Muscle volume compared to cross-sectional area is more appropriate for evaluating muscle strength in young and elderly individuals

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Abstract

Objective: the present study examined which of muscle volume (MV) and cross-sectional area (CSA) is appropriate for evaluating the relation with elbow flexor muscle strength in young and elderly individuals.

Methods: the subjects were 52 young (20–34 year; 30 men and 22 women) and 51 elderly individuals (60–77 year, 19 men and 32 women). The MV and maximal anatomical CSA (ACSA) of elbow flexors were determined by magnetic resonance imaging. The torque developed during maximal voluntary contraction of isometric elbow joint flexion was converted to force by dividing it by the forearm length of each subject.

Results: torque was significantly correlated with MV in young and elderly individuals ($r = 0.564–0.926$). Similarly, force was also significantly correlated with ACSA in each of them ($r = 0.637–0.906$). However, the y-intercepts of the regression lines for the ACSA-force relationship in young men and women were significantly higher than zero. There was no age effect on torque per MV, whereas force per ACSA was significantly higher in young adults than in elderly individuals.

Conclusion: for elbow flexors, MV compared to ACSA is appropriate for evaluating the size–strength relationship and the existence of age-related difference in muscle strength per size.

Keywords: maximal isometric contraction, joint torque, muscle force, magnetic resonance imaging, elderly

Introduction

The effect of ageing on muscle strength per size has been extensively argued in many studies. Nevertheless, previous findings on the subject are still in controversy. Some researchers [1–4] have reported that the muscle strength per size is higher for young adults than for elderly individuals, but others [5–8] have failed to find that difference. As an explanation for the discrepancy, Klein et al. [2] pointed out methodological difference among studies in measuring muscle size; i.e. the anatomical and physiological cross-sectional area (ACSA and PCSA) and muscle volume (MV).

Theoretically, the specific tension of a muscle is determined as the muscle force (F) per PCSA. This can be used to most properly evaluate one’s muscle strength per size. To calculate the PCSA of a muscle, however, MV, muscle fibre length and fibre pennation angle must be determined [9], and it is difficult to precisely measure all of these variables in vivo, notably in survey examining a large population. On the other hand, some researchers have also used the joint torque per MV (TQ/MV) or muscle mass as an index of muscle strength per size [5, 10–14]. This idea is based on that the MV–TQ relationship is equivalent to the PCSA–F relationship, if one assumes an identical muscle fibre/moment arm ratio for different individuals [10]. It is unclear, however, whether TQ is related to MV and correspondingly whether TQ/MV is substitute for the specific tension in elderly individuals.
Elbow flexor muscle size and strength

Table 1. Descriptive data on age, body height and body mass

<table>
<thead>
<tr>
<th>Variables</th>
<th>Young Men (n = 30)</th>
<th>Young Women (n = 22)</th>
<th>Elderly Men (n = 19)</th>
<th>Elderly Women (n = 32)</th>
<th>Significant differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>24.3 ± 2.5</td>
<td>23.4 ± 4</td>
<td>68.5 ± 3.7</td>
<td>67.5 ± 5.0</td>
<td>Young &lt; elderly</td>
</tr>
<tr>
<td>Body height (cm)</td>
<td>172.8 ± 5.2</td>
<td>161.3 ± 4.9</td>
<td>165.9 ± 4.7</td>
<td>152.8 ± 3.2</td>
<td>Men &gt; women; young &gt; elderly</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>67.5 ± 6.6</td>
<td>53.6 ± 5.7</td>
<td>65.2 ± 7.5</td>
<td>51.6 ± 6.0</td>
<td>Men &gt; women</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

In the case of a parallel-fibered muscle, the F per ACSA (F/ACSA) can also be helpful in assessing the muscle strength per size because the ACSA cuts all muscle fibres at the right angles and thus corresponds to the PCSA [15, 16]. For parallel-fibered elbow flexor muscles, Klein et al. [2] reported that F was significantly correlated with ACSA in each of young and elderly individuals. However, changes in ACSA seem to underestimate the loss of MV with ageing [5], suggesting that the age-related change in TQ/MV is different from that in F/ACSA. In other words, there is room for argument which of TQ/MV and F/ACSA is useful for assessing age-related differences in the muscle strength per size.

