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Upper limb muscle volumes in adult subjects

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Abstract

Muscle force-generating properties are often derived from cadaveric studies of muscle architecture. While the relative sizes of muscles at a single upper limb joint have been established in cadaveric specimens, the relative sizes of muscles across upper limb joints in living subjects remain unclear. We used magnetic resonance imaging to measure the volumes of the 32 upper limb muscles crossing the glenohumeral joint, elbow, forearm, and wrist in 10 young, healthy subjects, ranging from a 20th percentile female to a 97th percentile male, based on height. We measured the volume and volume fraction of these muscles. Muscles crossing the shoulder, elbow, and wrist comprised 52.5, 31.4, and 16.0% of the total muscle volume, respectively. The deltoid had the largest volume fraction (15.2% $\pm$ 1%) and the extensor indicis propius had the smallest (0.2% $\pm$ 0.05%). We determined that the distribution of muscle volume in the upper limb is highly conserved across these subjects with a three-fold variation in total muscle volumes (1427–4426 cm^3). When we predicted the volume of an individual muscle from the mean volume fraction, on average 85% of the variation among subjects was accounted for (average $p = 0.0008$). This study provides normative data that forms the basis for investigating muscle volumes in other populations, and for scaling computer models to more accurately represent the muscle volume of a specific individual.

Keywords: Upper limb; Muscle; Scaling; Imaging

1. Introduction

Humans vary greatly in size and shape, yet biomechanists often use generic musculoskeletal models with average parameters to evaluate muscle function and coordination. While this approach allows researchers to investigate general principles underlying human movement, it is unclear how conclusions derived from studies of generic models apply to individuals of different sizes.

Muscle force-generating properties used in models are often derived from cadaveric studies of muscle architecture. However, cadaveric specimens may not accurately reflect absolute or relative sizes of muscles in young, healthy subjects. Cadaveric studies of muscle architecture often focus on individual muscle groups; this is especially true for the upper limb, where muscle parameters have been measured separately for the shoulder (Langenderfer et al., 2004), elbow (An et al., 1981; Murray et al., 2000), and forearm and wrist (Lieber et al., 1990; Jacobson et al., 1992; Lieber et al., 1992). Thus, there are excellent data describing the relative size of muscles acting about a single joint in cadaveric specimens, but the relative sizes of muscle across joints in living subjects has not been evaluated.

Several fundamental questions remain unanswered. What are the relative sizes of muscles in the upper extremity? Are relative sizes of muscles consistent across subjects with different total muscle volume? How is muscle volume distributed among muscles crossing the shoulder, elbow, and wrist? We answered these questions by measuring volumes of 32 muscles of the upper limb in young healthy subjects using magnetic resonance imaging (MRI). This study provides the most comprehensive

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evaluation of muscle volumes in the entire upper extremity to date.

2. Methods

Ten subjects (5 female, 5 male, 24–37 years, 158–188 cm, 50–86 kg) with no history of injury or pathology of the upper limb were studied. The subjects varied from a 20th percentile female to a 97th percentile male (Gordon et al., 1989), by height (Table 1). All subjects were screened for MRI risk factors and provided informed consent in accordance with institutional guidelines. The dominant arm of each subject (right arm in all cases) was studied.

Each subject was imaged supine within a 1.5 T MRI scanner (GE Healthcare, Milwaukee, WI). Axial images were acquired from shoulder to wrist using two three-dimensional spoiled gradient echo sequences with 3 mm sections. Images of muscles crossing the shoulder were obtained with the body coil with TE = 3 ms, TR = 11.6 ms, flip angle (FA) = 30°, matrix = 512 × 192, bandwidth = ±31.25 kHz, and field of view (FOV) = 32 cm, resulting in a 16 min scan time. Elbow and forearm images were acquired using a flexed array long bone coil (Medical Advances, Milwaukee, WI) with TE = 5 ms, TR = 23 ms, FA = 45°, matrix = 320 × 192, bandwidth = ±15.63 kHz, and FOV = 16 cm, resulting in a 22 min scan time.

To calculate muscle volume, we reconstructed the three-dimensional geometry of the 32 upper limb muscles that cross the wrist, elbow, forearm, and shoulder (glenohumeral joint) (Fig. 1). Muscle boundaries were identified and manually outlined, or segmented, in the axial images, and a three-dimensional polygonal surface was created for each muscle from the outlines (3D-Doctor, Able Software Corp., Lexington, MA). One individual performed all segmentation. Thirty-two muscles were segmented in 4 subjects; 31 were segmented in 6 subjects. The palmaris longus was not identified in 6 subjects; this muscle is absent in some individuals (Dalley and Moore, 1999).

The accuracy of estimating muscle volume from MRI has been established by Tingart et al. (2003); they measured the volume of rotator cuff muscles in cadavers using MRI of the intact shoulder and water displacement of the dissected muscles, and reported differences of less than 4%. We assessed accuracy and repeatability of our MRI protocol. A cylindrical phantom (volume = 77 cm^3) was imaged and its volume estimated using the protocols defined above. Reconstructed volumes measured within 1.4% (1.1 cm^3) of known volume for images obtained with the body coil, and within 0.4% (0.3 cm^3) for images obtained using the long bone coil. To test segmentation reliability, representative muscles from the body coil images (deltoid) and from the long bone coil images (brachioradialis) for one subject were segmented three times. Reconstructed volumes varied by a maximum of 1.2% (3.0 cm^3) for deltoid; volumes varied by a maximum of 4.4% (1.2 cm^3) for brachioradialis.

