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Scaling of peak moment arms of elbow muscles with upper extremity bone dimensions

Wendy M. Murray[a,*], Thomas S. Buchanan[b], Scott L. Delp[c]

[a] Rehab Research & Development Center (153), VA Palo Alto Health Care System, 3801 Miranda Avenue, Palo Alto, CA 94304, USA
[b] Mechanical Engineering Department, University of Delaware, Newark, DE 19716, USA
[c] Biomechanical Engineering Division, Mechanical Engineering Department, Stanford University, Stanford, CA 04305, USA

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Abstract

It is often assumed that moment arms scale with size and can be normalized by body segment lengths or limb circumferences. However, quantitative scaling relationships between moment arms and anthropometric dimensions are generally not available. We hypothesized that peak moment arms of the elbow flexor and extensor muscles scale with the shorter distance (D_s) between the elbow flexion axis and a muscle's origin and insertion. To test this hypothesis, we estimated moment arms of six muscles that cross the elbow, digitized muscle attachment sites and bone surface geometry, and estimated the location of the elbow flexion axis in 10 upper extremity cadaveric specimens which ranged in size from a 5′0″ female to a 6′4″ male. D_s accurately reflected the differences in peak moment arms across different muscles, explaining 93–99% of the variation in peaks between muscles in the same specimen. D_s also explained between 55% and 88% of the interspecimen variation in peak moment arms for brachioradialis, biceps, and ECRL. Triceps peak moment arm was significantly correlated to the anterior–posterior dimension of the ulna measured at the olecranon ($r^2 = 0.61$, $p = 0.008$). Radius length provides a good measure of the interspecimen variation in peaks for brachioradialis, biceps, and ECRL. However, bone lengths were not significantly correlated to triceps moment arm or anterior–posterior bone dimensions. This work advances our understanding of the variability and scaling dimensions for elbow muscle moment arms across subjects of different sizes.

Keywords: Elbow; Muscle; Moment arms; Scaling

1. Introduction

Quantitative descriptions of moment arms are essential for understanding muscle function. Moment arms transform the forces developed by muscles into the rotational moments that generate movements. The force developed by a muscle depends on both its length (Gordon et al., 1966) and its velocity (Hill, 1938), and moment arm determines the change in musculotendon length (An et al., 1984) and musculotendon velocity (Delp and Loan, 1995) during joint rotation. Moment arms also play an important role in determining muscle contributions to joint stiffness (Hogan, 1990).

Moment arms of muscles that flex and extend the elbow have been quantified in anatomical specimens (Amis et al., 1979; An et al., 1981; Gerbeaux et al., 1996; Murray et al., 1995). The magnitudes of the reported moment arms vary dramatically across these studies, and there is no explanation for the observed variability. As a result, it remains unclear how moment arms vary among human subjects and how previously reported moment arms could be used to estimate moment arms of an individual. An et al. (1981) normalized elbow muscle moment arms measured in six specimens by a factor involving the cross-sectional area of the dissected forearm. Gerbeaux et al. (1996) normalized elbow extension moment arms estimated for the triceps brachii in three specimens by ulna length. However, the effectiveness of different anthropometric factors for reducing interspecimen variation in elbow muscle moment arms has not been evaluated.

We hypothesized that the peak moment arms of the elbow flexor and extensor muscles scale with the shorter distance (D_s) between the elbow flexion axis and a

*Corresponding author. Tel.: +1-650-493-5000; fax: +1-650-493-4919.
E-mail address: murray@roses.stanford.edu (W.M. Murray).

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muscle's origin and insertion. This hypothesis is based on a simple geometric representation of the elbow joint, where the axis of rotation and each muscle's attachment sites and path are approximated by a triangle (Fig. 1, cf. van Zuylen et al., 1988; Wilkie, 1959). In this two-dimensional formulation, the geometry dictates that the moment arm is always less than or equal to D_s. Thus, we expect D_s will be highly correlated to peak moment arm. Because muscles wrap around the bone surfaces near the elbow joint, we also expect that peak moment arms can be influenced by anterior–posterior dimensions of the bones. To test our hypothesis, we estimated moment arms of six muscles that cross the elbow, digitized the muscle attachment sites and bone surface geometry, and estimated the location of the elbow flexion axis in 10 upper extremity cadaveric specimens.

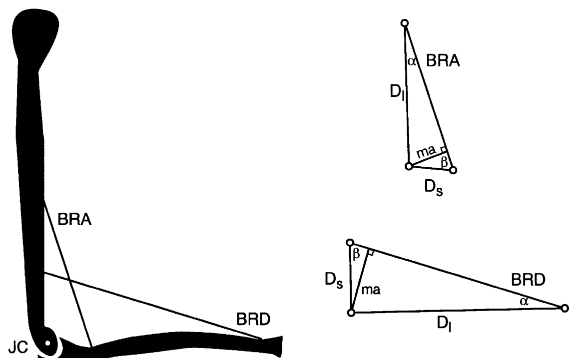

Fig. 1. A simple, two-dimensional, geometric representation of the elbow joint and the paths of the brachialis (BRA) and the brachioradialis (BRD), from which the hypothesis for this study was derived. Specifically, the joint center (JC), and a muscle's origin and insertion sites form a triangle. Based on geometry, the maximum value of moment arm (ma) is the shorter distance (D_s) between the joint center and a muscle's attachment sites on the bone.

