Chapter 19
Upper Limb Muscle Volumes in Adults

Katherine R. Saul, Scott L. Delp, Garry E. Gold, and Wendy M. Murray

Abstract Muscle force-generating properties used in models are derived from measurements of muscle architecture, such as volume, cross-section, and fiber length. While the peak force a muscle can produce is related to its physiological cross-sectional area, several studies of muscle architecture have shown that muscle volume is an excellent predictor of joint moment-generating capacity, and is an important parameter for evaluating strength in the upper limb and for model development. Researchers have classically relied on dissection of cadavers to assess architectural properties of the muscles of the upper limb, including muscle volume, fiber length, sarcomere length, and pennation angle. Medical imaging approaches, including computed tomography, magnetic resonance imaging, and ultrasound have also been used to assess muscle force-generating properties in living subjects. In this review, the strengths and weaknesses of these approaches for assessing muscle volume in the upper limb are discussed. The volumes of muscles in the upper limb as measured by a number of researchers are summarized and compared. A study in which a magnetic resonance imaging approach is used to assess the muscle volumes of all the muscles crossing the shoulder, elbow, and wrist in living subjects is highlighted. It has been shown that the distribution of muscle volume in the upper limb is highly conserved across these subjects with a threefold variation in total muscle volumes (1,427–4,426 cm^3). The studies discussed in this review provide normative data that form 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.

Abbreviations

CT	Computed tomography
MRI	Magnetic resonance imaging
PCSA	Physiological cross-sectional area
TE	Echo time
TR	Repetition time

K.R. Saul (✉)
Department of Biomedical Engineering, Wake Forest School of Medicine,
Medical Center Boulevard, Winston-Salem, NC 27157, USA

VT-WFU School of Biomedical Engineering and Sciences, Winston-Salem, NC 270157, USA
e-mail: katesaul@gmail.com

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19.1 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 derived from measurements of muscle architecture, such as muscle volume, physiological cross-sectional area, and optimal fiber length (Zajac 1989). While the peak force a muscle can produce is related to its physiological cross-sectional area (defined in more detail below), several studies of muscle architecture have shown that muscle volume is also an excellent predictor of joint moment-generating capacity (Fukunaga et al. 2001; Holzbaur et al. 2007a). When compared to an anatomical cross-sectional area, muscle volume is a better predictor of strength in the upper limb (Akagi et al. 2009). Therefore, muscle volume is an important parameter for evaluating the strength of upper limb muscles and for developing models of the upper limb.

Frequently these parameters are determined via cadaveric studies of muscle architecture. However, cadaveric specimens may not accurately reflect the 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 (Jacobson et al. 1992; Lieber et al. 1990, 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 in many studies.

Several fundamental questions must be answered. What are the relative sizes of muscles in the upper extremity? Are the 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? In this review, we describe measurements of upper limb muscle size using dissection and various imaging techniques. In addition, we focus on a study in which these questions were addressed by measuring volumes of 32 muscles of the upper limb in young healthy subjects using magnetic resonance imaging (MRI) (Holzbaur et al. 2007b). This review provides a comprehensive evaluation of muscle volumes in the entire upper extremity.

19.2 Physiological Cross-Sectional Area

The isometric force a muscle can generate depends on the number of fibers in a muscle, the lengths of the fibers, and the orientation of the fibers relative to the tendon (Gans 1982). Physiological cross-sectional area (PCSA) is just one of a number of quantitative measures that are used to characterize the structural design of a muscle, often referred to as muscle architecture (Lieber and Friden 2000; Zajac 1989). PCSA is a measure of the muscle's total volume, normalized so that the maximum isometric force-generating capability of muscles with different numbers, lengths, and orientations of fibers can be directly compared based only on anatomical measurements.

The relationship of PCSA to the maximum isometric force a muscle can produce has been established experimentally. Of particular interest is a study by Spector et al. (1980) that quantified the forces produced by the soleus and the gastrocnemius in adult cats *in situ* and also characterized the architectural design of the contralateral muscles in the same animals. This study demonstrated that if the total volume of a muscle was normalized by optimal fiber length (the fiber length at which maximum isometric force is produced), and this normalized volume was corrected for the pennation angle of the fibers (the orientation of the fibers relative to the tendon), the resulting "physiological cross-sectional area" was directly proportional to maximum isometric force. Thus, PCSA provides an anatomically based, quantitative measure of the relative force-generating capacity of muscles of different sizes and architectural design. In fact, if PCSA is scaled by the specific tension of individual muscle fibers (the force generated per unit area), which can be considered to be a constant for all muscles (Zajac 1989), maximum isometric force can be accurately predicted.

Important points to keep in mind are embedded in the definition of PCSA. First, calculated PCSA is only proportional to the maximum force a muscle can produce if volume is normalized by *optimal* fiber length (Lieber 1993). This caveat about optimal fiber length is an important point because the force a muscle can produce varies with fiber length and muscles are capable of producing force over a large range of fiber lengths (Gordon et al. 1966). In addition, the traditional definition of PCSA incorporates a correction factor for pennation angle; specifically, the normalized volume is multiplied by the cosine of the pennation angle. This was critical in the study described above because the forces produced by the cat muscles were quantified by attaching their tendons to a force transducer. The force transmitted through the tendon differs from the force developed by the muscle fibers when the fibers are not oriented along the line of pull of the tendon.