Muscle volume was determined for each of the 314 muscles from 10 subjects. Total muscle volume of the upper limb was determined for each subject as a sum of all their individual muscle volumes (31 or 32 muscles). The mean volume for each muscle for 10 subjects was calculated, as was mean total muscle volume.

To determine the distribution of muscle volume among muscles of a given subject, we calculated volume fraction ($\mathrm{Fraction_m}$), expressed as a percentage of total muscle volume (V_{total}), for each muscle:

$$\mathrm{Fraction_m} = 100 \times V_{\mathrm{m}}/V_{\mathrm{total}}, \tag{1}$$

where V_{m} is individual muscle volume for a given subject. The mean volume fraction for each muscle across subjects was also calculated.

To determine whether muscle distribution is consistent across subjects with different total muscle mass, we

Table 1
Subject characteristics

Subject[a]	Age	Height (cm)	Percentile[b] (height)	Weight (kg)	Percentile[c] (weight)	Humerus length (cm)	Radius length (cm)	Ulna length (cm)	Arm length[c] (cm)	Arm circumference[d] (cm)	Forearm circumference[d] (cm)
F1	24	157.5	20	49.9	5	29.7	21.0	23.4	50.7	26.7	20.9
F2	36	162.6	50	49.9	5	31.2	23.1	25.8	54.3	25.2	21.7
F3	30	162.6	50	59.0	40	31.2	22.2	24.9	53.4	27.2	23.9
F4	24	165.1	65	52.2	10	32.1	23.1	24.6	55.2	25.9	21.5
M1	28	172.7	35	72.6	30	35.1	24.3	27.6	59.4	33.5	27.5
M2	27	175.3	50	83.9	70	31.5	23.4	26.1	54.9	35.5	28.5
M3	37	175.3	50	93.0	90	34.2	25.2	28.2	59.4	35.1	29.9
F5	26	177.8	99	72.6	90	34.2	24.6	27.0	58.8	31.5	25.5
M4	27	177.8	65	72.6	30	34.5	25.8	27.9	60.3	34.1	28.0
M5	27	188.0	97	86.2	75	38.1	27.0	30.3	65.1	35.2	29.3
Mean female (±SD)	28.0 (5.1)	165.1 (7.6)	56.8 (28.7)	56.7 (9.6)	30.0 (36.6)	31.7 (1.7)	22.8 (1.3)	25.1 (1.3)	54.5 (2.9)	27.3 (2.5)	22.7 (1.9)
Mean male (±SD)	29.2 (4.4)	177.8 (6.0)	59.4 (23.5)	81.6 (8.9)	59.0 (27.5)	34.7 (2.4)	25.1 (1.4)	28.0 (1.5)	59.8 (3.6)	34.7 (0.8)	28.6 (1.0)
Mean total (±SD)	28.6 (4.5)	171.5 (9.3)	58.1 (24.8)	69.2 (15.8)	44.5 (34.1)	33.2 (2.5)	24.0 (1.8)	26.6 (2.0)	57.2 (4.2)	31.0 (4.3)	25.7 (3.4)

[a]The letter in the subject designation indicates the gender of the subject.
[b]Percentile values based on height and weight are based on Gordon et al. (1989).
[c]Arm length was calculated from the image data as the sum of the length of the radius and humerus.
[d]Forearm and arm circumference was measured from the image data as the largest circumference measured on any axial slice.

