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Moment-generating capacity of upper limb muscles in healthy adults

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Abstract

Muscle strength and volume vary greatly among individuals. Maximum isometric joint moment, a standard measurement of strength, has typically been assessed in young, healthy subjects, whereas muscle volumes have generally been measured in cadavers. This has made it difficult to characterize the relationship between isometric strength and muscle size in humans. We measured maximum isometric moments about the shoulder, elbow, and wrist in 10 young, healthy subjects, ranging in size from a 20th percentile female to a 97th percentile male. The volumes of 32 upper limb muscles were determined from magnetic resonance images of these same subjects, and grouped according to their primary function. The maximum moments produced using the shoulder adductors (67.9 ± 28.4 Nm) were largest, and were approximately $6.5(\pm 1.2)$ times greater than those produced using the wrist extensors (10.2 ± 4.6 Nm), which were smallest. While there were substantial differences in moment-generating capacity among these 10 subjects, moment significantly covaried with muscle volume of the appropriate functional group, explaining between 95% ($p < 0.0001$; shoulder adductors) and 68% ($p = 0.004$; wrist flexors) of the variation in the maximum isometric joint moments among subjects. While other factors, such as muscle moment arms or neural activation and coordination, can contribute to variation in strength among subjects, they either were relatively constant across these subjects compared to large differences in muscle volumes or they covaried with muscle volume. We conclude that differences in strength among healthy young adults are primarily a consequence of variation in muscle volume, as opposed to other factors.

Keywords: Upper limb; Strength; Scaling; Imaging; Biomechanics

1. Introduction

Studies that characterize strength of upper limb muscles have typically involved measurement of the maximum moment generated about a single joint in differing subject populations (Amis et al., 1980; Engin and Kaleps, 1980; Otis et al., 1990; Winters and Kleweno, 1993; Delp et al., 1996; Buchanan et al., 1998). As a result, it is difficult to combine data from previous studies to determine the relative moment-generating capacity of the different joints of the upper limb. Studies that characterize strength of the entire upper limb often focus on functional tasks, such as weight lifting (Hortobagyi et al., 1989) or pushing (Roman-Liu and Tokarski, 2005). While evaluating strength in the context of a functional task is important, these relatively complex tasks may highlight the motor coordination required to complete that specific task, rather than revealing the maximum moment-generating capacity of each muscle group. Garner and Pandy (2001) reported the moment-generating capacity of the muscles crossing the shoulder, elbow, forearm, and wrist in three male subjects, and provided valuable insight into the relative strength of upper limb muscles in this population.

Upper limb muscle size has typically been characterized in cadaveric specimens (An et al., 1981; Lieber et al., 1990, 1992; Jacobson et al., 1992; Murray et al., 2000; Langenderfer et al., 2004). The physiologic cross-sectional areas of muscles in cadavers do not reflect the absolute size

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Table 1
Subject characteristics and maximum isometric moments

Subject[a]	Age	Height (cm)	Percentile[b] (height)	Weight (kg)	Percentile[b] (weight)	Shoulder moments (Nm)		Elbow moments (Nm)		Wrist moments (Nm)	
						Abduction	Adduction	Flexion	Extension	Flexion	Extension
F1	24	157.5	20	49.9	5	31.6	43.0	23.5	23.1	10.3	6.7
F2	36	162.6	50	49.9	5	39.2	48.0	35.2	28.4	7.6	6.7
F3	24	162.6	50	59.0	40	28.3	42.8	38.0	24.0	14.4	6.8
F4	30	165.1	65	52.2	10	41.3	43.5	32.4	23.5	8.6	7.0
M1	28	172.7	35	72.6	30	75.1	81.4	78.2	62.3	22.7	14.0
M2	27	175.3	50	83.9	70	55.6	91.1	68.3	57.6	26.6	12.9
M3	37	175.3	50	93.0	90	79.7	111.7	90.8	52.3	37.2	19.3
F5	26	177.8	99	72.6	90	34.4	33.3	30.3	26.2	12.4	4.8
M4	27	177.8	65	72.6	30	79.3	88.9	82.1	69.1	22.4	9.8
M5	27	188.0	97	86.2	75	82.3	95.6	78.1	61.4	18.9	13.8
Mean female (±SD)	28.0 (5.1)	165.1 (7.6)	56.8 (28.7)	56.7 (9.6)	30.0 (36.6)	34.9 (5.4)	42.1 (5.4)	31.9 (5.5)	25.0 (2.2)	10.7 (2.7)	6.4 (0.9)
Mean male (±SD)	29.2 (4.4)	177.8 (6.0)	59.4 (23.5)	81.6 (8.9)	59.0 (27.5)	74.4 (10.8)	93.7 (11.3)	79.5 (8.1)	60.5 (6.2)	25.6 (7)	14.0 (3.4)
Mean total (±SD)	28.6 (4.5)	171.5 (9.3)	58.1 (24.8)	69.2 (15.8)	44.5 (34.1)	54.7 (22.3)	67.9 (28.4)	55.7 (25.9)	42.8 (19.2)	18.1 (9.3)	10.2 (4.6)