Comparing PCSAs among muscles with different architectural designs allows researchers to quantitatively understand differences in force-generating capacity between muscles. However, when comparing the same muscle (i.e., the triceps brachii from a small female to the triceps brachii of a large male) or muscle groups across individuals, it seems that differences in muscle volume dominate the observed variability across subjects. For example, while in one study the relative variance (standard deviation/mean) of triceps volume was 47% (Holzbaur et al. 2007b), optimal fascicle length in triceps long head has been shown to have a relative variance of only 17% (Murray et al. 2000). It is for this reason that muscle volume is an excellent predictor of joint moment-generating capacity (Fukunaga et al. 2001; Holzbaur et al. 2007a), and why muscle volume is of such importance for researchers interested in understanding upper limb function from the context of *in vivo* anatomy.

19.3 Cadaveric Approach

The most common method by which the distribution and architecture of muscle has been assessed has been via dissection of cadaveric specimens. Typically, fresh frozen upper limbs are thawed and the muscles dissected and fixed in formalin, after which the architectural measurements can be made. This approach has the advantage of allowing detailed characterization of the volume, cross section, muscle belly and fiber length, tendon length, pennation angle, and sarcomere length of muscle. It is straightforward to combine these measurements to calculate PCSAs of individual muscles, which can then be scaled by specific tension to calculate the maximum isometric muscle force human muscles can produce. Because muscle forces cannot be directly measured in human subjects noninvasively, these results are of general interest. In addition, maximum isometric force is also an important parameter in biomechanical models (Zajac 1989).

Several studies have characterized the muscles of the upper limb using a cadaveric approach. Architecture of the forearm and hand muscles have been measured by Brand et al. (1981), Lieber et al. (1990, 1992), and Jacobson et al. (1992). The architecture of muscles crossing the elbow (An et al. 1981; Murray et al. 2000) and shoulder (Bassett et al. 1990; Langenderfer et al. 2004; Veeger et al. 1991; Wood et al. 1989) have also been measured. It is notable, however, that none of these studies assessed all of the muscles of the arm in the same specimens. In addition, while dissection of cadaveric specimens permits characterization of architectural details of muscle, it has some important limitations. The demographics of the specimen population are generally uncontrolled, and therefore may not be typical of the population at large. In particular, as described below, muscle volumes of cadaveric specimens do not represent those of young, healthy adults. In addition, dehydration effects may further underestimate muscle volume by 4–9% (Ward and Lieber 2005). Thus, while cadaveric dissection provides access to all of the parameters necessary to calculate PCSA, and therefore, maximum isometric force, the force magnitudes calculated using this approach are only valid for subjects with comparable muscle volumes to the cadaveric specimens.

19.4 Imaging Approaches

Medical imaging techniques, such as computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound, allow researchers to study muscle volume, fiber arrangement, and cross-sectional areas of muscle in living subjects. All of the modalities have been used to quantify muscle volumes, and have demonstrated accuracies for volumetric measurements between 1% and 5% (Audenaert et al. 2009; Berg et al. 2007; Tingart et al. 2003).

CT is a valuable modality for its speed of acquisition and its capacity to readily distinguish among bone, fat, and muscle. For that reason, it has been used to evaluate the infiltration of fat into muscle, for example in the gluteal muscles (Jolivet et al. 2008). It has been rarely used to characterize the upper limb, though it has been used to analyze the muscle, fat, and bone composition of the forearm in the trained and untrained limbs of male tennis players (Maughan et al. 1986). The difficulty associated with determining borders among individual muscles, as well as the radiation dosage, has limited its use in studies of this type when MRI is available.

MRI has been shown to provide enhanced contrast between anatomical borders of individual muscles while avoiding the radiation exposure of CT (Juul-Kristensen et al. 2000a; Lehtinen et al. 2003). 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%. While MRI allows one to capture information about a large number of muscles in an acquisition, it is extremely time consuming to manually identify the borders of the muscles to calculate muscle volumes, and reliable tools for automated segmentation of individual muscles have proven difficult to develop despite the enhancement of borders inherent to the imaging technique. In addition, the high clinical costs, long imaging times, and limited access associated with the modality limit its use in large studies. For this reason, cheaper and faster alternatives have been explored.

Ultrasound has also been considered as an alternative to either MRI or CT, as an inexpensive, portable method (Teefey et al. 1999) to accurately image muscle and fat (Juul-Kristensen et al. 2000b; Miyatani et al. 2000, 2004). However, because of the relatively limited field of view of ultrasound, estimates of muscle volume must be made from measurements of muscle thickness, limb length, and knowledge of the approximate shape of the muscle of interest (e.g. cylindrical, Miyatani et al. (2004) or triangular, Audenaert et al. (2009)). This approach has been used to successfully determine the volumes of deltoid (Audenaert et al. 2009), extensor digitorum communis (Brorsson et al. 2008), and elbow flexor and extensor muscles (Fukunaga et al. 2001; Miyatani et al. 2004), as well as fiber length and pennation angle (Fukunaga et al. 2001).

As compared to the cadaveric approach, medical imaging techniques have the benefit of providing a means to quantify important muscle architectural parameters in living human subjects. Thus, these valuable data can be acquired for populations of subjects for whom cadaveric specimens are not generally available. These populations include young, healthy adults, children, and persons with physical disabilities or musculoskeletal impairments. In contrast, an important limitation to imaging methods is that no imaging technique successfully quantifies all of the parameters necessary to calculate PCSA as traditionally defined (muscle volume normalized by optimal fiber length, corrected for pennation angle). A particularly important limitation is the inability to easily quantify optimal fiber length via imaging techniques. MRI provides a means to accurately quantify muscle belly lengths (e.g. Holzbaur et al. 2007b), and ultrasound is frequently used to quantify muscle fiber lengths (Maganaris et al. 2001). However, how these measured lengths relate to the optimal fiber length of a given muscle in a given subject cannot be quantified using either MRI or ultrasound. Thus, most imaging studies that estimate PCSA from their data normalize the measured muscle volumes by muscle belly lengths or fiber lengths measured from imaging, and scaled to better approximate optimum lengths using ratios of optimal fiber length to fascicle length measured in cadaveric experiments (Holzbaur et al. 2007b; Klein et al. 2001). However, these approximated fiber lengths may not correspond to optimum lengths for the particular subjects. Importantly, exciting advances in imaging techniques include methods that can track fiber architecture using MRI (Sinha et al. 2006), will may ultimately enable measurement of muscle volume, muscle belly length, muscle fiber length, and pennation angle using the same modality. Also, new methods have been developed that allow imaging of muscle at the sarcomere level (Llewellyn et al. 2008), which could ultimately allow fiber lengths measured using ultrasound to be normalized to fiber length.

