# Muscle volume is a major determinant of joint torque in humans

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## ABSTRACT

Muscle force (MF) is linearly related to physiological cross-sectional area (CSA), which is obtained from muscle volume (MV) divided by fibre length. Taking into account the fact that joint torque (TQ) is determined by MF multiplied by the moment arm, the maximal TQ would be a function of MV. This proposition was tested in the present study by investigating the relationship between MV and TQ for elbow flexor (EF) and extensor (EE) muscles of 26 males. The MVs of EF and EE were determined from a series of muscle CSA by magnetic resonance imaging (MRI), and pennation angle (0) and FL by ultrasonography (US). Maximal isometric TQ was measured at right angle of elbow joint for EF and EE. There was a highly significant correlation between MV and TQ both for EF and EE (r = 0.95 and 0.96 respectively) compared with that between muscle CSA and TQ, suggesting the dependence of TQ on MV. Furthermore, prediction equations for MV ( $MV_{ULT}$ ) from muscle thickness (MT) measured by US was developed with reference to  $\mathrm{MV}_{\mathrm{MRI}}$  by the MRI on 26 subjects, and the equations were applied to estimate MV of healthy university students (CON; 160 males) and sports athletes (ATH; 99 males). There were significant linear relationships between MV<sub>LUT</sub> and TQ both for EF (r = 0.783) and EE (r = 0.695) for all subjects (n = 259). The MV<sub>ULT</sub> was significantly higher in ATH (by 32% for EF and 33% for EE, respectively) than in CON. Similarly, significantly greater TQ was observed in ATH (by 35% for EF, 37% for EE, respectively). The  $\theta$  for EE showed no difference between both groups (17.8° for CON and 17.5° for ATH). On the other hand, the TQ to MV ratio were identical for CON and ATH. The results reveal that the muscle volume of the upper arm is a major determinant of joint torque (TQ), regardless of athletic training.

Keywords joint torque, muscle volume, specific tension, ultrasound.

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Human movement is produced by muscles that generate torque around joints. Muscle force (MF) is related to its physiological cross-sectional area (PCSA) which is estimated from muscle volume (MV), fibre length (FL) and pennation angle ( $\theta$ ). Architectural parameters such as CSA, MV, FL,  $\theta$  and moment arm, therefore, are important measures for evaluating human movement performance (Lieber 1992, Roy & Edgerton 1992). It is generally accepted that a close relation exists between muscle CSA and its ability to generate force (Ikai & Fukunaga 1968, Maughan et al. 1983, Young et al. 1985, Fukunaga et al. 1996). Moreover strength training increases both CSA and MF (Ikai & Fukunaga 1970). Many previous studies have reported inconsistent results whether or not the force per unit CSA is affected by training. Some papers indicated lower force per CSA in trained

athletes (Sale et al. 1987, Always et al. 1990) and others showed no significant differences between trained and control subjects (Ikai & Fukunaga 1968, Schantz et al. 1983, Maughan et al. 1984). This discrepancy of the results for force per CSA is caused partly by the differences in CSA measurement, i.e. anatomical and PCSA. From a physiological point of view, the muscle size should be evaluated from physiological (not anatomical) CSA, because in pennate-fibre muscles the anatomical CSA does not include all CSAs of fibres at right angles to their long axes (Kawakami et al. 1995, Fukunaga et al. 1996). Because joint torque (TQ) has a dimension of (force × length) and that of MV is (physiological  $CSA \times FL$ ). The TQ would be theoretically related to MV, and the ratio TQ to MV is considered as an index of specific tension (Lynch et al. 1999).

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To evaluate the MV some scanning techniques have been developed such as magnetic resonance imaging (MRI), X-ray computerized tomography (CT), dualenergy X-ray absorptiometry (DEXA) and ultrasonography (US). The MRI, CT and DEXA have proved to be highly reliable methods to determine MV. But the cost required, radiation exposure and limited access to instrument often limits their use (Heymsfield et al. 1990). The US has the same advantages as those of CT or MRI in visualizing fat and muscle tissues and is more applicable for field use and repeated measurements (Abe et al. 1994, Ishida et al. 1995). Hence US techniques have been successfully used to measure muscle CSA (Sipila & Suominen 1993) and thickness in vivo (Abe et al. 1994). Prevalence of this method prompted us to use it to estimate MV (Miyatani et al. 2000).