[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).

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of muscles in the upper limb in young healthy subjects (Holzbaur et al., 2007). Magnetic resonance imaging (MRI) allows assessment of muscle volume and other features (Asakawa et al., 2002; Pappas et al., 2002; Tingart et al., 2003) in subjects for whom we can also assess moment-generating capability.

Isometric strength is highly correlated to muscle volume and cross-sectional area at the elbow (Kanehisa et al., 1994; Fukunaga et al., 2001; Klein et al., 2001). The shoulder and wrist differ in structural complexity and purpose from each other and from the elbow; thus, it is unclear if a relationship between muscle volume and isometric strength also exists at these joints. If such a relationship were to exist, it would provide insight to the functional design of the upper limb, and elucidate a general principle governing the transformation from muscle mass to physical strength.

The purpose of this study is (1) to assess the relative moment-generating capacity of muscles at the shoulder, elbow, and wrist in males and females, and (2) to evaluate the degree to which variation in moment-generating capacity among subjects can be explained by differences in their muscle volumes.

2. Methods

Ten subjects (5 females, 5 males, 24–37 years, 158–188 cm tall, 50–86 kg) with no history of injury or pathology of the upper limb were studied. The subjects ranged from a 20th percentile female to a 97th percentile male (Gordon et al., 1989), based on height (Table 1). All subjects provided informed consent in accordance with institutional guidelines. The dominant arm of each subject was tested; in all cases the right limb was dominant.

Isometric joint moments produced during a maximum voluntary contraction were quantified for six muscle groups using a Biodex System3

