Eur J Appl Physiol (2002) 87: 304–307
DOI 10.1007/s00421-002-0638-9

SHORT COMMUNICATION

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Muscle force and muscle torque in humans require different methods when adjusting for differences in body size

Accepted: 10 February 2002 / Published online: 29 May 2002

Abstract Different methods for adjusting muscle strength (*S*) to normalise for differences in various estimates of body size [such as body mass (*m*) or, infrequently, some other anthropometrical measurements] have been either proposed or applied when presenting the results of muscle function tests in various medical, ergonomic, and sport related studies. However, the fact that the relationship between *S* and body size may differ when muscle torque (measured using a standard isokinetic apparatus) and muscle force (measured using a dynamometer) are recorded has not been taken into account. To address this problem, we tested both muscle force and muscle torque under isometric conditions in six different muscle groups. The relationship assumed between *S* and *m* was $S = k \cdot m^b$ and, according to a simple mechanical model based on geometrical similarity we developed, the exponential parameter b would be expected to equal 1.00 and 0.67 for torque and force, respectively. The experimentally obtained values for the parameter b were higher for muscle torque than for muscle force in five out of the six muscle groups tested ($P = 0.068$; Wilcoxon matched pairs test). Despite a relatively wide scatter, the mean (SD) values were also close to those predicted, being b = 0.67 (0.19) (corresponding to the *allometric scaling* method) and b = 1.02 (0.34) (corresponding to the *ratio standards* method) for muscle force and for muscle torque, respectively. Therefore, we concluded that the ratio standards and allometric scaling should be employed to adjust *S* for body size when muscle torque and muscle force, respectively, are tested.

Keywords Strength · Test · Body mass · Allometric

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Introduction

Muscle strength (*S*) [i.e. maximal voluntary force (*F*) or torque (*T*) exerted under standardized mechanical conditions] is often measured in various fields of human movement-related sciences. One problem in presenting *S* data is allowing for the effect of body dimensions. Therefore, comparisons of measured *S* adjusted for body mass (*m*) or other body size variables, rather than comparisons of absolute *S*, are usually used throughout the exercise, sport and medical science literature.

Two methods for adjusting *S* for body size have usually been applied. The first method, *allometric scaling,* is based on the principle called either geometric or biological similarity (McMahon 1984). Specifically, recorded *S* should be divided by *m* or any other mass-related variable at the power of two-thirds. The second method requires the calculation of the so-called *ratio standards,* for which *S* per unit of body size is obtained by dividing *S* by *m* (c.f. Davies and Dalsky 1997; Sunnegardh et al. 1988). Therefore, while the allometric scaling method implies that *S* increases at a slower rate than *m* (i.e. *S* per $\text{kilogram}^{2/3}$ is the correct adjustment for *m*), the ratio standards presume that *S* increases proportionally to *m* (i.e. *S* per kilogram^1 is the correct adjustment for *m*). Since *S* represents an important physiological variable in a number of movement-related sciences, both of the above methods have been recently tested and discussed (Challis 1999; Davies and Dalsky 1997; Neder et al. 1999). Despite these efforts, the optimal method for adjusting *S* for differences in body size still remains open to discussion. We believe that a part of the problem originates from the fact that previous studies have not considered qualitative differences between *S* assessed by measuring force (*F*) and *S* assessed by measuring *T*. As a consequence, *S* adjusted for body size has not been consistently studied and/or applied.

To address this problem, we developed a simple mechanical model representing the action of knee extensors in standardized test conditions (see Fig. 1, shaded area). Either F (measured using a load cell, LC) or T (measured using an isokinetic apparatus; not depicted) are recorded. The lever arm of the force exerted by the muscle (F_m) with respect to the centre of knee joint K is a, while the lever arm of the measured F with respect to the same joint is b. The F recorded by LC is:

$$F = \mathrm{a}/\mathrm{b}\, F_{\mathrm{m}}, \quad (1)$$

where a/b represents the leverage of the shank with respect to F_{m} and F. If all the subjects tested are geometrically similar (see McMahon 1984 for presumption of geometric similarity), the leverage would not depend on body size since both lever arms would change proportionately. Since F_{m} depends on the physiological-cross-sectional area of knee extensors, it should be proportional to $m^{2/3}$ (i.e. $F_{\mathrm{m}} \propto m^{2/3}$). According to Eq. 1, the same should be true for F, suggesting that F should also be proportional to $m^{2/3}$. Therefore, S, as assessed by the F_{m}recorded, should be adjusted for body size using allometric scaling.