The purpose of the present study was twofold. First, a new method for estimating MV was developed by means of US method combined with anthropometric measurements. Second, dependence of TQ on MV was tested by studying the correlation of these two parameters. By using this method the relationship between MV and TQ of elbow flexor (EF) and extensor (EE) muscles were investigated to observe an effect of athletic training on specific tension index (TQ/MV).

### METHODS

#### Measurement and calculation of MV and TQ

Subjects. Twenty-six male university students (age:  $25.7 \pm 2.9$  years, body height:  $169.4 \pm 7.3$  cm, body weight:  $68.5 \pm 9.6$  kg) volunteered for the study. The subjects were fully informed about the procedures to be used as well as the purpose of the study. Written informed consent was obtained from all the subjects.

Muscle volume measurements by MRI. Series cross-sectional images of the upper arm were obtained by MRI scans with a body coil (Signa 1.5T, GE, Milwaukee, WI, USA). Subjects lay supine in the body coil with his upper arm extended and relaxed. Transverse scans were carried out for the upper arm every 10 mm. From each crosssectional image, outlines of the each elbow flexor and extensor muscles were traced, and digitized by using a personal computer (Power Macintosh 7500/100, Apple, Tokyo, Japan), and the anatomical CSA was calculated. The maximal anatomical CSAs of individual muscles were adopted to represent maximal anatomical CSAs (ACSA<sub>max</sub>) of EF and EE. By summing the anatomical CSA of the muscle along its length and then multiplying the sum by the interval of 10 mm, MV (MV<sub>MRI</sub>) was determined. The muscle length was determined from the number of images in which respective muscle was visible.

Measurement of elbow joint torque. Maximal voluntary isometric TQ was measured by means of a specially designed dynamometer (Vine, Tokyo, Japan). The measurement of elbow flexion and extension TQ were carried out with the subject seated, keeping 90° of elbow joint angle with the upper arm supported on the horizontal plane on a padded table. The subject's wrist was fixed at the end of the lever arm in a position halfway between supination and pronation. Isometric TQ were measured two to three times and the maximal value was adopted. The order of the measurements was randomized and a rest of approximately 1-min was allowed between trials to exclude an effect of fatigue. The TQ was then converted to muscle force (MF) by using previously reported moment arm lengths (MA) of respective muscles for EF and EE (Kawakami et al. 1994), i.e.  $MF = TQ \times (MA)^{-1}$ .

Measurement of muscle layer thickness by US. Muscle layer thickness (MT) of EF (biceps brachii and brachialis) and EE (triceps brachii) muscles were measured with a B-mode ultrasonic apparatus (SSD-500, Aloka, Tokyo, Japan). Precision and linearity of the image reconstruction have been confirmed elsewhere (Kawakami et al. 1993). A single cross-sectional plane was imaged at 40% of the distance from the lateral epicondyle to the acromion process of the scapula, starting at the lateral epicondyle. The elbow was in an extended position. A transducer with a 5-MHz scanning head was placed perpendicular to the tissue interface and to the underlying humerus. The subcutaneous adipose tissue-muscle interface and the muscle-bone interface were identified from the US image, and the distance from the adipose tissue-muscle interface and the muscle-bone interface was adopted as MT (Kawakami et al. 1995, Miyatani et al. 2000) (Fig. 1).

Measurement of pennation angle and fascicle length for EE by US. The pennation angle and fascicle length of triceps brachii were measured by means of the US. The angle between the echo of the deep aponeurosis of the triceps and echoes from interspaces among the fascicle of the long head of triceps on the same site for determining MT were measured as  $\theta$  (Kawakami *et al.* 1993). From the MT and the  $\theta$ , the length of fibre (FL) across the deep and superficial aponeuroses was estimated from the following equation:

$$FL = MT \times (\sin \theta)^{-}$$

*Calculation of physiological cross-sectional area of muscles by MRI.* The PCSA of EF and EE was calculated from the following equation:

$$PCSA = MV \times \cos \theta \times FL^{-1}$$



Figure 1 Ultrasonic cross-sectional images of elbow flexor (EF) and elbow extensor (EE). MT represents muscle thickness.