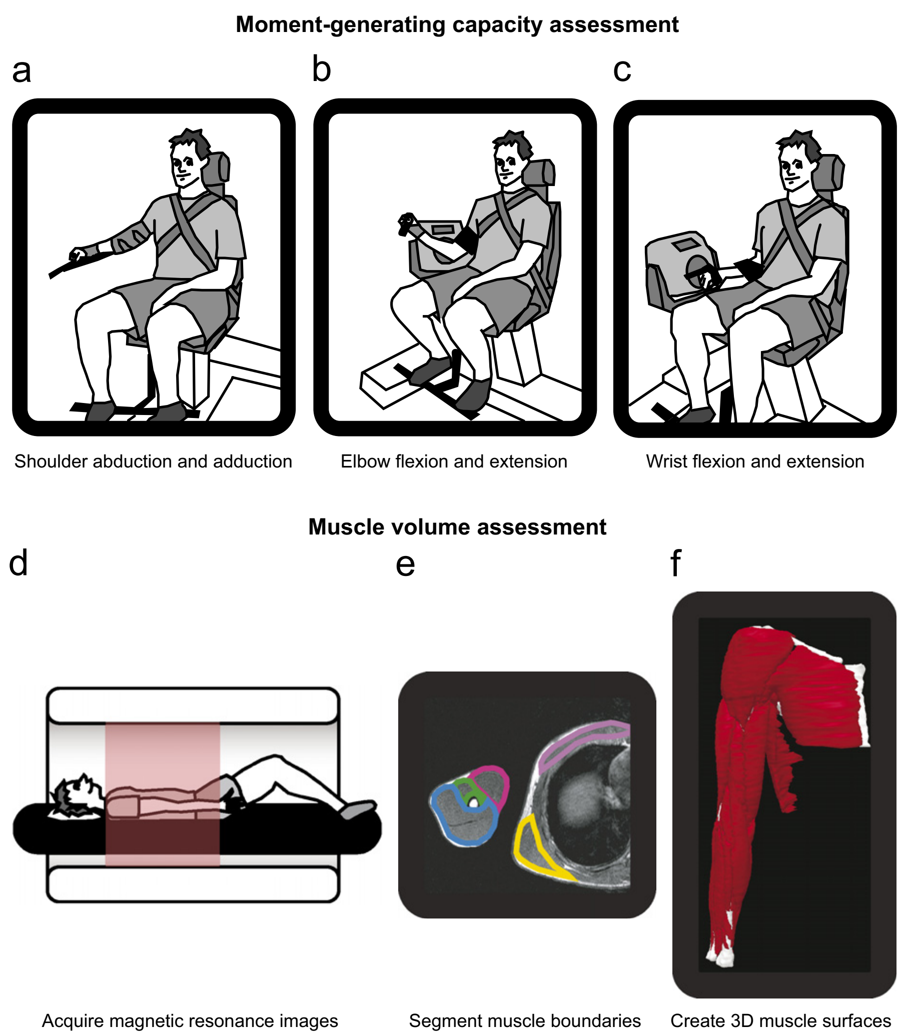

Fig. 1. Muscle volume and moment-generating capacity assessments. Maximum isometric moment-generating capacity (top) was assessed at the (a) shoulder (in abduction and adduction), (b) elbow (in flexion and extension), and (c) wrist (in flexion and extension). The elbow and wrist were braced during maximal shoulder tasks, and the wrist was braced during maximal elbow tasks. The subject was restrained to minimize torso motion. Muscle volume was assessed (bottom) using (d) magnetic resonance imaging to acquire images for the anatomical region shown shaded in red. (e) Muscle boundaries were identified on individual images and (f) three-dimensional muscle surfaces were created from these boundaries. Volumes were calculated based on these surfaces.

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(Biodex Medical Systems, Shirley, NY). Maximum shoulder abduction and adduction moments were assessed with the shoulder positioned at 60° abduction with the elbow braced in an extended posture (IMAK Products Corporation, San Diego, CA), the forearm in neutral rotation, and the wrist braced in neutral flexion and deviation (Thermoskin by United Pacific Industries, Kilsyth, Australia) (Fig. 1a). Extension and flexion moments at the elbow were assessed with the elbow in 90° flexion, the forearm supinated, the shoulder in neutral abduction, and the wrist braced in a neutral posture (Fig. 1b). Extension and flexion moments at the wrist were measured with the wrist in a neutral posture, the forearm pronated, the shoulder in neutral abduction, and the elbow flexed to 90° (Fig. 1(c)). For all tests, the subject was seated, and the torso restrained with straps placed around the trunk. For each test, the axis of rotation of the joint of interest was aligned with the center of rotation of the dynamometer. Because the Biodex System3 attachments for shoulder and elbow tests transmit load through the wrist to the hand grip, we used rigid splints to brace distal joints not being tested. We also modified the hand grip so that the hand was fixed to the grip with a padded locking cuff, allowing effective force transmission for all isometric tests and restricting rotation of the hand on the grip. Finally, the choice of joint postures was intended to isolate the muscle group being tested.

For each muscle group, we collected three trials of 3 s duration. Data were sampled at 100 Hz. Subjects were instructed to produce a maximum voluntary contraction and were given visual and verbal feedback to encourage performance. To minimize the effects of fatigue, 60 s of rest was provided in between trials, and the order in which joints were tested was randomized across subjects.