19.5 Comprehensive Upper Limb Muscle Volume Assessment

One study (Holzbaur et al. 2007b) provides a comprehensive assessment of muscle volume in the upper limb for all muscles crossing the shoulder, elbow, and wrist in the same subjects. This study also presents calculated estimates of PCSAs for these muscles. While the accuracy of PCSA values determined from medical imaging has limitations (as we have described in this review), the authors demonstrated in a follow up study that the muscle volumes were strongly correlated to total isometric strength at the shoulder, elbow, and wrist (Holzbaur et al. 2007a). The strong relationship between muscle volume and joint strength has also been observed in other studies (Akagi et al. 2009; Fukunaga et al. 2001). As such, documentation of muscle volumes, and the variability in volume and distribution across different subjects and populations, is of interest to study.

The dominant arm of ten subjects (5 females, 5 male, 24–37 years, 158–188 cm tall, 50–86 kg) with no history of injury or pathology of the upper limb was studied. The subjects varied from a 20th percentile female to a 97th percentile male (Gordon et al. 1989), based on height (Table 19.1).

Each subject was imaged in a supine position 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 the 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, the three-dimensional geometries of the 32 upper limb muscles that cross the wrist, elbow, forearm, and shoulder (glenohumeral joint) were reconstructed (Fig. 19.1). 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,

Table 19.1 Subject characteristics

Subject[a]	Age	Height (cm)	Percentile[b] (height)	Weight (kg)	Percentile[b] (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	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	24	162.6	50	59.0	40	32.1	23.1	24.6	55.2	27.2	23.9
F4	30	165.1	65	52.2	10	31.2	22.2	24.9	53.4	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	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
M5	27	188.0	97	86.2	75	38.1	27	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)

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This table presents important anthropometric measurements for the subjects studied in Holzbaur et al. (2007), including height, weight, and length and circumference of the upper limb.

[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.

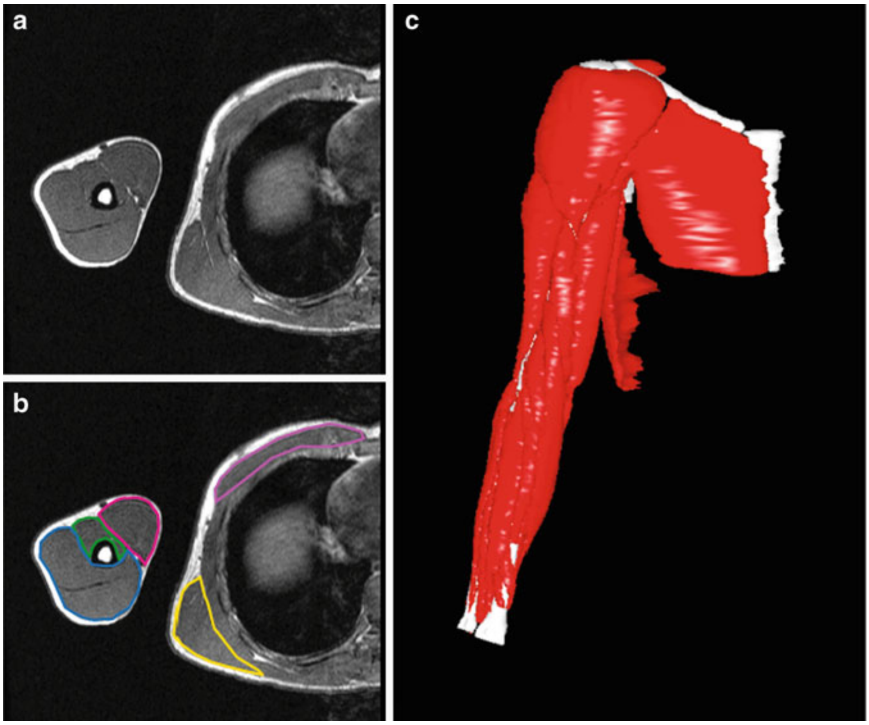

Fig. 19.1 Reconstructed muscle volumes for a representative subject. On each axial image (**a**) muscle structures were identified and the boundaries were manually outlined (**b**). The boundaries were used to create three-dimensional surfaces (**c**), from which volume and length were measured for each muscle. (Reprinted from Holzbaur et al. (2007b). With permission)

Able Software Corp., Lexington, MA). Thirty-two muscles were segmented in 4 subjects; 31 were segmented in 6 subjects. The palmaris longus was not identified in six subjects; this muscle is absent in some individuals (Dalley and Moore 1999).

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 across all ten subjects was calculated, as was the mean total muscle volume.