For EE, FL and  $\theta$  of the long head of triceps was used. For EF, FL was estimated from the MRI-determined muscle length and reported FL to muscle length ratio (Kawakami *et al.* 1994).

Development of prediction equations for MV. Based on an assumption that  $(MT)^2$  and L reflect anatomical CSA and muscle length, respectively, muscle volume index  $(MVI_{ULT})$  of EF and EE was determined as follows:

 $MVI_{ULT} = L \times (MT)^2$ 

The  $MVI_{ULT}$  was linearly related to  $MV_{MRI}$  for both EF and EE with significant correlation coefficients (Fig. 2).

From the multiple regression analyses between ultrasonic and anthropometric variables and  $MV_{MRI}$ , the following prediction equations for MV ( $MV_{ULT}$ ) were obtained, i.e.

Elbow flexors : MV = 2.586 BH - 1.259 BW+ 7.057 CIR + 0.524 (MVI<sub>ULT</sub> of EF) - 447.46

Elbow extensors : MV = 3.478 BH - 0.180 BW+ 6.674 CIR + 0.382 (MVI<sub>ULT</sub> of EE) - 559.36

where MV, BH, BW, CIR are muscle volume, body height, body weight, circumference of upper arm at the same site for measuring MT, respectively. The MV obtained from prediction equation ( $MV_{ULT}$ ) indicated higher correlation coefficients to  $MV_{MRI}$  (EF: r = 0.943, EE: r = 0.932) than those for  $MVI_{ULT}$ . The standard error of estimation (SEE) of  $MV_{ULT}$  was lower (6–8%) than that of  $MVI_{ULT}$  (8–10%). Thus the  $MV_{ULT}$  was used for EE and EF in the present study.

### Effect of athletic training on MV to TQ ratio

Subjects were 160 male students (CON) and 99 male athletes (ATH) in university (Table 2). The ATH group



Figure 2 Relationship between muscle volume index ( $MVI_{ULT}$ ) calculated from ultrasonic method and absolute muscle volume by MRI ( $MV_{MRI}$ ). EF: elbow flexor, EE: elbow extensor.

consisted of such sports events as basketball (n = 20), handball (n = 20), volleyball (n = 20), weightlifting (n = 19) and track and field (n = 20). None suffered from neuromuscular diseases or from any other medical or psychiatric disorders. All subjects gave informed consent to the study, which was approved by the University of Tokyo ethics committee.

The MV (MV<sub>ULT</sub>) was determined using prediction equations using US described above. The TQ was also measured by identical procedures to the above. The ratio of TQ to MV (TQ/MV) was computed to represent specific tension for EF and EE (Lynch *et al.* 1999).

#### Statistics

Descriptive statistics include mean and standard deviations (SD). The relationships between muscle dimensions (ACSA<sub>max</sub>, PCSA, MV) and functional measures (TQ and MF) were studied by the linear regression analysis, and the correlation coefficient (r) was calculated using the method of least squares. A one-way analysis of variance was used to identify the significant difference in the descriptive data between the CON and ATH. The probability level accepted for statistical significance was set at P < 0.05.

## RESULTS

The MF was linearly related to ACSA<sub>max</sub> and PCSA. The correlation coefficients were higher for PCSA and MF (EF: r = 0.95, EE: r = 0.91) than ACSA<sub>max</sub> and MF (EF: r = 0.71, EE: r = 0.89). On the other hand, TQ was related more to MV (higher *r*) than to ACSA<sub>max</sub> (Table 1).

Anthropometric variables such as body height, weight, limb length and circumference as well as MT were significantly higher in ATH than in CON (Table 2). The MV, TQ and TQ/MV are shown in Table 3. The ATH showed larger MV than CON by 32% (EF) and 33% (EE), and greater TQ by 35% (EF) and 37% (EE) than CON. Pennation angles of EE were  $17.5 \pm 2.2^{\circ}$  (ATH) and  $17.8 \pm 3.1^{\circ}$  (CON)

 Table 1 Correlation coefficients between joint torque (TQ) and muscle CSA and muscle volume

	TQ		
	EF	EE	
ACSA <sub>max</sub>	0.705*	0.888**	
PCSA	0.945***	0.906***	
MV	0.935***	0.921***	

ACSA<sub>max</sub>: maximal anatomical cross-sectional area. PCSA: physiological cross-sectional area. MV: muscle volume. Subjects were 26 university students. \*P < 0.05, \*\*P < 0.01, \*\*\*P < 0.001.