For each subject, the maximum isometric moment produced using a given muscle group was calculated after the testing session was completed. For each trial, maximum moment was determined by identifying the 0.5 s window during which the largest moment was maintained, and then averaging over the window (Fig. 2). The maximum moments from all three trials were averaged to estimate the representative moment produced for that muscle group. The average coefficient of variation (standard deviation/mean) for all muscle groups and all subjects was 6.5%, indicating that each subject produced comparable moments in repeated trials. To compare relative strengths at each joint, we used the Wilcoxon Signed-Ranks test ($n = 10$), with an experiment-wide $p < 0.05$, adjusted for multiple comparisons using the Bonferonni correction to $p < 0.0033$ for individual comparisons.

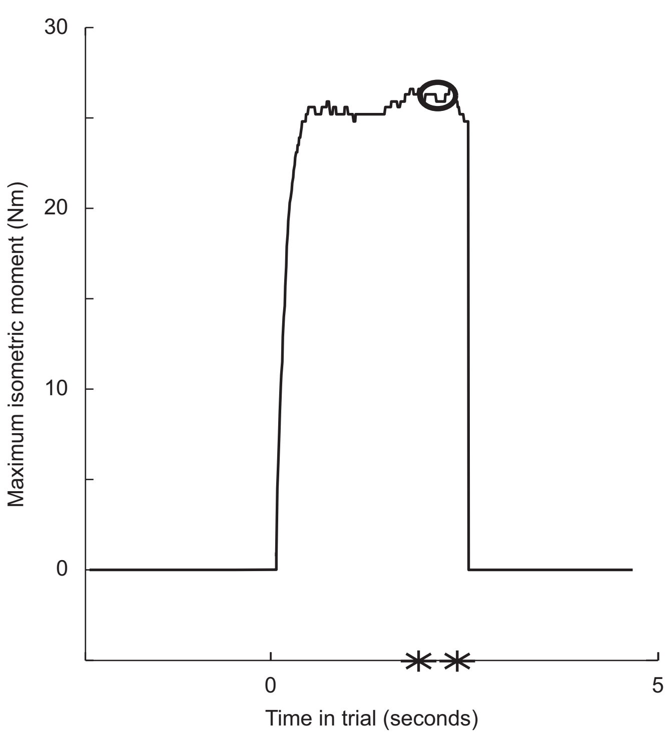

Fig. 2. Example data trace for a single 3 s trial. This example was obtained from the test of elbow extension moment for subject F5. Stars indicate the 0.5 s period during which the highest average moment was recorded. The circle indicates the peak moment determined by averaging over the 0.5 s period.

Table 2
Functional groups of muscles

Shoulder abduction	Shoulder adduction
Deltoid	Latissimus dorsi
Subscapularis	Pectoralis major
Supraspinatus	Infraspinatus
	Teres minor
	Teres major
	Coracobrachialis
Elbow flexion	**Elbow extension**
Biceps brachii	Triceps brachii
Brachialis	Anconeus
Brachioradialis	Supinator
Pronator teres	
Wrist flexion	**Wrist extension**
Flexor carpi radialis	Extensor carpi radialis longus
Flexor carpi ulnaris	Extensor carpi radialis brevis
Palmaris longus	Extensor carpi ulnaris
Flexor digitorum superficialis	Extensor digitorum communis
Flexor digitorum profundus	Extensor digiti minimi
Flexor pollicis longus	Extensor indicis propio
Abductor pollicis longus	Extensor pollicis longus
	Extensor pollicis brevis

The same subjects were imaged in a 1.5 T MRI scanner (GE Healthcare, Milwaukee, WI), and three-dimensional reconstructions were created of the geometry of the 32 muscles of the upper limb crossing the shoulder (glenohumeral joint), elbow, and wrist (Fig. 1d–f). From these reconstructions we measured the volume of each muscle. We provide details on volume determination and establish the accuracy of this method in a previous publication (Holzbaur et al., 2007).