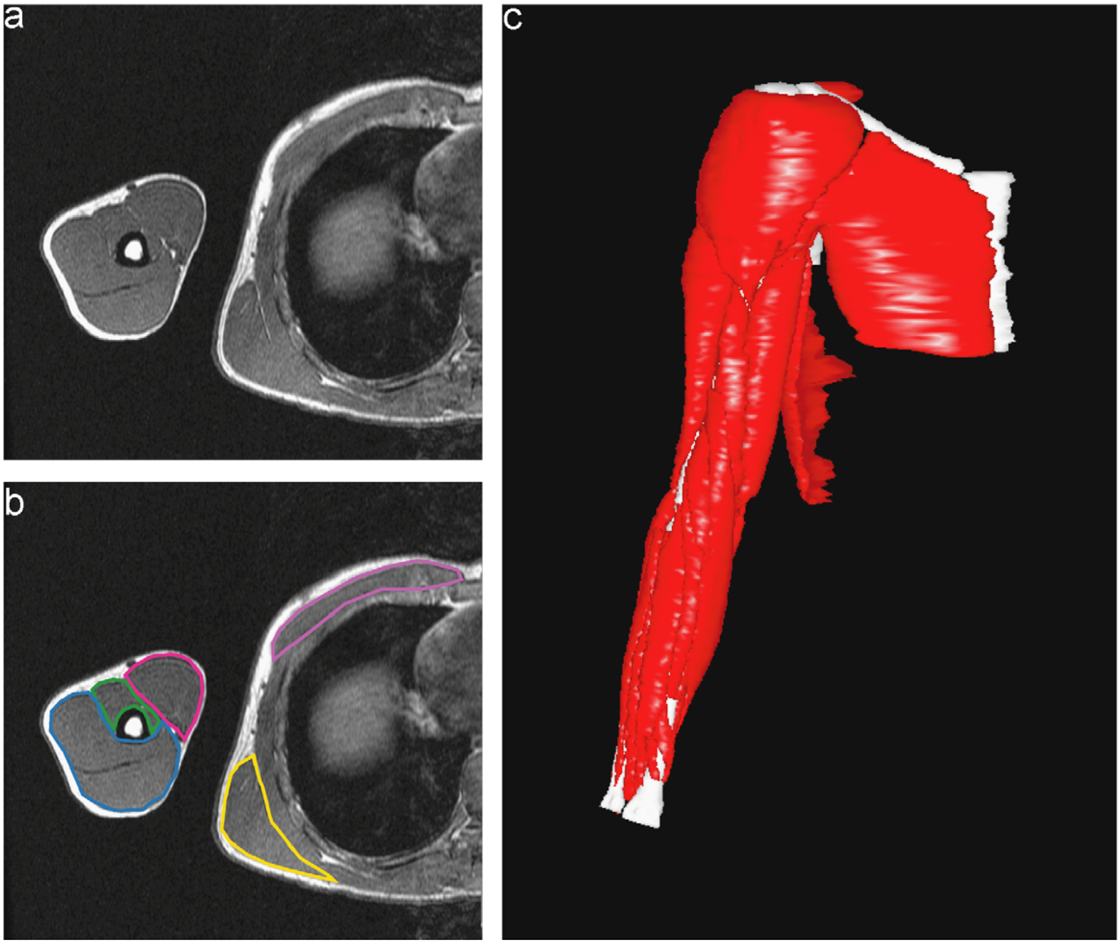

Fig. 1. Reconstructed muscle volumes for a representative subject. On each axial image (a) we identified muscle structures and manually outlined the boundaries (b). We used the boundaries to create three-dimensional surfaces (c), and measured volume and length for each muscle.

compared volume fraction across 10 subjects. We examined the degree to which the mean volume fraction for a given muscle represented the volume fraction for an individual subject by comparing measured muscle volumes to volumes predicted by multiplying the mean volume fraction by total muscle volume of a subject.

To determine how muscle is distributed among the shoulder, elbow, and wrist, we calculated the total volume of muscle crossing each joint for each subject and compared these distributions across subjects. Muscles that cross more than one joint were considered with the joint of their primary action (groups indicated in Fig. 2). We also calculated mean muscle volume at each joint.

Physiologic cross-sectional area (PCSA), an important parameter in maximal muscle force estimation, was estimated as

$$\mathrm{PCSA} = \left(V_{\mathrm{m}}/L_{\mathrm{m}}^{\mathrm{meas}}\right)\left(L_{\mathrm{m}}/L_{\mathrm{m}}^{0}\right), \tag{2}$$

based on measured volumes (V_{m}), measured muscle length ($L_{\mathrm{m}}^{\mathrm{meas}}$), and muscle length to optimal fiber length ratios ($L_{\mathrm{m}}/L_{\mathrm{m}}^{0}$) available from literature (An et al., 1981; Lieber et al., 1990; Jacobson et al., 1992; Lieber et al., 1992; Murray et al., 2000; Langenderfer et al., 2004). Muscle length was measured from the reconstructed volumes as the length of the centroidal path from most proximal appearance of the muscle to most distal (Lieber et al., 1992). Tendon length was excluded. Some muscles have architectural parameters measured separately for multiple compartments or heads. For these muscles (deltoid, latissimus dorsi, pectoralis major, biceps brachii, triceps brachii, extensor digitorum communis, flexor digitorum profundus, and flexor digitorum superficialis) average ratios of muscle length to optimal fiber length (Lieber et al., 1992; Murray et al., 2000; Langenderfer et al., 2004) were used. Calculations of PCSA and PCSA fraction as a percentage of total upper limb PCSA, and means for these values across subjects, were calculated in the manner described for volume calculations. PCSA fraction was compared to volume fraction for each muscle using paired T tests.

Anthropometric measures, including humerus, radius, and ulna lengths, total arm length, arm circumference, and forearm circumference, were obtained for each subject. Arm length was calculated from the image data as the sum of radius length and humerus length. Forearm and arm circumference were measured from the image data as the