To determine the distribution of muscle volume among the muscles of a given subject, the volume fraction (Fraction_m), expressed as a percentage of total muscle volume, was calculated for each muscle:

$$\text{Fraction}_\text{m} = 100 \times V_\text{m} / V_\text{total}, \tag{19.1}$$

where V_m is the individual muscle volume and V_total is the total upper limb muscle volume for a given subject. The mean volume fraction for each muscle across the ten subjects was also calculated. The subject-specific volume fraction across all ten subjects was compared, and the degree to which the mean volume fraction for each muscle represented the volume fraction for an individual subject was examined by comparing the measured muscle volumes to the volumes predicted by multiplying the mean volume fraction by the total muscle volume of a subject.

To determine how muscle is distributed among the shoulder, elbow, and wrist the total volume of muscle crossing each joint for each subject were compared across subjects. Muscles that cross more than one joint were considered with the joint of their primary action (groups indicated in Fig. 19.2).

Physiological cross-sectional area (PCSA), an important parameter in maximal muscle force estimation, was estimated for all muscles based on the measured volumes (V_m), measured muscle length (L_m^{meas}), and muscle length to optimal fiber length ratios (L_m/L_m^o) available in the literature (An et al. 1981; Jacobson et al. 1992; Langenderfer et al. 2004; Lieber et al. 1990, 1992; Murray et al. 2000) according to the following equation:

$$\mathrm{PCSA} = \left(\frac{V_m}{L_m^{meas}}\right)\left(\frac{L_m}{L_m^o}\right) \tag{19.2}$$

Muscle length was measured from the reconstructed volumes as the length of the centroidal path of each volume from most proximal appearance of the muscle to the most distal (Lieber et al. 1992). Tendon length was not included in this calculation. 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 extensor digitorum superficialis) average ratios of muscle length to optimal fiber length (Langenderfer et al. 2004; Lieber et al. 1992; Murray et al. 2000) were used. Calculations of PCSA for each muscle, PCSA fraction as a percentage of total PCSA of the upper limb, and total PCSA at each joint, and means for these values across the ten subjects were calculated in the same manner as described for the volume calculations above. PCSA fraction was compared to volume fraction for each muscle using a paired *T* test.

Anthropometric measures, including humerus length, radius length, ulna length, total arm length, arm circumference, and forearm circumference, were measured on each subject. Arm length was calculated from the image data as the sum of the length of the radius and humerus. Forearm and arm circumference were measured from the image data as the largest circumference measured on any axial slice. The length of each muscle was compared to the radius length of that subject using linear regression to determine if muscle lengths scale with bone lengths.

19.6 Muscle Distribution in the Upper Limb

As reported by Holzbaur et al. (2007b), the muscles with the largest volume fractions are the deltoid and triceps. The deltoid (DELT) has the largest mean volume fraction of the muscles crossing the shoulder (15.2% ± 1.0%) and coracobrachalis (CORACO) has the smallest (0.9% ± 0.3%) (Fig. 19.2). The triceps (TRI) (combined three heads) has the largest volume fraction of muscles crossing the elbow (14.5% ± 0.7%) and anconeus (ANC) has the smallest (0.4% ± 0.08%). For muscles crossing the wrist, flexor digitorum profundus (FDP) has the largest volume fraction (3.7% ± 0.45%) and extensor indicis propius (EIP) has the smallest (0.2% ± 0.05%).

The distribution of muscle in the upper limb was consistent across the 10 subjects, despite a three-fold variation in total muscle volumes (1,427–4,426 cm^3) (Table 19.2). Pectoralis major showed the largest variation, with a standard deviation of 2.0% of total muscle volume, and extensor pollicis longus showed the least with 0.04% standard deviation. 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 all 10 subjects (Fig. 19.3). When the volume of an individual muscle was predicted 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 ($r^2 = 0.67$, $p = 0.003$).

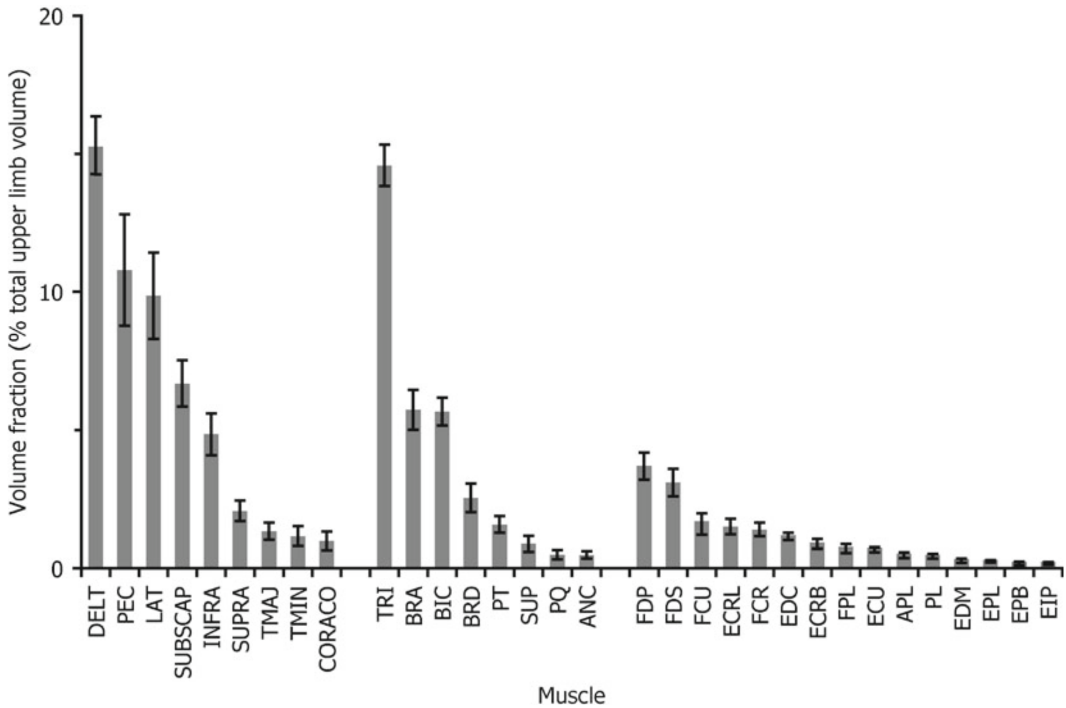

Fig. 19.2 Volume fractions for upper limb muscles. Muscles are grouped by anatomical region (shoulder, elbow and forearm, and wrist) and ordered within each group from largest volume fraction to smallest. The bar for each muscle represents the mean volume fraction with error bars representing one standard deviation for ten subjects. The abbreviations for muscle names are defined in Table 19.2. Reprinted from Holzbaur et al. (2007b). With permission)