If an isokinetic apparatus is used to test S, the recorded T is equal to the muscle T:

$$T = F_{\mathrm{m}}\mathrm{a} \quad (2)$$

Under the presumption of geometric similarity, F_{m} is proportional to $m^{2/3}$ (see the previous paragraph), while the lever arm a, as any other length, should be proportional to $m^{1/3}$. Their product gives $T \propto m^{2/3} \cdot m^{1/3} = m$. This means that muscle T should be proportional to m. Therefore, S, as assessed by the recorded T, should be adjusted for body size using the ratio standards.

In this study we tested F and T of the same muscle groups to relate them to m. We hypothesized that the results we obtained would be in line with the predictions of the model suggesting that S assessed by the measured F and S assessed by T would require different methods when adjusting for differences in body size.

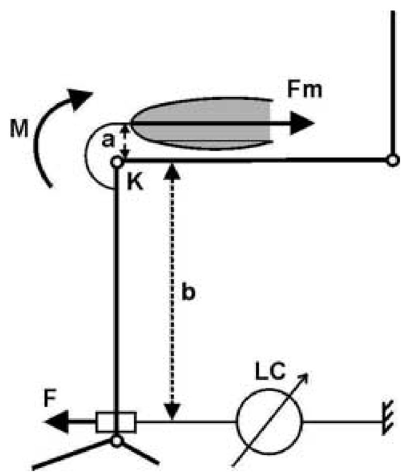

Fig. 1. Diagram of the tests of the knee extensor force and torque. For details and definitions see the text

Methods

Subjects

A group of 16 subjects participated in the experiments performed on elbow and knee muscles. Of them 3, together with 13 additional subjects, participated in the experiments on hip muscles performed 2 months later. All subjects belonged to a population of physically active men aged 22–47 years who had no history of neurological disorders. Active athletes were excluded from the sample. Subjects received a complete explanation of the purpose and procedures of the investigation and gave their consent. The study was approved by the Ethics Committee of Umea University.

Procedure

The standard measurements of body height and m were obtained. Isometric S of elbow flexors, elbow extensors, knee flexors, knee extensors, hip flexors and hip extensors was obtained using both an isokinetic apparatus (Biodex) and a KKM-1 dynamometer (AB Bofors) having a digital display (the linearity and reliability being better than 0.4% and 0.5%, respectively). Hereafter in the text we will refer to the T and F_{m} test when the isokinetic apparatus and the dynamometer, respectively, were used for the assessment of S. As a consequence, S of each of the six muscle groups tested was obtained separately as T exerted and as F exerted yielding a total of 12 tests in all.

In general, the T tests were performed under the standardized conditions described in detail in the Biodex manual, and the F_{m} tests were performed under similar conditions, particularly with regard to body posture and the fixing of body segments. The sequence of the tests was the same in all subjects, while a standard stretching and warming-up procedure preceded experimental sessions.

All tests of elbow and knee muscles were performed with the subject in the same seated position, the trunk being tightly strapped to the chair back using standard belts. The right upper leg was also fixed by a belt to the chair seat during the knee flexion and extension tests. Knee angle was fixed at an angle of 100° (180° corresponding to full extension) using either the standard lever of the isokinetic apparatus (T test) or a belt positioned at the subjects ankle joint (F test). In the elbow flexion and extension tests the upper arm was oriented horizontally (i.e. shoulder flexed at 90° with respect to the standard position) and supported by a horizontal pad. The lower arm was positioned vertically giving an elbow angle of 90°. The lower arm was fixed using either the standard lever of the isokinetic apparatus (T test) or a belt positioned at the subject's wrist joint (F_{m} test). The hip muscle tests were performed while the subject was standing on his left leg and holding tightly two handles to preserve his body posture. The hip angle was fixed at 150° using either the standard lever of the isokinetic apparatus (T test) or a belt fixed to the subject's ankle joint (F test).