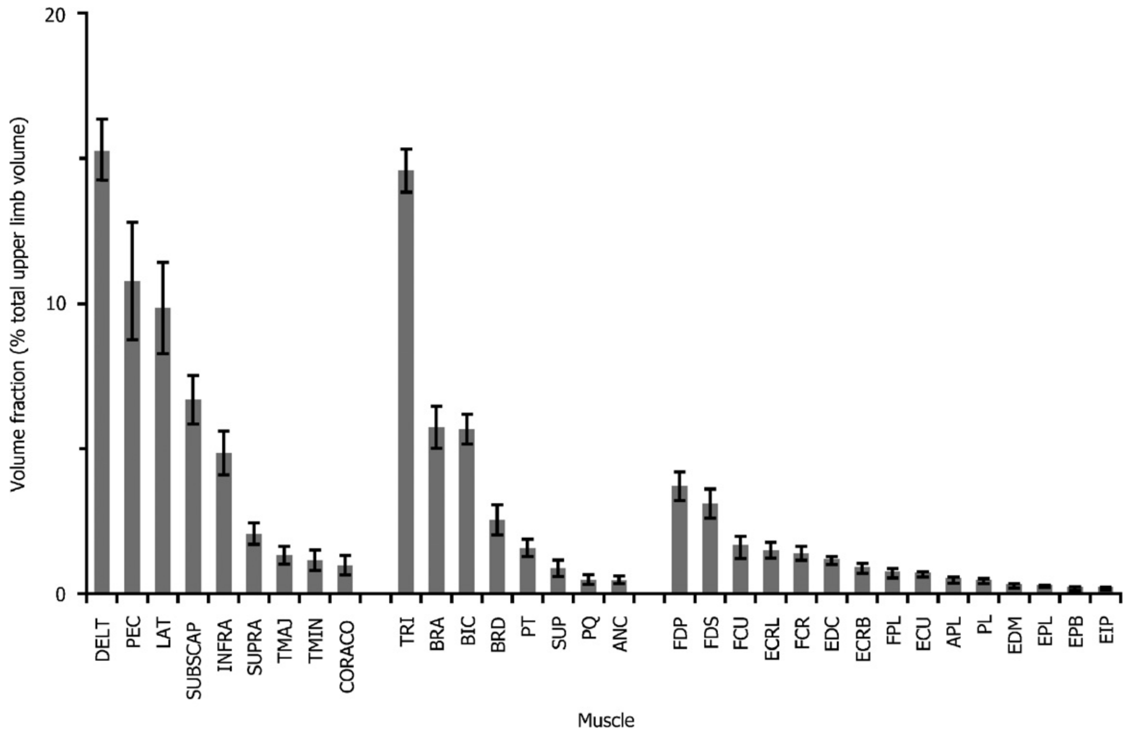

Fig. 2. Volume fractions for upper limb muscles. Muscles are grouped by anatomical region (shoulder, elbow and forearm, and wrist) and ordered within each group from largest volume fraction to smallest. The bar for each muscle represents the mean volume fraction with error bars representing one standard deviation for 10 subjects. The abbreviations for muscle names are defined in Table 2.

largest circumference measured on any axial slice. The length of each muscle was compared to the corresponding radius length using linear regression.

3. Results

The deltoid and triceps had the largest volume fractions. The deltoid had the largest mean volume fraction of muscles crossing the shoulder ($15.2\% \pm 1.0\%$) (Fig. 2). The triceps (combined three heads) had the largest volume fraction of muscles crossing the elbow ($14.5\% \pm 0.7\%$), and flexor digitorum profundus had the largest volume fraction ($3.7\% \pm 0.45\%$) crossing the wrist.

The distribution of muscle in the upper limb was consistent across the subjects, despite a three-fold variation in total muscle volumes (1427–4426 cm^3) (Table 2). Pectoralis major showed the largest variation, with a standard deviation of 2.0% of total muscle volume. The average standard deviation for all muscles was 0.4% of total muscle volume. The individual volume for a given muscle falls close to a line with a slope representing the average volume fraction for that muscle across 10 subjects (Fig. 3). When we predicted the volume of an individual muscle using the mean volume fraction, on average 85% of the variation among subjects was accounted for (average $p = 0.0008$). For all muscles, more than 70% of the variation was accounted for ($p < 0.001$), except for extensor pollicis brevis ($r^2 = 0.52$, $p = 0.015$), supinator ($r^2 = 0.68$, $p = 0.002$), and extensor indicis propius ($r^2 = 0.67$, $p = 0.003$).

The shoulder muscles comprised 52.5% of total muscle volume, elbow muscles comprised 31.5%, and wrist muscles comprised 16.0% (Fig. 4). Shoulder adductors made up 28.6% of total muscle volume, while abductors comprised 23.9%. At the elbow, flexors and extensors both made up approximately 15% of total muscle volume (15.3% and 15.0%, respectively). At the wrist, flexors (11.0%) had more than twice the muscle volume of extensors (5.0%).

On average, radius length accounted for 48% of variability in muscle length across subjects, although the relationship between bone length and muscle length varied among muscles. For deltoid, teres major, triceps, biceps, extensor carpi ulnaris, flexor carpi ulnaris, extensor pollicis longus, flexor digitorum superficialis, and flexor digitorum profundus, more than 70% of variability in muscle length was explained by radius length ($r > 0.84$, $p < 0.0008$) (Fig. 5). The variability in lengths of other muscles (pectoralis major, infraspinatus, extensor carpi radialis longus, and abductor pollicis longus) was less explained by radius length, but still had significant correlation ($r > 0.74$, $p < 0.01$). Less than 30% of variability in muscle length was explained by changes in radius length for subscapularis, coracobrachialis, brachioradialis, anconeous, supinator, pronator quadratus, flexor carpi radialis, palmaris longus, flexor pollicis longus, and extensor pollicis brevis ($r < 0.55$, $p > 0.07$).