To evaluate the relationship between joint moment and muscle volume, we grouped the muscles according to their primary function (Table 2); these groups were determined using the peak moment arm of each muscle found using a musculoskeletal model that characterizes the geometry of the upper limb (Holzbaur et al., 2005). We compared the sum of the volumes of muscles in each group to the corresponding maximum moment measured for each subject using linear regression analysis. We used the coefficient of determination (r^2) to evaluate the degree of covariation in the maximum isometric moment and total muscle volume for a functional group. We also performed a multivariate analysis, considering the effect of muscle volume, muscle group, gender, and subject weight on the maximum isometric joint moment, with moment and volume measurements adjusted by taking the square root to normalize the range. This prevents bias due to differences in the ranges of volume and moment observed for the various functional groups. Results were considered significant for both analyses for $p < 0.01$.

3. Results

Maximum isometric moments varied substantially, both across different subjects and different functional muscle groups that were evaluated. Standard deviations for a given joint averaged 57% of the average moment,

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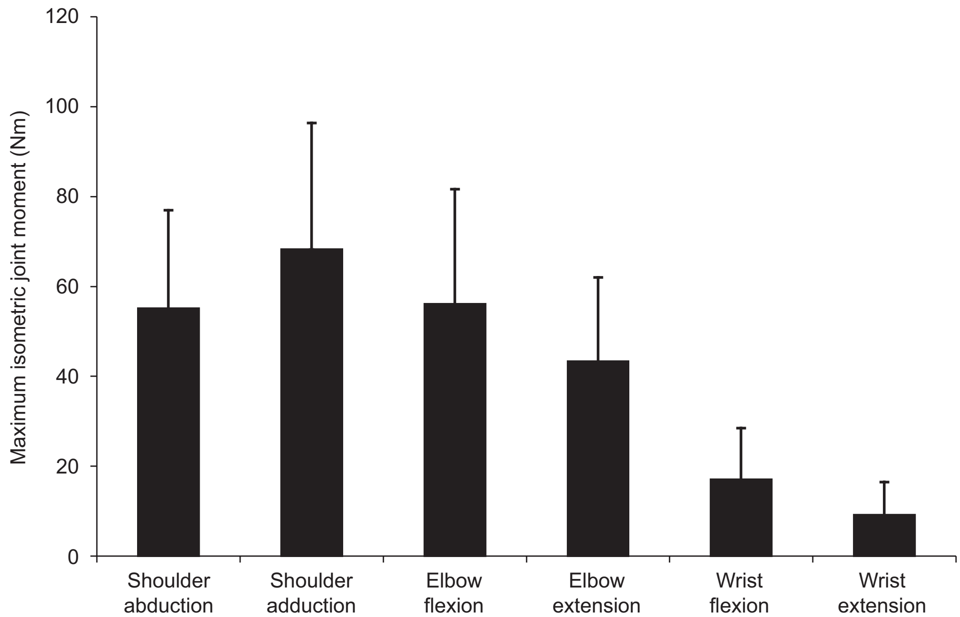

Fig. 3. Maximum isometric joint moments generated about the shoulder, elbow, and wrist. Bars indicate the mean for 10 subjects, with one standard deviation shown with the error bars.

illustrating the high variability in joint moments produced by these subjects. We observed over a sixfold difference ($p = 0.002$) in the maximum moments produced during shoulder adduction and wrist extension, the largest difference between any two functional groups we tested (Fig. 3). Elbow flexion moments were significantly greater than elbow extension moments ($p = 0.002$), which were greater than wrist flexion moments ($p = 0.002$), followed by wrist extension moments ($p = 0.002$).