The shoulder muscles comprise 52.5% of the total muscle volume, the elbow muscles comprise 31.4%, and the wrist muscles comprise 16.0% (Fig. 19.4). Shoulder adductors made up 28.3% of total muscle volume, while abductors comprised 24.0%. 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 the extensors (5.0%).

On average, the length of the radius accounted for 48% of the 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 the variability in muscle length was explained by the length of the radius ($r > 0.84$, $p < 0.0008$) (Fig. 19.5). The variability in the lengths of other muscles (pectoralis major, infraspinatus, extensor carpi radialis longus, and abductor pollicis longus) was less explained by radius length, but still had a significant correlation ($r > 0.74$, $p < 0.01$) between these two lengths. Less than 30% of the 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 ($r < 0.55$, $p > 0.07$).

The PCSA fraction calculated for each muscle was consistent across subjects (Table 19.2). Triceps had the largest PCSA fraction with 18.2% (±0.75%), and extensor pollicis brevis had the smallest

Table 19.2 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)				

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This table summarizes the mean values for muscle volume, PCSA, volume and PCSA fraction, and muscle length for the 32 muscles of the upper limb.

(0.28% ± 0.07%). 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 were significantly larger for PCSA fraction than for 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 a significantly larger PCSA fraction than volume fraction ($p < 0.001$).