Table 2 Physical characteristics of subjects

	Athlete $(n = 99)$	Control $(n = 160)$
Age (yr)	19.9 ± 0.9	$19.0 \pm 0.9$
Body height (cm)	$178.0 \pm 9.6$	$171.3 \pm 5.4$
Body mass (kg)	75.5 ± 12.8	$63.1 \pm 10.1$
Upper arm length (cm)	33.2 ± 2.3	31.7 ± 1.4
Upper arm circumference (cm)	29.9 ± 2.9	$26.5 \pm 2.8$
Muscle thickness (mm)		
EF	34.4 ± 3.7	$30.0 \pm 3.3$
EE	$37.1 \pm 5.0$	$30.3 \pm 4.9$

Values are mean  $\pm$  SD; P < 0.01.

without significant differences between the two groups. Fibre length of EE was significantly higher (14%) in ATH (112  $\pm$  16 mm) than in CON (97  $\pm$  22 mm). When FL was normalized to the upper arm length (*L*) the ratio FL to *L* was not significant between two groups, i.e. 3.3  $\pm$  0.6 for ATH and 3.1  $\pm$  0.6 for CON.

The relationships between MV and TQ are shown in Figure 3. It was observed that TQ was correlated significantly with MV for each subject group and for all subjects, i.e. EF: r = 0.71 (CON), r = 0.89 (ATH) and r = 0.78 (total), EE: r = 0.61 (CON), r = 0.84 (ATH) and r = 0.70 (total).

## DISCUSSION

The finding that MF is more related to PCSA than to ACSA<sub>max</sub> is similar to the results from previous studies (Fukunaga *et al.* 1996). This is not surprising, because PCSA refers to the total CSA of muscle fibres and hence reflects sum of forces developed in muscle fibres, while ACSA<sub>max</sub> does not include all the fibres especially in pennate muscles as triceps brachii. The present result clearly shows dependence of MF on PCSA in humans.

Table 3 Comparison of muscle volume (MV), joint torque (TQ) and TQ/MV of elbow flexor (EF) and elbow extensor (EE) between control and athlete

	Athlete $(n = 99)$	Control $(n = 160)$	Р
MV (cm <sup>3</sup>	)		
EF	$337 \pm 58$	255 ± 47	< 0.01
EE	$423 \pm 70$	$317 \pm 58$	< 0.01
TQ (Nm)	)		
EF	70.8 ± 14.9	$52.2 \pm 10.8$	< 0.01
EE	58.4 ± 13.5	42.6 ± 12.3	< 0.01
TQ/MV	(Nm cm <sup>-3</sup> )		
EF	$0.211 \pm 0.028$	$0.207 \pm 0.038$	NS
EE	$0.139 \pm 0.024$	$0.136 \pm 0.036$	NS

Muscle volume was estimated from US method. Joint torque for EE and EF were measured at 90° of elbow joint. Values are mean  $\pm$  SD. NS: not significant.



Figure 3 Relationship between joint torque (TQ) and muscle volume (MV). EF: elbow flexor, EE: elbow extensor. ATH: athletes, CON: healthy university students. MV was estimated from US method.

The present result indicated a significant higher correlation between TQ and MV than between TQ and ACSA<sub>max</sub>. This is in line with a previous report that TQ was more closely related to MV than CSA or circumference for ankle dorsiflexors and plantar flexors (Gadeberg *et al.* 1999). Considering that TQ is a resultant moment of MF and MA, i.e.