While there were substantial differences in strength among these 10 subjects, an average of 80% of the variation in the maximum joint moments was accounted for by differences in muscle volumes between subjects, as determined using regression analysis ($n = 10$) (Fig. 4). At the shoulder, 90% of the variation in maximum shoulder abduction moment was accounted for by the sum of the volumes of the shoulder abduction muscles ($p < 0.0001$) (Fig. 4a). The total volume of shoulder adductors explained 95% of variation in maximum isometric shoulder adduction moment ($p < 0.0001$) (Fig. 4b). At the elbow, 83% of variation in flexion moment ($p = 0.0001$) (Fig. 4c) and 76% of the extension moment was accounted for by muscle volumes ($p = 0.0006$) (Fig. 4d). At the wrist, 68% of variation in flexion moment ($p = 0.0035$) (Fig. 4e) and 68% of variation in extension moment ($p = 0.0035$) (Fig. 4f) were accounted for by the volume of wrist flexor muscles and extensor muscles, respectively.

The multivariate analysis considering muscle volume, muscle group, gender, and subject weight revealed a significant effect on maximum isometric joint moment only for muscle volume ($p < 0.001$). The within-subject correlation coefficient was 0.373, indicating that 14% of the variation in maximum isometric joint moment was due to differences in subject-specific characteristics other than volume.

4. Discussion

This study is the first to evaluate moment-generating capacity of muscles about the shoulder, elbow, and wrist in a group of subjects with known muscle volumes. For each of the six functional muscle groups, the strongest subject generated moments that were approximately 2.5 times greater than the weakest subject. We observed over a sixfold difference in maximum isometric moments between the strongest (shoulder adductors) and weakest (wrist extensors) functional groups. Isometric moments produced during maximum voluntary effort significantly covaried with the sum of the volumes of muscles in the corresponding functional group. We conclude that variation in isometric strength among healthy young adults is primarily a consequence of differences in muscle volume.

The magnitude of isometric moment produced about a joint during maximum effort depends on levels of activation of muscles spanning the joint and joint posture (which influences both the mechanical advantages of muscles and muscle lengths); muscle force is highly dependent on its length (Gordon et al., 1966) and the architectural arrangement of the fibers of the muscle (Zajac, 1989). Because many different factors contribute to moment produced about a joint, it is interesting that muscle volumes covaried so strongly with isometric strength for six different muscle functional groups at three joints with substantial differences in geometric design and kinematic complexity. The high degree of variation in maximum joint moments explained by muscle volumes suggests that, while other factors have the potential to contribute to variation in isometric strength among subjects, they either were relatively constant across these subjects compared to the large differences in muscle volumes or they covaried with