This study compared the MV-TQ and ACSA-F relationships for elbow flexors in young and elderly individuals. We also examined age-related differences in TQ/MV and F/ACSA. We tested which of MV and ACSA is more appropriate for evaluating the size–strength relationship for elbow flexors.

Methods

Subjects

A total of 103 men (n = 49) and women (n = 54) voluntarily participated in this study as subjects. They were classified into four groups: young men (n = 30), young women (n = 22), elderly men (n = 19) and elderly women (n = 32). Their means and standard deviations (SDs) in age, body height and body mass are summarised in Table 1. The young subjects were sedentary, normal and moderately to highly active individuals and college athletes. Of the elderly subjects, 36 men and women participated in an organised Taijiquan programme for at least 1.5 h once a week and the remainders were physically active to a moderate degree or sedentary. All of the subjects were functionally independent in daily living. All measurements were performed for the subjects’ right arms. This study was approved by the Ethical Committee of the Faculty of Sport Sciences of Waseda University and was consistent with their requirement for human experimentation. Each subject was informed of the purpose and procedures of this study and possible risks of the measurements beforehand. Written informed consent was obtained from each subject.

Measurements of MV and ACSA of elbow flexors

A series of cross-sectional images of the right arm was obtained using an MRI (Signa 1.5T, GE Medical Systems, USA) with a 3 inch and a 5 inch round surface coils. Transverse scans were performed with a conventional T1-weighted Spin-echo sequence (a repetition time: 950 ms, an echo time: 9 ms, a slice thickness: 0.5 cm, an interspaced distance: 0 cm in young adults; a repetition time: 600 ms, an echo time: 10 ms, a slice thickness: 1 cm, an interspaced distance: 0 cm in elderly individuals). Imaging was carried out on a field of view of 16 × 16 cm with a 256 × 192 matrix. A marker was applied on the subjects’ skin surface at the level of 60% of the upper arm length (the distance from the acromial process of the scapula to the lateral epicondyle of the humerus). Within the device, the subjects lay in the supine position and their right arms were relaxed on a handmade wooden armrest. Their wrists were fixed in a position halfway between supination and pronation by using an unelastic belt. Since the armrest had slight list, their elbows were slightly bent (10° of elbow joint angle). Two scans were performed as follows. The first scans were carried out from the head of the humerus to the applied marker. The second scans were performed from the marker to the distal end of elbow flexors. From the scanned images, outlines of elbow flexors were digitised, and each CSA was measured using a personal computer (LaVie LL350/8, NEC, Japan) with an image analysis software (Osiris 4.19, University Hospital of Geneva, Switzerland). In this study, the biceps brachii and the brachialis were traced as the elbow flexors. Non-contractile tissue, which was imaged in different tones from contractile tissue, was excluded when digitising. The measurement was carried out one time by a highly trained analyst performing the similar analyses in a prior study [17]. The maximal value of CSA was adopted as ACSA. The MV was determined as stated below. In young adults, the CSA was added on alternate slices. Then, the sum was multiplied by 1 cm. In elderly individuals, the MV was calculated by multiplying the sum of the CSA of elbow flexors along their length by the interval of 1 cm. The repeatability of the MV measurement was assessed on 2 separate days with two subjects. The coefficients of variance (CVs) for test–retest of the MV values on each subject were 0.4% and 0.7%, respectively. In addition, the MV was measured by each of MRI protocols for young and elderly individuals with three subjects to confirm that the values of MV obtained here were not affected.
by the difference in MRI protocols. As a result, the CV of the two measured values was 0.3 ± 0.2% with the intra-class correlation coefficient of >0.999.

Measurements of TQ and F of elbow flexion
The TQ of elbow flexion was measured using a torque meter (VTE-002R, VINE, Japan). The subjects seated on a test chair, and their right arms were secured to the torque meter with an unelastic belt. The subjects kept 90° of shoulder joint flexion angle and elbow joint angle, and their wrists were fixed in a position halfway between supination and pronation. The subjects performed MVC of isometric elbow joint flexion for 3 s. The TQ data were amplified by a strain amplifier (DPM-611B, Kyowa, Japan). Afterwards, they were recorded through an A/D converter (PowerLab/16SP, ADInstruments, Australia) into a personal computer (LaVie LL350/8,) at 100 Hz sampling frequency and processed with a low-pass filter (cut-off frequency: 20 Hz). The TQ measurements were performed two times with at least a 5 min interval. If the difference between two values of TQ was >10% of the higher one, the TQ was measured one more time. In two or three TQ measurements, the highest value was adopted. The TQ was converted to F by dividing it by the forearm length (the distance from the head of radius to the processus styloideus) of each subject [17].