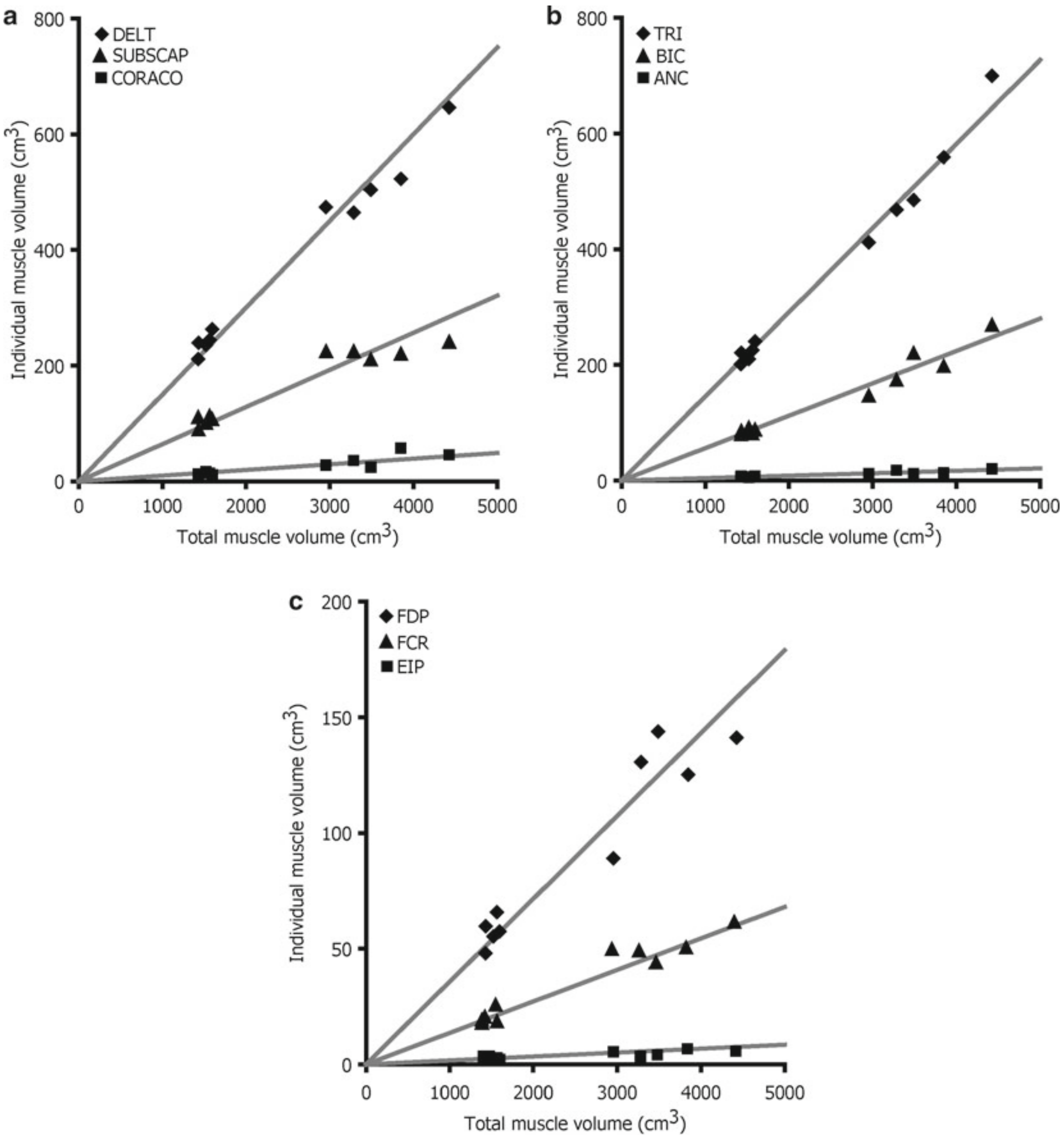

Fig. 19.3 Individual muscle volumes compared to total muscle volume for muscle crossing the shoulder (**a**), elbow (**b**), and wrist (**c**). The muscles with the largest volume fraction (*diamonds*), smallest fraction (*squares*), and an average fraction (*triangles*) for each muscle group are shown. For each muscle, the slope of the corresponding line is the average volume fraction calculated for ten subjects. For all the representative muscles shown, the volumes fall close to the appropriate average line, demonstrating consistent muscle distribution across all subjects. (Reprinted from Holzbaur et al. (2007b). With permission)

Pectoralis major had the largest variation of PCSA fraction across subjects, with a standard deviation of 1.4% of total muscle PCSA, and extensor pollicis longus had the least variation (standard deviation of 0.06%). The average standard deviation was 0.4% of total muscle PCSA.

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

A summary of muscle volumes reported by a number of studies is included in Table 19.3.

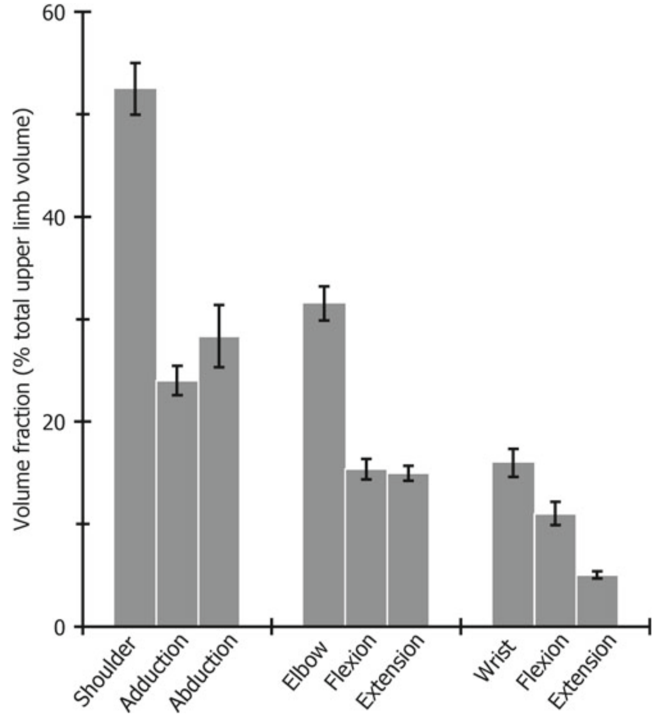

Fig. 19.4 Volume fraction for muscles crossing the shoulder, elbow and forearm, and wrist. Muscles are grouped with the joint of primary action (largest moment arm). The first bar in each group indicates the total volume fraction of all muscles crossing the joint of interest. The second and third bars 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. (Reprinted from Holzbaur et al. (2007b). With permission)

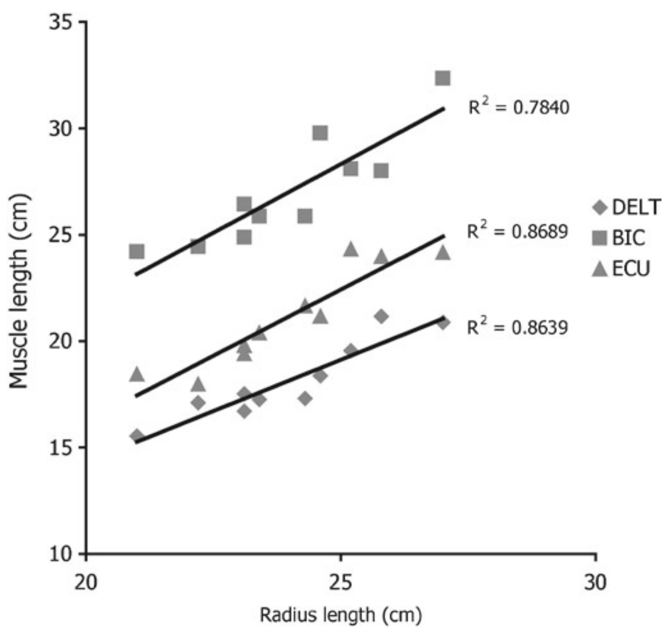

Fig. 19.5 Muscle length compared to radius length. The length of several muscles, including the deltoid (DELT, *diamonds*), biceps (BIC, *squares*), and extensor carpi ulnaris (ECU, *triangles*), correlated well ($r^2 > 0.7$) with radius length. (Reprinted from Holzbaur et al. (2007b). With permission)