Table 2
Muscle characteristics

Muscle	Abbreviation	Average volume (cm^3) (±SD)	Volume fraction (%) (±SD)	PCSA (cm^2) (±SD)	PCSA fraction (%) (±SD)	Length (cm) (±SD)
Latissimus dorsi	LAT	262.3 (147.2)	9.8 (1.5)	13.9 (6.5)	6.2 (1.0)	19.3 (3.3)
Pectoralis major	PEC	290.0 (169.0)	10.7 (2.0)	15.9 (8.3)	6.9 (1.4)	20.2 (2.2)
Deltoid	DELT	380.5 (157.7)	15.2 (1.0)	25.0 (8.7)	11.5 (0.8)	18.1 (1.8)
Supraspinatus	SUPRA	50.0 (20.4)	2.0 (0.3)	4.8 (1.6)	2.2 (0.3)	12.7 (1.2)
Infraspinatus	INFRA	118.6 (46.7)	4.8 (0.7)	11.9 (4.2)	5.5 (0.7)	14.0 (1.0)
Subscapularis	SUBSCAP	164.5 (63.9)	6.6 (0.8)	14.1 (4.4)	6.6 (0.7)	12.6 (1.4)
Teres minor	TMIN	28.0 (13.9)	1.1 (0.3)	3.7 (1.5)	1.7 (0.6)	11.5 (1.7)
Teres major	TMAJ	32.7 (16.3)	1.3 (0.3)	2.5 (0.9)	1.2 (0.3)	10.9 (1.9)
Coracobrachialis	CORACO	25.2 (16.6)	0.9 (0.3)	2.4 (1.3)	1.1 (0.2)	13.8 (2.7)
Triceps	TRI	372.1 (177.3)	14.5 (0.7)	40.0 (15.4)	18.2 (0.8)	27.0 (3.2)
Biceps	BIC	143.7 (68.7)	5.6 (0.5)	8.2 (3.4)	3.7 (0.3)	27.0 (2.6)
Brachialis	BRA	143.7 (63.7)	5.7 (0.7)	14.4 (5.9)	6.5 (0.6)	22.3 (2.1)
Brachioradialis	BRD	65.1 (36.0)	2.5 (0.5)	3.9 (1.8)	1.7 (0.3)	23.5 (2.5)
Anconeus	ANC	10.8 (5.2)	0.4 (0.1)	1.3 (0.6)	0.6 (0.1)	8.3 (1.7)
Supinator	SUP	19.7 (8.4)	0.8 (0.2)	2.3 (0.7)	1.1 (0.3)	8.8 (2.3)
Pronator teres	PT	38.4 (17.2)	1.5 (0.2)	6.5 (2.2)	3.0 (0.5)	16.1 (2.3)
Pronator quadratus	PQ	11.2 (5.8)	0.4 (0.1)	3.7 (1.9)	1.7 (0.5)	4.2 (0.5)
Extensor carpi radialis brevis	ECRB	21.6 (9.1)	0.9 (0.2)	2.5 (0.7)	1.2 (0.2)	17.6 (2.4)
Extensor carpi radialis longus	ECRL	37.5 (19.0)	1.5 (0.2)	2.7 (1.2)	1.2 (0.2)	22.2 (1.8)
Extensor carpi ulnaris	ECU	17.0 (7.4)	0.7 (0.1)	2.3 (0.9)	1.1 (0.2)	21.1 (2.4)
Flexor carpi radialis	FCR	34.8 (17.1)	1.3 (0.2)	3.9 (1.6)	1.8 (0.2)	22.6 (2.9)
Flexor carpi ulnaris	FCU	37.1 (13.6)	1.5 (0.3)	6.6 (2.0)	3.1 (0.6)	24.9 (2.0)
Palmaris longus	PL	10.0 (3.9)	0.4 (0.1)	1.4 (0.5)	0.7 (0.1)	6.0 (7.7)
Extensor digitorum communis	EDC	28.6 (12.7)	1.1 (0.1)	2.5 (0.8)	1.2 (0.2)	19.6 (3.2)
Extensor digiti minimi	EDM	7.0 (3.4)	0.3 (0.1)	0.9 (0.4)	0.4 (0.1)	17.6 (2.6)
Extensor indicis propius	EIP	4.2 (1.6)	0.2 (0.1)	0.8 (0.2)	0.4 (0.1)	9.5 (2.2)
Extensor pollicis longus	EPL	6.6 (3.4)	0.3 (0.0)	1.3 (0.5)	0.6 (0.1)	13.0 (2.9)
Extensor pollicis brevis	EPB	4.4 (2.2)	0.2 (0.1)	0.6 (0.2)	0.3 (0.1)	11.1 (2.6)
Flexor digitorum superficialis	FDS	74.2 (27.4)	3.0 (0.5)	6.0 (1.9)	2.8 (0.3)	24.5 (1.7)
Flexor digitorum profundus	FDP	91.6 (39.3)	3.7 (0.4)	8.4 (3.2)	3.8 (0.4)	23.4 (1.6)
Flexor pollicis longus	FPL	17.1 (6.3)	0.7 (0.2)	3.8 (1.3)	1.8 (0.3)	13.8 (1.7)
Abductor pollicis longus	APL	11.9 (5.7)	0.5 (0.1)	1.7 (0.6)	0.8 (0.1)	15.5 (2.1)
Total muscle volume		2554.0 (1166.7)				

The PCSA fraction calculated for each muscle was consistent across subjects (Table 2); the average standard deviation was 0.4% of total muscle PCSA. At the shoulder, deltoid, pectoralis major, and latissimus dorsi had PCSA fractions that were significantly smaller than the volume fraction for the same muscles ($p<0.001$). At the elbow, triceps, pronator teres, and pronator quadratus had significantly larger PCSA fraction than volume fraction ($p<0.001$), and biceps and brachioradialis had significantly smaller PCSA fraction than volume fraction ($p<0.001$). At the wrist, flexor carpi ulnaris, flexor pollicis longus, extensor carpi ulnaris, extensor pollicis longus, and extensor indicis propius had significantly larger PCSA fraction than volume fraction ($p<0.001$).

