the curves coincide (Fig. 2B). The mean value of this ratio for the shifted weight classes was 0.706 (Fig. 2B).

DISCUSSION

The principal conclusions of this study are that muscle strength and height are related by a common factor and that muscle strength approaches absolute maxima at heights of \( \sim 183\, \text{cm} \) for men and \( \sim 175\, \text{cm} \) for women, at least using current training techniques. Another conclusion is that the ratios of weight lifted to cross-sectional area in heavier athletes decline above a specific threshold, possibly because of an increasing percentage of noncontractile tissue contributing to body weight. A final conclusion is that these ratios in women are a constant fraction of the ratios in men when proper adjustment is made for gender differences in the thresholds at which the fraction of noncontractile tissue starts to increase.

Body-size-dependent limits of strength. The analysis here depends on the consideration that strength is ultimately determined by the cross-sectional area of the contractile tissue. In this construct, contractile tissue is defined as the contractile myofilaments, so that the weight lifted depends on the number of myofilaments arranged in parallel. A major object of training, therefore, is to maximize contractile tissue in the cross section. It has been shown, however, that individual muscle cells achieve an upper limit of size that cannot be increased by additional training (2). This finding suggests a reason for the relationship between height and strength. In athletes who have achieved maximum muscle fiber size, strength is determined by the numbers of cells in parallel. To the extent that muscle cell number is determined during maturation (9), the developmental factor that determines the final number of cells appears to be correlated closely with that which determines bone length.

Absolute limits of height. In terms of the principles outlined above, absolute limits of strength would be determined by an upper limit on the numbers of cells in cross section. By itself, a limit on the numbers of cells in parallel would not restrict height in the unlimited-class champions, but any disadvantage of taller height, such as having to lift the weights a greater distance, would restrict the height of these champions to the minimum necessary to achieve the upper limit of cell number.

Effects of noncontractile tissue. Although it is possible that larger lifters activate less of their contractile filaments, the more likely explanation for their reduced strength per cross-sectional area is that they carry more of their body mass as noncontractile tissue. An
increased percentage of nonmuscle tissue in body mass is expected in unlimited-class weightlifters; they have no need to minimize excess tissue. Thus, if a small increase of strength can be achieved by a large excess of supporting tissue, they will work to achieve this excess. The surprising finding is that the increase in the weight-height index began at lighter body weights and extended to the unlimited-weight class in a quasi-continuous way. It has been found that heavier participants in body-weight-restricted athletics, including weightlifting and wrestling, have a higher percentage of adipose tissue (5, 8). If the decline in the ratio of weight lifted to cross-sectional area is due to increased adiposity, the heaviest limited-class champions must have ~10% more of their body mass devoted to adipose tissue than the lighter lifters.

Allometric relationships. In 1956, Lietzke (6) showed that the weight lifted by holders of world records then current for body weights up to 90 kg varied with the two-thirds power of body mass, as expected if the athletes scaled proportionately and if the weights they lifted were proportional to their mean cross-sectional areas. Subsequent authors have reported that this “two-thirds strength” relationship does not hold (4, 7), but these authors included data for body-weight classes >90 kg. The present results agree with Lietzke’s conclusion up to body weights of 83 kg. Because Lietzke had only one record holder in each body-weight class, a slightly greater performance by his 90-kg champion is all that is required to reconcile the difference between his conclusions and the present findings.

The present study extends Lietzke’s conclusion (6) to suggest that muscle mass, but not body mass, varies almost exactly with the cube of height over the entire range of body sizes, so that strength varies almost exactly with height squared or with muscle mass to the two-thirds power. The qualifying phrase “almost exactly” is used here because the exponents are slightly larger than two and three, but the general principle remains the same.

A recent study concluded that allometric equations, i.e., single-power functions, such as Leitzke’s (6), do not accurately describe the relationship between performance and body mass in weightlifting (3). The present results agree with this criticism, but the differences in the disparate conclusions can be resolved with the explanation that the fraction of body mass devoted to noncontractile tissue increases abruptly in heavier lifters. This abrupt transition produces corners in the curves relating other parameters to body mass, and these corners preclude a good fit by any continuous allometric function relating a power of body mass to measures of strength.

Gender effects. Gender differences in strength and muscle growth are well known and expected. Women body builders cannot achieve the same muscle cross-sectional areas as men (1). This consideration leads to the expectation, found in lighter body-weight classes here, that women are taller than men in the same class. In the heavier classes, however, they were shorter than men of the same weight. The transition from taller at lighter weights to shorter at heavier weights was associated with increases in body thickness, indicated by the increased weight-height index, beginning at lighter weights for women. When corrections are made for the difference at which the transition occurred, the ratios of weight lifted to cross-sectional area for women and men were found to be a constant 70% across all body-weight-limited classes (Fig. 2B).

Morphometric comparisons of male and female weightlifters and body builders have shown that women have smaller muscle cross-sectional areas that correlate with smaller fiber cross-sectional areas (2). Some studies have shown no gender difference in the number of fibers in the muscles (8), and others have found differences (1). Although these findings suggest gender differences in performance, the ultimate explanation must provide a reason for the decreased ratio of contractile tissue to noncontractile tissue. These observations that women have smaller muscles, smaller fibers, and possibly fewer fibers would explain the present results only if the noncontractile tissue of women did not diminish proportionally, resulting in a diminished ratio of muscle mass to body mass. Another possible factor contributing to the lesser relative strength of women, less easy to measure experimentally, is that individual muscle cells in women have less of their cross-sectional areas devoted to contractile filaments.

REFERENCES