The subjects were instructed to exert either maximal T or F of the muscle group tested against the lever/belt and to retain it for 4 s. Each test was repeated twice with 2 min of rest and the higher result was taken for further analysis. A computer screen and a digital display provided feedback for the T and F_{m} exerted, respectively.

The relationship between S and m was assessed using the standard allometric technique (c.f. Challis 1999). In short, it was assumed that the best-fit of the m to S relationship would be $S = \mathrm{k} \cdot m^{\mathrm{b}}$. The logarithmic transformation of this relationship gives $\log S = \log \mathrm{k} + \mathrm{b} \log m$ giving a linear relationship between log S and log m. Therefore, the linear regression technique applied to these data provides a value of b that results in no correlation between $\mathrm{S}/m^{\mathrm{b}}$ (i.e. the relative S) and m for the particular group of subjects tested. The standard descriptive statistics were calculated for all the variables tested, while the Wilcoxon matched pairs test was employed to compare values of the regression parameter b obtained in the F and T tests of six muscle groups.

Results

The mean (SD) height of the subjects participating in the experiments on the elbow and knee muscles was 183.2 (8.3) cm, while their mean mass was 79.3 (12.0) kg. The values for the subjects participating in the experiments on hip muscles were 180.1 (6.9) cm and 80.7 (11.1) kg, respectively. The recorded *F* averaged across the subjects were 296 (63) N in elbow flexors, 232 (43) N in elbow extensors, 289 (38) N in knee flexors, 669 (116) N in knee extensors, 396 (78) N in hip flexors and 447 (61) N in hip extensors. The *T* recorded for the same muscle groups were 84 (15) N·m, 70 (15) N·m, 120 (28) N·m, 288 (81) N·m, 197 (43) N·m and 206 (59) N·m, respectively.

The main result of the study represents the relationship between *S* and body size (see Table 1). Most of the regression lines showed significant correlations between *S* estimates and *m* on the log-log scale. Five out of the six muscle groups tested showed steeper slopes for the *T* tested than for the *F* tested The averaged values of the slopes of six muscle groups were 0.67 (0.19) and 1.02 (0.34) for the *T* tested and *F* tested, respectively. The difference was close to the level of significance ($P = 0.068$; Wilcoxon matched pairs test).

Discussion

The main aim of the present study was to test the hypothesis that *S* assessed as *F* and *S* assessed as *T* require different methods when adjusting for differences in body size. Although the difference between the regression slopes was slightly below the level of significance, one should take into account that only six muscle groups were tested. In addition, the hip extensor muscles that showed the aforementioned untypical behaviour, also showed insignificant relationships between *m* and each of the two *S* estimates. Finally, the data averaged for all the muscle groups showed a striking correspondence with the predictions of the model. Therefore, we can conclude that both the model and the experimental results obtained suggest using b = 0.67 (allometric scaling method) and b = 1 (ratio standards method) when *F* and *T* are adjusted for differences in *m*, respectively.

Despite a remarkable conformity of the experimental data and the model-based predictions, one should also stress potential shortcomings of the study. For example, the scatter of the experimentally observed values of parameter b is rather wide, while the model is based on the presumption of a geometric similarity that does not fit very well to some comparisons (e.g. athletes of different specialization, children of different age, subjects of different sex). However, it should also be kept in mind that the results obtained are in line with a number of empirical and experimental findings of other authors. It is obvious that maximal *F* exerted against external objects (e.g. external load, or support) are smaller for bigger subjects when calculated per kilogram of *m*. Several recent studies have used different approaches in assessing the exponential parameter b that provide results independent of *m* when the recorded *S* was divided by m^b. For example, b = 0.51 was obtained for handgrip *F* (Vanderburgh et al. 1995), while b = 0.45–0.48 was obtained for *F* exerted against an external load (Batterham and George 1997). When maximal *T* of different muscle groups was tested, the assessed values were higher: b = 1 (Weir et al. 1999), b = 0.74 (Davies and Dalsky 1997) and b = 0.91–1.10 (Neder et al. 1999) were obtained. Since our analysis also suggests higher values for measured *T* than for *F* (i.e. b = 1 and b = 2/3 = 0.67, respectively), the aforementioned findings support our results. In addition, Challis (1999) demonstrated that b = 0.67 provides a better fit for weight lifting results than b = 1. Finally, Sunnegardh et al. (1988) applied the ratio standards for several maximal *F* and *T* obtained on 8 and 13 year-old-children. Adjusted *T* of different muscle groups showed the expected differences in favour of older children, but some adjusted *F* did not. Again, we believe that the ratio standards applied overestimated the effect of body size on measured *F* and, therefore, favoured lighter (i.e. younger) subjects.