4. Discussion

We have measured muscle volume and estimated PCSA for the 32 muscles that cross the wrist, elbow, forearm, and shoulder. We have established that volume and PCSA fractions were consistent across these individuals with different total muscle volumes, and we have determined the distribution of muscle across the major joints of the upper limb. Interestingly, we observed that the muscle volume crossing the wrist on the flexor side is twice as large as the extensor side (Fig. 4). The wrist had the largest imbalance between antagonist muscle groups of any joint in the upper limb. In addition, the two largest muscles crossing the wrist were the flexor digitorum profundus and flexor digitorum superficialis, two muscles that flex the fingers. This highlights the importance of considering the role of finger muscles when examining wrist function (Gonzalez et al., 1997).

Our calculation of PCSA did not include scaling by cosine of pennation angle, as is done in some other studies (Sacks and Roy, 1982). Here we address only the force-generating capability of the fibers themselves; scaling by pennation can be incorporated by researchers as a separate step. Further, we used an estimate of fiber length rather than optimal fiber length in our PCSA calculation because we do not have measures of sarcomere length for these muscles. This may affect magnitudes of the PCSA estimates. However, despite these limitations, we are able to observe the possible effects of including a muscle length

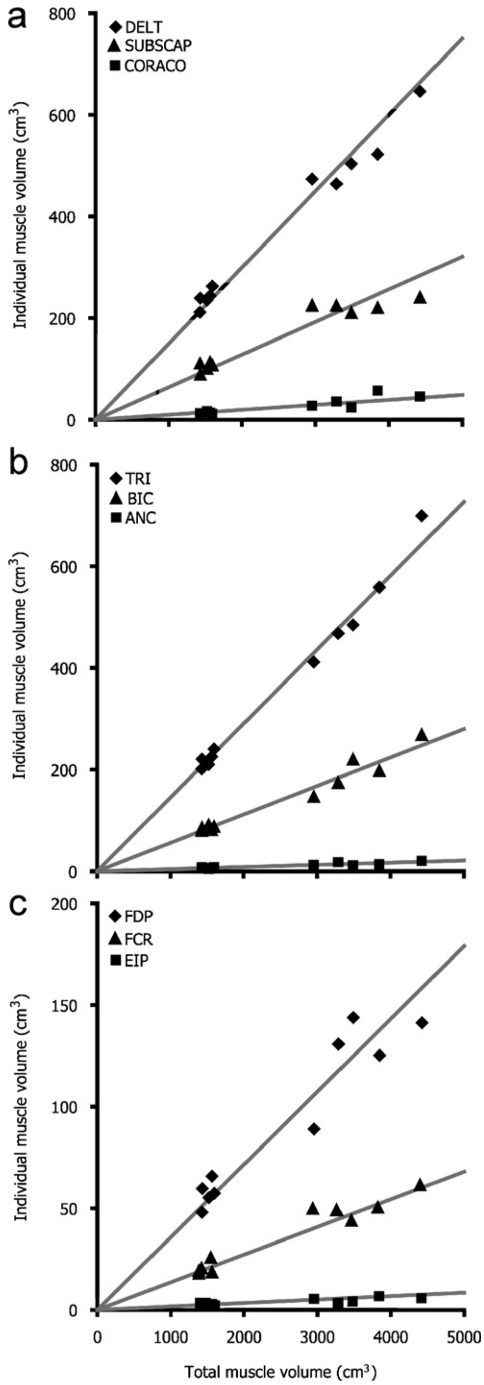

Fig. 3. Individual muscle volumes compared to total muscle volume for muscle crossing the shoulder (a), elbow (b), and wrist (c). The muscles with the largest volume fraction (diamonds), smallest fraction (squares), and an average fraction (triangles) for each muscle group are shown. For each muscle, the slope of the corresponding line is the average volume fraction calculated for 10 subjects. For all the representative muscles shown, the volumes fall close to the appropriate average line, demonstrating consistent muscle distribution across all subjects.

measurement on the distribution of muscle. For example, we noted that at the shoulder, muscles for which volume fraction and PCSA fraction were statistically different always had reduced PCSA fraction. This is consistent with the relatively long optimal fiber lengths (average = 12.9 cm)