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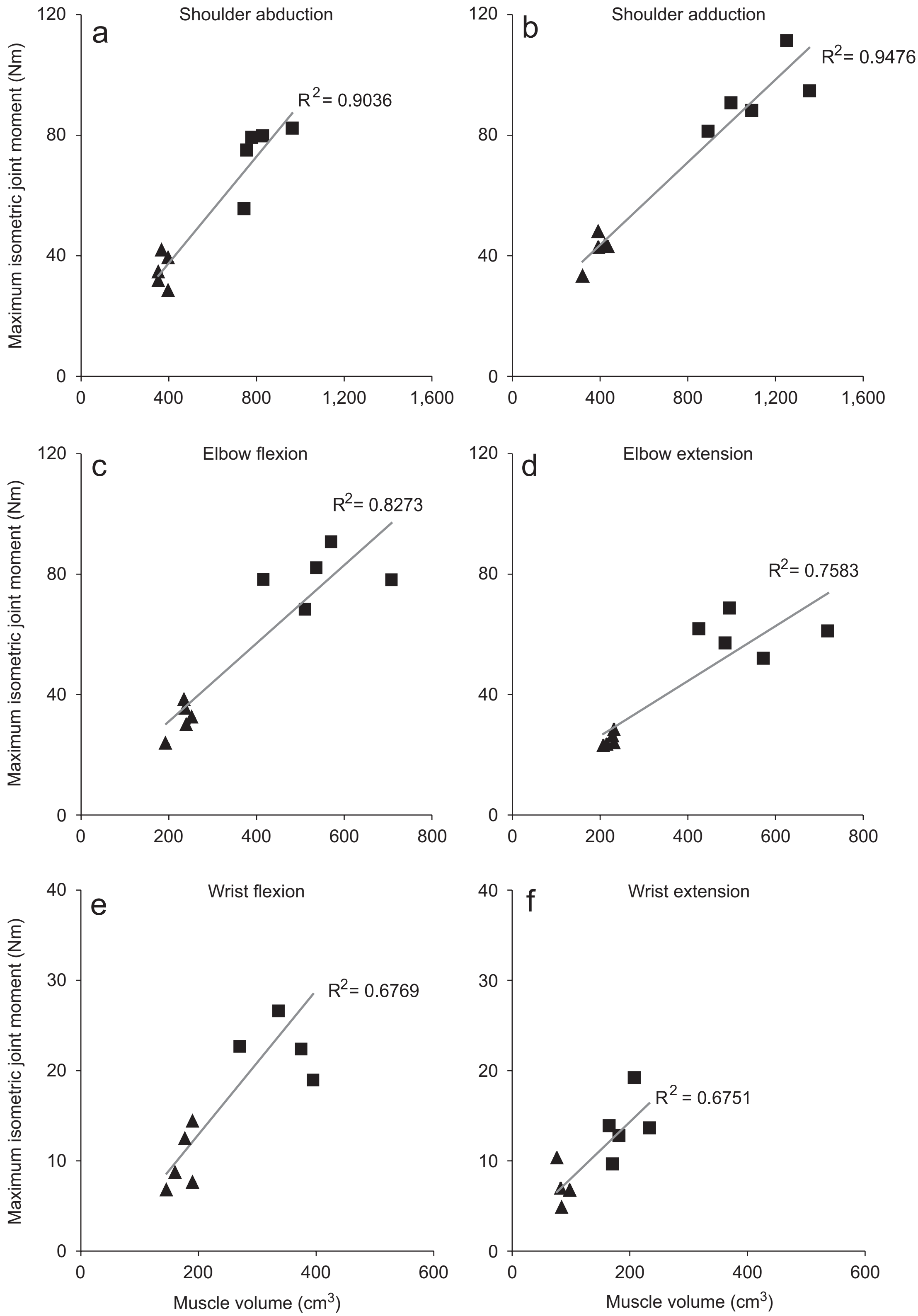

Fig. 4. Maximum isometric moment versus total volume of muscles in the corresponding functional group. Data points for all 10 subjects are shown as squares (male subjects) and triangles (female subjects) for shoulder abduction (a) and adduction (b), elbow flexion (c) and extension (d), and wrist flexion (e) and extension (f). Strong correlations ($r^2 > 0.67$, $p < 0.0001$) between moments and volumes indicate that most of the variation in strength across subjects can be explained by the differences in muscle volume.

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muscle volume. We previously observed coefficients of variation (SD/mean) on the order of 10–20% for moment arms and muscle fascicle lengths measured from cadaveric specimens that spanned a comparable height range as these subjects (Murray et al., 2000, 2002). In contrast, the coefficient of variation for total muscle volume for 10 subjects studied here was approximately 45%. The large differences in muscle volume between subjects accounted for a high fraction of differences in moment-generating capacity among individuals.

Muscle volumes obtained from cadaveric experiments do not correspond to the magnitude of joint moments measured at the shoulder and elbow in adult human subjects. We have shown (Holzbaur et al., 2007) that muscle volumes from cadaveric studies (An et al., 1981; Lieber et al., 1990, 1992; Jacobson et al., 1992; Murray et al., 2000; Langenderfer et al., 2004) are consistent with muscle volumes of the smallest individuals in our study. However, only previously measured values of maximal moment for wrist flexion and extension (Delp et al., 1996) are consistent with the smaller individuals in this study. This mismatch between cadaveric data and previous literature describing moment-generating capacity at the shoulder and elbow in living subjects explains why it has been difficult to represent accurately the magnitudes of isometric moments for these joints using computer models that are derived from cadaveric data (see Holzbaur et al., 2005 for summary).