A number of studies have dealt with various variables and factors affecting both *S* and *m*, such as sex, age, or level of physical activity (Davies and Dalsky 1997; Neder et al. 1999; Vanderburgh et al. 1995). Although it is the most frequently used, *m* may not be as effective as bone-free lean tissue mass (Davies and Dalsky 1997) or limb muscle mass (Neder et al. 1999) when adjusting *S* for body size. Therefore, one can assume that different populations will require slightly different methods of adjusting *S* for body size, despite the results of theoretical and experimental analyses suggesting unique solutions. The wide range of b values obtained when adjusting *S* (see the previous paragraph) speaks in favour of this assumption. However, the aim of the present study was just to evaluate the body size related adjustment applied to the results of standard *S* tests. Moreover, the distinction evaluated between the F_m and *T*

Table 1. Slopes of the linear regressions between the logarithm of muscle strength (estimated as either force or torque) and the logarithm of body mass

Muscle Group	Elbow		Knee		Hip	
	flexors	extensors	flexors	extensors	flexors	extensors
With respect to force	0.97 ($P < 0.01$)	0.53 ($P > 0.05$)	0.56 ($P < 0.01$)	0.70 ($P < 0.05$)	0.79 ($P > 0.05$)	0.45 ($P > 0.05$)
With respect to torque	1.01 ($P < 0.01$)	0.97 ($P < 0.01$)	1.01 ($P < 0.01$)	1.39 ($P < 0.01$)	1.28 ($P < 0.01$)	0.41 ($P > 0.05$)

adjustment should remain independent of all the above effects that could affect the results of S tests in different groups of subjects. Therefore, we conclude that taking into account this problem in future studies more consistent results for routine S tests could be provided, as well as a more reliable methodology for muscle function tests in general.

Acknowledgements The authors wish to thank Dr. Albert Crenshaw for valuable suggestions. This study was supported in part by a grant from The Swedish Sport Research Council (Centrum for Idrottsforskning).

References

Batterham AM, George KP (1997) Allometric modeling does not determine a dimensionless power function ratio for maximal muscular function. J Appl Physiol 83:2158–2166

Challis JH (1999) Methodological report: the appropriate scaling of weightlifting performance. J Strength Condit Res 13:367–371

Davies MJ, Dalsky GP (1997) Normalizing strength for body size differences in older adults. Med Sci Sports Exerc 29:713–717

McMahon TA (1984) Muscles, reflexes and locomotion. Princeton Press, Princeton, N.J

Neder JA, Nery LE, Silva AC, Andreoni S, Whipp BJ (1999) Maximal aerobic power and leg muscle mass and strength related to age in non-athletic males and females. Eur J Appl Physiol 79:522–530

Sunnegardh J, Bratteby L-E, Nordesjo L-O, Nordgren B (1988) Isometric and isokinetic muscle strength, anthropometry and physical activity in 8 and 13 year-old Swedish children. Eur J Appl Physiol 58:291–297

Vanderburgh PM, Mahar MT, Chou CH (1995) Allometric scaling of grip strength by body mass in college-age men and women. Res Q Exerc Sport 66:80–84

Weir JP, Housh TJ, Johnson GO, Housh DJ, Ebersole KT (1999) Allometric scaling of isokinetic peak torque: the Nebraska Wrestling Study. Eur J Appl Physiol 80:240–248