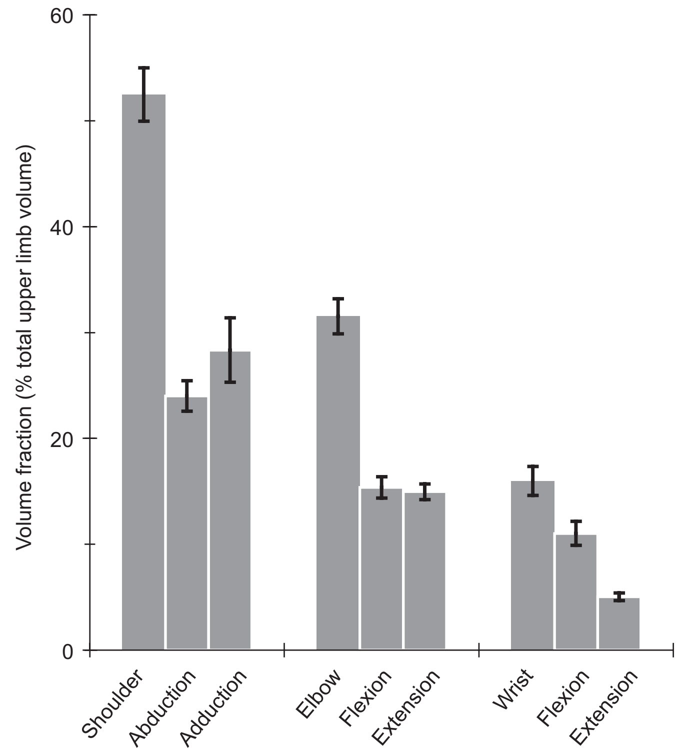

Fig. 4. Volume fraction for muscles crossing the shoulder, elbow and forearm, and wrist. Muscles are grouped with the joint of primary action (largest moment arm). The first bar in each group indicates the total volume fraction of all muscles crossing the joint of interest. The second and third bars in each group indicate volume fraction of muscles at a joint capable of creating abduction or adduction of the shoulder, flexion or extension of the elbow, and flexion or extension of the wrist.

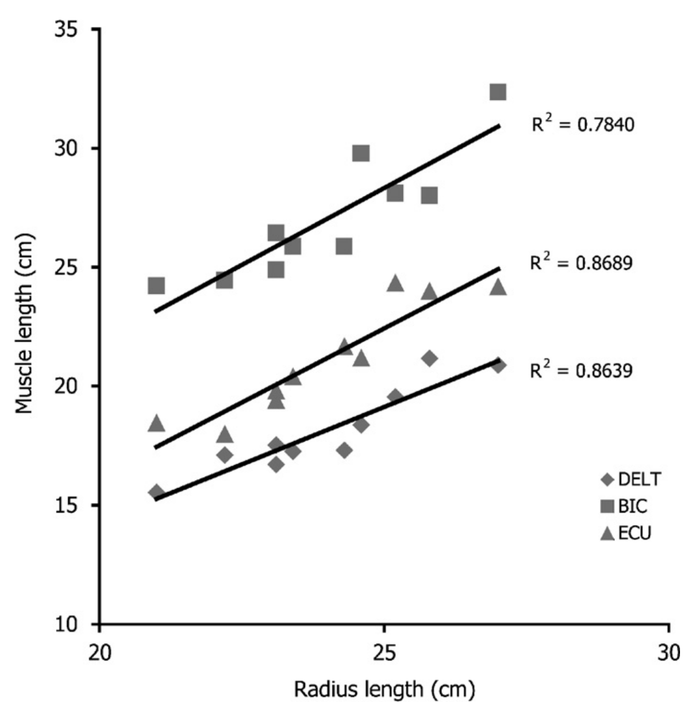

Fig. 5. Muscle length compared to radius length. The length of several muscles, including the deltoid (DELT, diamonds), biceps (BIC, squares), and extensor carpi ulnaris (ECU, triangles), correlated well ($r^2 > 0.7$) with radius length.

(Langenderfer et al., 2004) of muscles crossing the shoulder. At the wrist, muscles for which PCSA and volume fractions were different demonstrated increased PCSA fraction. This indicates that these muscles had relatively short optimal fiber lengths (average = 6.5 cm) (Lieber et al., 1990; Jacobson et al., 1992; Lieber et al., 1992). There was no distinct trend for muscles crossing the elbow.

We have presented muscle volumes and PCSAs and have shown how they scale for individuals of different size. Muscle fiber length, optimal fiber length, and moment arms may also scale with an individual's size, though we did not quantify those parameters here. There is evidence that moment arms for muscles crossing the elbow may scale with bone length or other bone dimensions, and that the degree of this scaling varies across muscles (Murray et al., 2002). It is unknown how moment arms may scale for muscles crossing other joints. Future work to determine scaling rules for moment arm and fiber length is necessary to create subject specific models that account for variations in these parameters.

Male subjects in this study were observed to have a stronger relationship between height and weight and total muscle volume than did female subjects. There was very little difference in total muscle volume among the five female subjects, despite the large range in height and weight. For the male subjects, there was a trend toward increased muscle volume with height ($r^2 = 0.77$, $p = 0.05$) and weight ($r^2 = 0.40$, $p = 0.25$). Further study is necessary to determine if these relationships are observed in a larger group of subjects.

Despite these observed differences between genders with respect to total muscle volume, we did not observe a difference between genders with respect to distribution of muscle in these 10 subjects. Therefore, these data suggest that once total muscle volume of a subject is known, individual muscle volume can be estimated without regard to gender. We did not observe strong relationships between total or individual muscle volumes and the other anthropometric measurements we measured.

The strong scaling of individual muscles and muscle groups with total muscle volume can be highlighted by normalizing subject-specific volumes by corresponding mean volumes for all 10 subjects (Fig. 6). When normalized total volume for a subject is compared to the normalized volume of muscle crossing each joint, all points fall near a line of unity slope with $r^2 = 0.9818$. This indicates that, for each subject, the sizes of individual muscles increase uniformly as total upper limb volume increases, and that the mean distribution of muscle in this study captures the distribution of muscle for each individual subject. That is, a single number, which we call the scaling ratio, can be used to represent the total and individual muscle volume of a subject. For a given muscle, a ratio greater than 1 indicates that its volume is larger than the mean. By assessing the volume of just a few muscles, the size of any subject can be estimated and the volume of all muscles can be determined using volume distributions reported in this study.