Statistical analyses
Descriptive data are presented as means ± SDs. In each group, a simple regression analysis was performed to calculate Pearson’s product-moment correlation coefficients between MV and TQ and between ACSA and F and to examine whether each y-intercept for each regression line differs from zero. A two-way analysis of variance (ANOVA) [2 × 2, age (young, elderly), gender (men, women)] was used to test the effects of the age and gender on each of TQ, MV, TQ/MV, F, ACSA and F/ACSA. When the age-by-gender interaction and the Levene Test of Homogeneity of Variances were significant, a one-way ANOVA was conducted on every group categorised by the two factors. When the F value was significant as a result of the one-way ANOVA, a multiple comparison test (Tamhane’s T2 test) was performed to test the significance of difference between average values. The variables for elderly men and women were expressed as percentages of mean values of the corresponding variables for young men and women, respectively. The differences in the percentages between TQ and MV, between F and ACSA and between TQ/MV and F/ACSA were tested by a two-way repeated measures ANOVA [2 × 2, TQ vs MV; F vs ACSA; TQ/MV vs F/ACSA, gender (men, women)]. Statistical significance was set at \( P < 0.05 \).

Results
There were significant correlations between MV and TQ for elderly men \( (r = 0.564, P < 0.05) \) and women \( (r = 0.683, P < 0.001) \) as well as young men \( (r = 0.760, P < 0.001) \) and women \( (r = 0.926, P < 0.001) \) (Figure 1). Similarly, F was also significantly correlated with ACSA in each group (elderly men: \( r = 0.637, P < 0.01 \); elderly women: \( r = 0.697, P < 0.001 \); young men: \( r = 0.784, P < 0.001 \); young women: \( r = 0.906, P < 0.001 \)) (Figure 1). The y-intercepts of the regression lines between ACSA and F in young men and women were significantly higher than zero (young men: \( P < 0.01 \); young women: \( P < 0.05 \)), while the corresponding difference was not significant in each of the MV–TQ relationships (Figure 1).

Age-related differences in TQ, MV, TQ/MV, F, ACSA and F/ACSA for elbow flexors are summarised in Table 2. For TQ, MV and F, age-by-gender interaction and the Levene Test of Homogeneity of Variances were significant. As a result of the one-way ANOVA, there were significant differences among every group. There was no significant age-by-gender interaction for ACSA, and significant effects of age and gender on ACSA were found. For TQ/MV and F/ACSA, age-by-gender interaction was not significant. There were no significant age and gender effects on TQ/MV, whereas F/ACSA was significantly higher for young adults than for elderly individuals.

There was no significant difference between the percentages of TQ and MV (Table 2). Conversely, the percentage of F was significantly lower than that of ACSA (Table 2). Consequently, the percentage of TQ/MV was significantly higher than that of F/ACSA (Table 2). In each case, the gender difference was not significant.

Discussion
The current result indicated that, for elbow flexors, MV is a determinant of TQ in elderly as well as young adults. This is contrary to the previous finding [14] that, for plantar flexors, TQ was not related to MV in elderly individuals as opposed to in young adults. Morse et al. [14] showed that the activation level in plantar flexors during MVC of plantar flexion for elderly men was lower than that for young men, but such difference was not found in elbow flexors [2, 18]. Hence, the discrepancy between the previous and present studies may be attributed to the difference in the examined muscle groups: elbow flexor versus plantar flexor muscles. Differences in the relationships with age and the parameters of muscle strength per size in this study, however, cannot be affected by such activation levels, since they were determined on the same subjects. On the other hand, the present correlation coefficients between muscle size and strength were wide-ranging (Figure 1). Although it is difficult to explain the reason, the correlation coefficients reported in prior studies have also ranged from around 0.50 [8, 19, 20] to >0.90 [10, 21–23]. In other words, all the present values were within the range. Hence, there appears to be no essential difference among the correlation coefficients for each group.