2. Methods

Using 10 unembalmed upper extremity specimens taken from nine cadavers, we examined the relationships between dimensions of the upper extremity and moment arms of muscles that cross the elbow. The cadaveric specimens ranged in size from a 5′0″ female to a 6′4″ male (see Table 1 for bone dimensions from each specimen, other anthropometric dimensions of these specimens are also reported in Murray et al., (2000). All protocols followed the guidelines and regulations for use of human cadaveric material at Northwestern University (Chicago, IL), the site of data collection. The biceps brachii, brachialis, brachioradialis, extensor carpi radialis longus (ECRL), pronator teres, and triceps brachii were studied. Specimen and muscle preparations have been described previously (Murray et al., 2000, 1995). Muscle attachment sites were marked on the humerus as the muscles were released from their origins. After completion of the experimental protocol for estimating moment arms (see below), muscle insertion sites were also marked on the radius and ulna.

Moment arms were estimated using the tendon displacement method (An et al., 1984), which involves computing the partial derivative of measured tendon displacement with respect to joint angle. That is,

$$\mathbf{ma} = \frac{\partial \ell}{\partial \theta}. \tag{1}$$

The upper extremity was mounted on a horizontal surface, and was supported at the humeral head and the medial epicondyle. Each muscle was connected to a position transducer (Celesco Transducer Products, Canoga Park, CA) with a wire. The position transducer loaded the muscle with a constant tension of 7.5 N and was capable of ± 0.3 mm accuracy and ± 0.02 mm resolution. Elbow flexion angle was measured with an

Table 1
Bone lengths and anterior–posterior dimensions[a] (all dimensions in cm)

Specimen label[b]	Humerus length	Radius length	Ulna length	A–P dimension of ulna (olecranon)	Radius of capitulum	Radius of trochlear groove
M10	34.0	26.6	28.9	2.4	1.2	0.8
M5	32.9	25.1	26.6	2.3	1.1	0.8
M3 (L)	33.5	24.4	26.4	2.2	1.1	0.8
F7	32.1	24.1	26.2	2.0	0.9	0.7
M2 (R)	33.1	24.0	25.9	2.3	1.1	0.9
M1	29.4	23.6	25.0	2.5	1.1	0.8
F4	31.6	23.5	25.1	2.0	1.0	0.6
F8	31.7	23.2	24.6	2.2	0.9	0.6
F6	31.1	22.6	24.2	2.0	1.0	0.8
F9	30.6	22.1	24.0	1.8	1.0	0.7

[a] Bone lengths and anterior–posterior dimensions were quantified after specimens were dissected, each elbow joint was disarticulated, and the bones were disinfected. Bone lengths were measured from the most superior point to the most inferior point on each bone using a meter stick. The anterior–posterior dimension of the ulna was measured at the level of the olecranon; the distance between the most anterior point of the trochlear notch and the most posterior point of the olecranon process was calculated from the digitized bone surfaces. The radii of the capitulum and trochlear groove were estimated as described in Methods.

[b] M indicates male specimen, F indicates female specimen, M2 and M3 are the right and left arms from the same specimen, respectively.

electrogoniometer (Penny and Giles Biometrics, United Kingdom) that was mounted on a manual goniometer. The axis of the goniometer was aligned with the transepicondylar line of the humerus, and was secured to the humeral shaft and the forearm. The outputs of the position transducer and the electrogoniometer were sampled at 15 Hz while the forearm was slowly moved through its range of motion. The forearm was maintained in the neutral forearm position (0°, or mid-pronation/supination) during data collection.

Each muscle was constrained to follow its anatomical path. The wires that connected biceps and brachialis to the position transducer were routed underneath the fascia surrounding the intertubercular sulcus. The experimental set-up ensured that the paths of brachialis and triceps were maintained close to the humeral shaft, as would be expected from anatomy. Pronator teres and ECRL were routed through holes drilled through the midpoints of their respective origins on the humerus. Brachioradialis was routed through a hole drilled slightly distal to the midpoint of its origin because more muscle fibers attach along the distal portion of its origin.

Moment arms of the elbow muscles vary as a function of elbow position and were estimated between 20° and 120° flexion for the elbow flexors and 30°–120° flexion for triceps. Tendon displacement data was collected as the elbow was passively extended for the flexors and as the elbow was passively flexed for the extensors. Data was collected over a broader range of motion, but data collected in the initial 5°–10° of motion was less repeatable than the remainder of the trial. Moment arms are only reported over the range of motion in which we are the most confident. Five trials of tendon displacement vs. elbow flexion angle were collected per muscle. The numerical derivative of each trial was digitally filtered using a second order Butterworth filter with a cut-off frequency of $1\,\mathrm{rad}^{-1}$. The five filtered derivatives were averaged to estimate moment arm. The peak moment arm from the averaged data is reported. Intertrial variability was small across all muscles and specimens. The average standard deviation of the peak moment arm was 0.1 cm (1% of brachioradialis and 6% of pronator teres peak). Moment arms for brachialis in one specimen and ECRL in another specimen are not reported due to difficulties in dissection and data collection, respectively.