Moment-generating capacity depends on joint position, but we report strength for a single posture for each joint as we sought to quantify the degree of variability in isometric moment-generating capacities for healthy individuals spanning a broad size range. We did not measure the moment–angle relationship over the range of motion; the general relationships between isometric moment and joint posture have been previously established for the shoulder, elbow, and wrist (Amis et al., 1980; Otis et al., 1990; Delp et al., 1996; Buchanan et al., 1998; Garner and Pandy, 2001). While the relative strengths presented here (Fig. 3) may not reflect relative strength in different limb configurations, the significant relationship identified between volume and moment should not be affected by the choice of posture. Rather, the entire moment–angle relationship will be affected similarly by the volume of the muscles, because the distribution of muscle is conserved for these subjects (Holzbaur et al., 2007). The joint postures for the current study were chosen because they are functional positions near the posture in which maximum moment-generation is expected.

Muscle volumes explained 66–95% of the variations in isometric moments across six functional groups. The experimental technique could contribute to differences in the amount of variation explained across muscle groups. For example, misalignment or movement of the joint center relative to the dynamometer is known to affect measurements of isometric moment (Arampatzis et al., 2005). To minimize these effects and restrict changes in posture we braced the distal upper limb joints and the hand at the grip. In general, changes in joint posture during testing were most evident in rotations at the wrist. This had little effect on joint centers for the elbow and shoulder, but had a larger effect on wrist alignment. Because moments generated at the wrist are smaller than moments at the elbow and shoulder, and because the force at the hand is applied closer to the rotation axis for the wrist, the measured wrist moments are the most sensitive to variations in subject alignment. Similarly, the resolution of our strength measurement device (1 Nm) is a larger proportion of the isometric moments measured at the wrist (~10% for wrist extension) than at the elbow or shoulder (~2%). Finally, because the range of moments measured at the wrist is smaller, this can also reduce the magnitude of correlation coefficients that were calculated (Atkinson and Nevill, 1998). It is likely that these factors contributed to the lower correlations observed between muscle volumes and isometric moments produced at the wrist.

We have previously shown (Holzbaur et al., 2007) that the distribution of muscle volume in the upper limb is conserved across individuals with dramatically different total upper limb muscle volume. For example, the volume of muscles capable of adducting the shoulder accounts for approximately 28% of the total volume of muscle in the upper limb, regardless of overall muscle volume of the individual. In contrast, only about 5% of total upper limb muscle volume is capable of extending the wrist. The approximately sixfold difference in muscle volume observed between these two functional groups is comparable to the difference in their isometric strength, measured in this study.

We observed a marked difference between the moment-generating capacity of male and female subjects. We selected the male and female subjects to obtain a wide range of sizes, taking care to choose subjects such that weight and height ranges of the male and female subjects overlapped, and were surprised that the strength and muscle volume data were so separated. We have previously shown that muscle volume distributions are consistent between these male and female subjects, despite differences in total muscle volume (Holzbaur et al., 2007). In addition, the multivariate analysis did not show an effect of gender on maximum isometric joint moment that was independent from the effect of muscle volume. That is, the women generated smaller moments at each joint primarily because they had less muscle volume.

It has been suggested that distribution of muscle within the upper limb may be related to the requirement to reduce mass at the distal end of the extremity (Bramble and Lieberman, 2004). Our data suggest that not only is muscle volume, and therefore mass, highest at the shoulder and lowest at the wrist, but that isometric strength at these joints is coupled to volume in a way that is also conserved across individuals. Large moments about the shoulder are needed to move the entire upper limb, whereas smaller moments about the wrist are adequate to move the hand.

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The stereotyped distribution of muscle volume and relative strength in this population of healthy young adults suggests consistent design of the upper limb. Whether these relationships are preserved in other human populations, such as the elderly or individuals with physical impairments, or whether these relationships are substantially altered by specialized training (such as the exercise regimens adopted by athletes) requires further investigation.

This study provides data sets for maximum isometric joint moment-generating capacity measured for six functional muscle groups of the upper limb in a group of subjects with known muscle volumes. These data have multiple applications, including improved parameter estimation for musculoskeletal modeling and creation of models that more closely represent individuals of different size.

Acknowledgments

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