 $TQ = MF \times MA.$ 

It has been shown in animal studies (Roy & Edgerton 1992) that MF is determined as follows:

$$MF = PCSA \times SPT \times \cos \theta$$

where SPT is the specific tension of muscle and  $\theta$  is the pennation angle. This equation can be used for humans based on our results. As PCSA = MV × FL<sup>-1</sup>, it follows that

$$TQ = MV \times FL^{-1} \times SPT \times \cos \theta \times MA$$
$$= MV \times SPT \times MA \times FL^{-1} \times \cos \theta$$

Thus, TQ should be dependent on MV if MA to FL ratio and  $\theta$  are assumed to be identical among subjects. Previous studies reported that the moment arm of ankle joint measured by MRI was correlated with foot length (Rugg *et al.* 1990), and that FL to muscle length ratio was independent of individuals (Wickiewicz *et al.* 1983). If this is the case, the ratio FL to MA may not be affected by individual differences in muscle size. Furthermore, pennation angles of triceps brachii muscle ranged from 12 to 27° without significant differences between CON and ATH. Considering also the fact that the effect of pennation angle on MF is negligible in the present subjects because of extremely low of cosine factor of pennation (0.98–0.89). Collectively, it can be concluded that MV is a major determinant of TQ.

The present study further showed that the MV of the upper arm can be estimated from US and anthoropometric measurements. Several attempts have been made to estimate MV on the basis of anthropometric methods (Jones & Pearson 1969, Heymsfield *et al.* 1982, Rice *et al.* 1990). The SEE values in the present study were significantly lower (6–8%) as compared with those reported by Rice *et al.* (1990) who reported the SEE of EF and EE volumes of 15 and 10%, respectively. Miyatani *et al.* (2000) reported higher correlation (r = 0.962, n = 26) between MV estimated by US and measured by MRI accompanying with 7.2% of SEE, indicating in good agreement with present result. Thus it could be said that the prediction equations for MV obtained by US are more accurate those obtained by the previous studies based only on anthropometry.

The TQ to MV ratio, regarded in this study as analogous to specific tension of muscle, was significantly lower in EE than EF. Kawakami et al. (1994) reported that there was not significant difference in specific tension between EE and EF. There are three possibilities that could explain the difference. First, significantly lower TQ to MV ratio of EE might be partly because of the TQ measurement. Kawakami et al. (1994) reported that the maximal torque of EE has been shown at the more extended position than 90°, indicating the maximum torque was 10% higher for EE than for EF. Thus, it is considered to be underestimated the EE torque in the present study. Secondly, an effect of pennation angle should be considered. The pennation angle is higher for EE than for EF that is a parallel-fibred muscle. The loss of force transmission from muscle fibres to tendon might have resulted in lower TQ to MV ratio for EE. Finally, there might be intermuscle differences in moment arm to FL ratios. According to Kawakami et al. (1994) the moment arm to FL ratio was significantly higher for EE (2.7) than for EF (average: 2.0; biceps brachii: 2.1 and brachialis: 1.9). This may also partly induce difference of TQ to

MV ratio between EE and EF. Taken together, the differences in TQ to MV ratio between EF and EE in the present study could be related to the differences in torque measurement as well as muscle architecture.

Interestingly, there was no significant difference in TQ/MV between CON and ATH. As shown in the present study, TQ/MV can represent specific tension of muscle if we assume constant MA/FL and pennation angle between individuals. No consensus has been reached as to whether the specific tension (or force per unit CSA) is affected by resistance training or not. Previous studies on humans have shown conflicting results. Sale et al. (1987) and Always et al. (1990) reported lower force per CSA in trained athletes. However, others have indicated no significant differences in specific tension between trained and control subjects (Schantz et al. 1983, Maughan et al. 1984). The specific tension is affected by such factors as fibre types (Thorstensson 1976, Nygaard et al. 1983) and neural activation (Komi & Karlsson 1979). The muscle fibre types of athletes are different, depending on sports events, i.e. high-power athlete posses higher percentages of fast twitch fibres while endurance athletes have more slow twitch fibres (Saltin et al. 1977). The athletes in the present study consisted of various sports events such as ball games, weight lifting and track and field, suggesting that the present subjects had various fibre types. This might be able to explain similar TQ to MV ratio between ATH and CON.

In conclusion, the present results indicated that TQ is closely related to MV, and that MV can be accurately estimated by means of ultrasonic measurements. The TQ to MV ratio, an index of specific tension, was similar in athlete and control subjects, suggesting similar specific force-producing potential between these groups.

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