Table 19.3 Summary of muscle volumes from multiple studies

Muscle	Abbreviation	Average volume (cm^3) Holzbaur	Garner	Langenderfer	Veeger (1991)	Veeger (1997)	An	Murray	Lieber et al. (1990)	Lieber et al. (1992)
Latissimus dorsi	LAT	262.3	549.7	193.2	226.1					
Pectoralis major	PEC	290.0	676.4	127.5	202.6					
Deltoid	DELT	380.5	792.9	204.4	314.4					
Supraspinatus	SUPRA	50.0	89.2	23.8	36.2					
Infraspinatus	INFRA	118.6	225.4	64.5	109.8					
Subscapularis	SUBSCAP	164.5	318.6	86.3	138.6					
Teres minor	TMIN	28.0	38.7	18.7	28.3					
Teres major	TMAJ	32.7	231.4	49.3	88.3					
Coracobrachialis	CORACO	25.2	80.0	16.1	30.6	42.0				
Triceps	TRI	372.1	620.0	152.3	99.7	379.0	152.6	153.5		
Biceps	BIC	143.7	365.8	56.2	111.2	128.0	64.2	69.4		
Brachialis	BRA	143.7	266.0	72.6		122.0	59.3	53.5		
Brachioradialis	BRD	65.1	83.2	20.2		66.0	21.9	21.2		18.0
Anconeus	ANC	10.8				11.0	6.7			
Supinator	SUP	19.7	34.1			17.0	10.9			
Pronator teres	PT	38.4	80.4			33.0	18.7	15.4		16.9
Pronator quadratus	PQ	11.2				12.0				5.3
Extensor carpi radialis brevis	ECRB	21.6					15.8		14.6	
Extensor carpi radialis longus	ECRL	37.5	166.6[a]				18.3	13.8	12.5	
Extensor carpi ulnaris	ECU	17.0	28.7				14.9		14.4	

(continued)

Table 19.3 (continued)

		Average volume (cm^3)								
Muscle	Abbreviation	Holzbaur	Garner	Langenderfer	Veeger (1991)	Veeger (1997)	An	Murray	Lieber et al. (1990)	Lieber et al. (1992)
Flexor carpi radialis	FCR	34.8	57.0				12.4		11.5	
Flexor carpi ulnaris	FCU	37.1	67.7				15.2		16.3	
Palmaris longus	PL	10.0					5.1			4.2
Extensor digitorum communis	EDC	28.6					23.5			16.9
Extensor digiti minimi	EDM	7.0								4.2
Extensor indicis propius	EIP	4.2								3.2
Extensor pollicis longus	EPL	6.6								5.3
Extensor pollicis brevis	EPB	4.4								
Flexor digitorum superficialis	FDS	74.2					35.9			42.2
Flexor digitorum profundus	FDP	91.6								57.0
Flexor pollicis longus	FPL	17.1								10.6
Abductor pollicis longus	APL	11.9								

This table summarizes the mean muscle volume measurements for several representative studies of upper limb muscle volume (An et al. 1981; Garner and Pandy 2003; Holzbaur et al. 2007b; Langenderfer et al. 2004; Lieber et al. 1990; Lieber et al. 1992; Murray et al. 2000; Veeger et al. 1991, 1997).

[a]The value for ECRL represents the combined ECRL and ECRB (Garner and Pandy, 2003).

19.7 Distribution of Muscle Across Joints

It has been shown that volume fraction and PCSA fraction were consistent across individuals with different total muscle volumes. A number of interesting observations about the way muscle is distributed across joints with respect to their function can be made. Interestingly, the muscle volume crossing the wrist on the flexor side is twice as large as the extensor side (Fig. 19.4). The wrist has the largest imbalance between antagonist muscle groups of any joint in the upper limb. In addition, the two largest muscles crossing the wrist are the flexor digitorum profundus and flexor digitorum superficialis, two muscles that flex the fingers. This highlights the importance of considering the role of the finger muscles when examining the function of the wrist (Gonzalez et al. 1997).

19.8 Physiological Cross-Sectional Area Distribution

By comparing the PCSA fraction and the volume fraction for muscles of the upper limb, one can observe the possible effects of including a muscle length measurement on the distribution of muscle. At the shoulder, the muscles for which the volume fraction and PCSA fraction were statistically different always had a reduced PCSA fraction. This is consistent with the fact that muscles crossing the shoulder have relatively long optimal fiber lengths (average = 12.9 cm) (Langenderfer et al. 2004). At the wrist, the muscles for which the 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) (Jacobson et al. 1992; Lieber et al. 1990, 1992). There was no distinct trend for muscles crossing the elbow.

It should be noted that in the calculations of PCSA made by Holzbaur et al. (2007b), scaling by the cosine of pennation angle was not performed. In this case, only the force-generating capability of the fibers themselves is considered; scaling by pennation can be incorporated by researchers as a separate step. Further, an estimate of fiber length was used rather than optimal fiber length in the PCSA calculation because measures of sarcomere length were unavailable. As discussed above, to date, medical imaging approaches are not able to capture information about optimal fiber length in living subjects.

19.9 Gender Differences

The Holzbaur et al. (2007b) study included both male and female subjects, and was able to note some differences in the subject groups. Male subjects were observed to have a stronger relationship between height and weight and total muscle volume than did the female subjects. There was very little difference in total muscle volume among the five female subjects, despite the large range in their 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.

Though there were observed differences between genders with respect to total muscle volume, a difference between genders with respect to the distribution of muscle was not observed. Therefore, these data suggest that once the total muscle volume of a subject is known, individual muscle volume can be estimated without regard to gender. No strong relationships between total or individual muscle volumes and the other anthropometric measurements were observed.

19.10 Scaling of Muscle Volume

The strong scaling of individual muscles and muscle groups with total muscle volume can be highlighted by normalizing the subject-specific volumes by the corresponding mean volumes for all ten subjects (Fig. 19.6). When the 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 size of individual muscles relative to the mean muscle volumes is the same as the ratio of total upper limb muscle volume to the mean total upper limb volume. For example, the tallest subject in the Holzbaur et al. study had a total muscle volume that was approximately 1.7 times the mean found in that study. This subject also had a volume of muscle crossing the shoulder that was approximately 1.7 the mean volume of muscle crossing the shoulder. That is, a single number, 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 the volume distributions reported in this study.