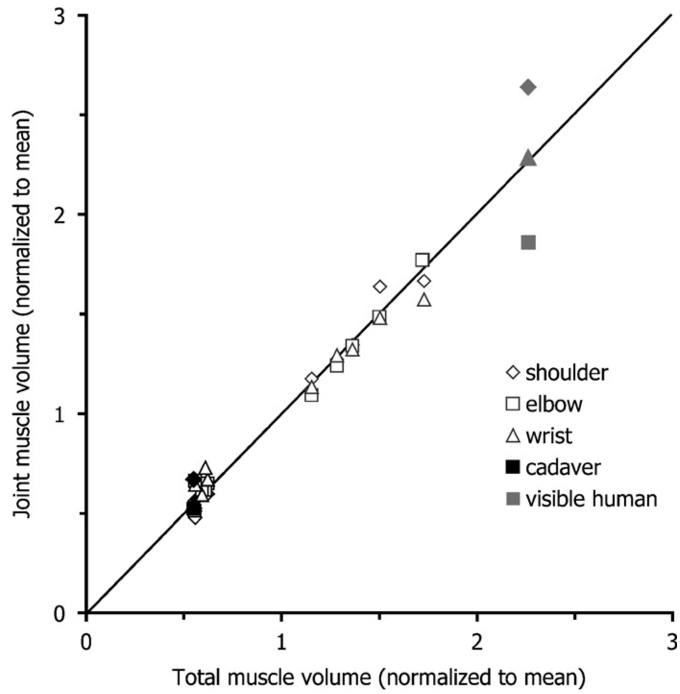

Fig. 6. Volume of muscles crossing a joint (normalized by mean muscle volume crossing the joint) compared to total muscle volume (normalized by mean total muscle volume). The subjects in this study (open data points) demonstrated uniform scaling of individual muscle volume with total muscle volume, as demonstrated by the points falling on the unity line. Data from cadaveric studies (An et al., 1981; Lieber et al., 1990; Jacobson et al., 1992; Lieber et al., 1992; Murray et al., 2000; Langenderfer et al., 2004) (black data points), when normalized by the corresponding mean volumes from this study, also fall on this line, indicating muscle volume distribution equivalent to that found in this study. Muscle volumes from cadaver studies are equivalent to the smallest females in this study. Muscle volumes from the Visible Human Data set (from the National Library of Medicine, National Institutes of Health) (gray data points, Garner and Pandy, 2001), when normalized by the means from this study, do not fall on the unity line, indicating that the shoulder muscles are relatively larger and the elbow muscles are relatively smaller than those found in this study. In addition, the volumes from the Visible Human Data set are almost 2.5 times the mean found in this study.

This study provides a normative data set that allows for investigation of other populations. Many researchers study populations that may have different muscle distributions, such as children, athletes, or patients following spinal cord injury or stroke. We may now be able to detect differences in muscle proportions from healthy adult subjects, which may help researchers uncover changes in muscle function with training or disease.

We compared our measurements of total muscle volume and muscle distribution to existing measurements of muscle volume for the shoulder (Langenderfer et al., 2004), elbow (An et al., 1981; Murray et al., 2000), and wrist (Lieber et al., 1990; Jacobson et al., 1992; Lieber et al., 1992) (Fig. 6). The volumes measured in these studies were normalized by the corresponding mean muscle volume measured in our study for comparison with scaling ratios measured for our subjects. The distribution of muscle measured in cadaveric studies of muscles crossing the shoulder, elbow, and wrist was the same as the distribution measured here, as evidenced by the fact that average scaling ratios for these studies also fall on the unity line. However, the total muscle volume reported by these previous studies is consistent with the smallest female subject in our study. One previous study used volumes of the Visible Human Male (from the National Library of Medicine, National Institutes of Health) (20 muscles common to this study) to investigate muscle architecture and force-generating capabilities (Garner and Pandy, 2001). This individual exhibits less constant scaling ratios among muscles crossing different joints than did subjects in our study; the volume of muscle crossing the shoulder was relatively larger than that crossing the elbow, and the volume of muscle crossing the wrist was relatively smaller. Only muscles common to both studies were considered in this analysis. In addition, the total muscle volume was equivalent to a male with much larger total muscle volume than the largest male in our study. The difference in muscle distribution in the Visible Human Male may be due to exercise related adaptation.

Measurements of volume fraction have also been made for forearm and hand muscles by Brand et al. (1981). Substantial agreement was observed between the volume fractions measured for muscles common to both studies ($r^2 = 0.9381$, $p < 0.00001$).

This study provides a wealth of data regarding the range of total muscle volume in normal adults of both genders and the distribution of this volume among muscles. We have shown that, given mean volume fractions reported here, a single parameter is sufficient to scale all upper limb muscles to represent a typical individual with different total muscle volume. We believe that this is powerful information for understanding the relationship among muscles of the upper limb and for supporting results of modeling and simulation that use mean muscle properties to understand muscle function.

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