No significant effect of age on TQ/MV was found in both genders. This supports the finding of Landers et al. [24],
indicating that, for elbow flexors, the age-related decline in muscle strength is a function of reduced MV. Conversely, F/ACSA was significantly higher in young adults than in elderly individuals (Table 2). In this study, the y-intercept of a regression line between ACSA and F was significantly higher than zero in young men and women (Figure 1). Bruce et al. [25] have reported that the regression line between muscle CSA and F cannot have a true intercept because if there is no muscle (i.e. independent variable equals zero), there must be no force (i.e. dependent variable must equal zero). If this idea can also be applied to the MV–TQ relationship, the present result indicates that the age-related change in muscle strength per size should be evaluated not using F/ACSA but using TQ/MV. On the other hand, the significantly higher y-intercept of the regression line between ACSA and F from zero in young adults appears to result in the overestimation of their strength per size of elbow flexors and correspondingly the age-related difference in the muscle strength per size. Another possibility is the discrepancy in the rate of decline in MV and ACSA with ageing. The greater difference between the percentages of MV and ACSA compared with between TQ and F implies that the age-related decline in ACSA is not

Table 2. Age-related changes in TQ, MV, TQ/MV, F, ACSA and F/ACSA of elbow flexor muscles

<table>
<thead>
<tr>
<th>Variables</th>
<th>Young (n = 30)</th>
<th>Elderly (n = 19)</th>
<th>Significant differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>TQ (Nm)</td>
<td>61.1 ± 9.6</td>
<td>48.9 ± 7.4</td>
<td>YM &gt; EM &gt; YW &gt; EW</td>
</tr>
<tr>
<td>MV (cm³)</td>
<td>257 ± 41</td>
<td>207 ± 20</td>
<td>YM &gt; EM &gt; YW &gt; EW</td>
</tr>
<tr>
<td>TQ/MV (N/cm²)</td>
<td>23.9 ± 2.4</td>
<td>23.7 ± 3.0</td>
<td>n.s.</td>
</tr>
<tr>
<td>F (N)</td>
<td>265 ± 38</td>
<td>216 ± 36</td>
<td>YM &gt; EM &gt; YW &gt; EW</td>
</tr>
<tr>
<td>ACSA (cm²)</td>
<td>18.2 ± 2.9</td>
<td>16.2 ± 1.6</td>
<td>Men &gt; women; young &gt; elderly</td>
</tr>
<tr>
<td>F/ACSA (N/cm²)</td>
<td>14.7 ± 1.4</td>
<td>13.4 ± 1.7</td>
<td>Young &gt; elderly</td>
</tr>
</tbody>
</table>

Values are mean ± SD.

TQ, joint torque; MV, muscle volume; F, muscle force; ACSA, anatomical cross-sectional area; YM, young men; YW, young women; EM, elderly men; EW, elderly women. The variables for elderly men and women were expressed as percentages of mean values of the corresponding variables for young men and women, respectively. For TQ, MV and F, the interaction between the age and gender was significant. Significant difference in percentage: F < ACSA, TQ/MV > F/ACSA.
always accompanied by that in MV. In plantar flexors too, the age-related decline in MV appeared to be greater than that in ACSA [5]. This discrepancy might be affected by age-related differences in limb length. To clarify this point, the upper arm length for elderly men and women were determined as differences in limb length. To clarify this point, the upper arm length seems to have an insignificant effect on the discrepancy between age-related decreases in MV and ACSA. Thus, the use of ACSA seems to overestimate muscle size for elderly individuals and correspondingly underestimates their muscle strength per size.

For both TQ/MV and F/ACSA, gender effects on them were not significant (Table 2). Previous studies [26–28] reported that there is no difference in strength per size of elbow flexors between young men and women. Considering that there were no significant differences in the percentages of all variables between genders (Table 2), there appears to be no difference in strength per size of elbow flexors between genders, both for young and elderly individuals.

In summary, MV is found to be a determinant of TQ both in young and elderly individuals. Moreover, all the y-intercepts of the regression lines between MV and TQ in each group were not significantly different from zero. Thus, MV compared to ACSA is more appropriate for assessing the size–strength relationship and the age-related difference in the muscle strength per size for elbow flexors.

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**Key points**

- TQ was significantly correlated with MV in young and elderly individuals.
- For elbow flexors, MV compared to ACSA was more appropriate for evaluating the size–strength relationship.
- Using TQ/MV, the age-related difference in the strength per size of elbow flexors was not found.

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**Conflicts of interest**

None.

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**References**


Elbow flexor muscle size and strength


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