To facilitate comparison of muscle volumes measured from a number of the studies discussed in this review documenting muscle volumes at the shoulder (Langenderfer et al. 2004), elbow (An et al. 1981; Murray et al. 2000), and wrist (Jacobson et al. 1992; Lieber et al. 1990, 1992), the volumes measured in these studies were normalized by the corresponding mean muscle volume measured in the Holzbaur et al. study (Fig. 19.6). In this way, scaling ratios from all of these studies could be readily compared. The distribution of muscle measured in cadaveric studies of muscles crossing the shoulder, elbow, and wrist was the same as the distribution measured in the Holzbaur et al. study in living subjects, as evidenced by the fact that the 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 subjects. One previous study used the volumes of the Visible Human Male (from the National Library of Medicine, National Institutes of Health) to investigate muscle architecture and force-generating capabilities (Garner and Pandy 2001). This individual exhibits less constant scaling ratios among the muscles crossing different joints than did the subjects in the other studies; 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 the Garner and Pandy and Holzbaur et al studies were considered in this analysis. In addition, the total muscle volume of the Visible Human Male was very large compared to that of the other subjects and specimens in the literature. The difference in muscle distribution in the Visible Human Male may be due to exercise related adaptation. Comparing the mean muscle volumes from cadaveric studies and imaging based studies also reinforces the conclusion that muscle volumes in younger subjects are much larger than those measured in cadavers (Table 19.3).

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

19.11 Applications to Other Areas of Health and Disease

In this review, muscle volumes and PCSAs and how they scale for individuals of different size have been presented. Muscle fiber length, optimal fiber length, and moment arms may also scale with an individual's size. For example, 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

Table 19.4 Key features of upper limb muscle volume in young adults

1. Muscle volume and fiber arrangement, also called muscle architecture, are the major determinants of the force-generating capacity of muscle.
2. Imaging and dissection methods are both useful for characterizing muscle volume and architecture.
3. PCSA is an important measurement for predicting individual muscle force-generating capacity, while muscle volume can be used to evaluate differences in overall strength between individuals.
4. Volume fraction is consistent among healthy adults with different total muscle volumes.
5. Total muscle volumes vary substantially among individuals, and between studies of cadavers and living subjects.
6. The wrist has the largest volume imbalance between antagonist muscle groups of any joint in the upper limb.

This table lists the key facts regarding upper limb muscle volume, including how it is assessed, how it is distributed in the upper limb, and how it varies among individuals.

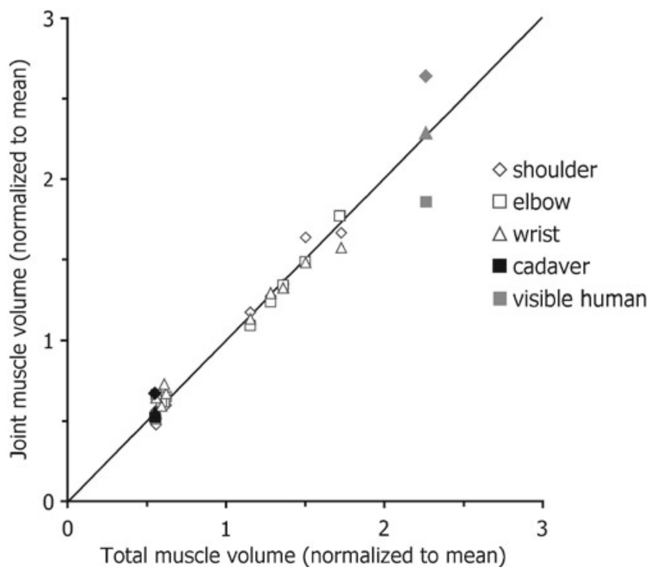

Fig. 19.6 Volume of muscles crossing a joint (normalized by mean muscle volume crossing the joint) compared to total muscle volume (normalized by mean total muscle volume). The subjects in the Holzbaur et al. (2007b) study (*open data points*) demonstrated uniform scaling of individual muscle volume with total muscle volume, as demonstrated by the points falling on the unity line. Data from cadaveric studies (An et al. 1981; Jacobson et al. 1992; Langenderfer et al. 2004; Lieber et al. 1990; Lieber et al. 1992; Murray et al. 2000) (*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 Holzbaur et al. Muscle volumes from cadaver studies are equivalent to the smallest females in Holzbaur et al. Muscle volumes from the Visible Human Dataset (from the National Library of Medicine, National Institutes of Health) (*grey data points*, Garner and Pandy 2001), when normalized by the means from Holzbaur et al. 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 other studies. In addition, the volumes from the Visible Human Dataset are almost 2.5 times the mean found in Holzbaur et al. (Reprinted from Holzbaur et al. (2007b). With permission)

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.

The studies presented in this review provide a normative data set that allows for investigation of other populations. Many researchers study populations that may have different distributions of muscle, 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.

Summary points

- Physiological cross-sectional area is an important measurement for predicting individual muscle force-generating capacity, while muscle volume can be used to evaluate differences in overall strength between individuals.
- Imaging and dissection methods are both useful for characterizing muscle volume and architecture.
- Dissection methods allow researchers to obtain measurements of muscle volume, optimal fiber length, and pennation angle in the same specimens, and permit accurate calculations of PCSA.
- Volumes in young healthy subjects are much larger than cadaveric specimens, so forces calculated from PCSAs measured in cadavers may be of limited applicability.
- Muscle volumes measured with medical imaging approaches are strongly correlated with strength in living subjects.
- Volume fraction is consistent among healthy adults with different total muscle volumes.
- Various studies of upper limb muscle show consistent volume fraction measurements; however, magnitudes of muscle volume can vary widely across individuals and studies.
- The wrist has the largest volume imbalance between antagonist muscle groups of any joint in the upper limb, with approximately twice as much as muscle volume on the flexor side.

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