To estimate the distance between each muscle's attachment sites and the elbow flexion axis and to quantify anterior–posterior dimensions of the bones, we digitized the muscle attachment sites and the proximal and distal articular surfaces of each bone. After completion of the moment arm measurements, all of the musculature was removed from each specimen, the elbow, radioulnar, and radiocarpal joints were disarticulated, and the previously marked boundaries of the attachment sites were etched on the bone. The bones were disinfected in 10% bleach solution for 5–7 days. The articular surfaces and attachment sites were digitized using a Faro SpaceArm (Faro Technologies, Inc., Lake Mary, FL), and displayed using HyperSpace software (Mira Imaging, Inc.). Digitization of a given bony landmark was repeatable to within 1 mm.

A single point was used to represent each muscle's origin and insertion. For attachment sites that encompassed a surface on the bone (e.g., origin of brachialis), the bone surface within the boundary of the attachment site was digitized and used to compute the centroid. For muscles that have a narrow region of attachment (e.g., origin of brachioradialis), we parametrized the attachment site as a curve or a line, and calculated its midpoint. The centroids of the origin of brachialis and the insertion of triceps were not on the bone surfaces and were translated along the surface normal to place them on the surface of the humerus and ulna, respectively. The effective origin of the triceps was defined as the origin of its lateral head. Because the long and short heads of biceps originate on the scapula, which was not digitized, a point along the intertubercular sulcus of the humerus was defined as the effective origin of biceps. Similarly, because ECRL inserts on the second metacarpal, the styloid process of the radius was defined as its effective insertion. (See webpage of Journal of Biomechanics: http://www.elsevier.nl:80/inca/publications/store/3/2/1 for muscle attachment sites).

The elbow flexion axis (λ) was estimated as the vector connecting the centers of the capitulum and the trochlear groove of the humerus (Chao and Morrey, 1978; Gerbeaux et al., 1996; London, 1981; Shiba et al., 1988). We used the digitized geometry of the articular surface of the distal humerus to fit a sphere to the surface of the capitulum and a circle to the trochlear groove. We estimated the centers of the capitulum and the trochlear groove as the centers of the fitted sphere and circle, respectively. We also estimated the radii of the capitulum and trochlear groove from these data. The anterior–posterior dimension of the ulna was calculated from the digitized articular surface of the ulna (Table 1).

The perpendicular distance (D) between the elbow flexion axis (λ) and a muscle attachment site was calculated using the distance formula between a point and a line. That is,

$$D = \frac{||\lambda \times \mathbf{P_0P_i}||}{||\lambda||}, \tag{2}$$

where $\mathbf{P_0P_i}$ is the vector connecting the center of the capitulum (P_0), a point on the elbow flexion axis, and the centroid (or midpoint) of the attachment site (P_i). We defined D_s as the shorter of the distances between the axis and each muscle's two attachment sites. The relative positions of the humerus, radius, and ulna were determined based on the complementary geometry of the articular surfaces of the distal humerus, proximal ulna, and proximal radius, and the complementary geometry of the distal radius and distal ulna.

The relationships between peak moment arms and six bone dimensions were evaluated for each muscle using linear regression analysis (McClave and Dietrich, 1991). The six bone dimension were: D_s, radius of the capitulum, radius of the trochlear groove, the anterior–posterior dimension of the ulna measured at the level of the olecranon, humerus length, and the length of the forearm bone to which the muscle attaches. We used the coefficient of determination (r^2) to evaluate how much of the total variation in peak moment arms was accounted for by each bone dimension. That is,

$$\text{VAF (variation accounted for)} = 100 \times r^2. \tag{3}$$

Results were considered significant for $p<0.10$. Because moment arms for each muscle were compared to multiple bone dimensions, individual regressions required a higher level of significance. Based on the Bonferroni method, a 90% confidence level for all six comparisons corresponds to a correlation coefficient (r) of $r = 0.730$ ($p<0.017$) for a sample size of $n = 10$ (brachioradialis, biceps, pronator teres, and triceps), and $r = 0.760$ ($p<0.017$) for a sample size of $n = 9$ (brachialis and ECRL). Our regression analysis on interspecimen variation in peak moment arms has a statistical power of 69%.

3. Results

The shorter distance (D_s) between the axis of rotation and each muscle's attachment sites accurately reflected the differences in peak moment arms across different muscles. When all of the muscles in this study were considered ($n = 58$), D_s was highly correlated ($r = 0.982$; $p<0.0001$) to the magnitude of peak moment arm and accounted for 97% of the overall variation in peaks (Fig. 2). This trend is also evident in individual specimens; the variation in D_s explained 93–99% of the differences in peaks between muscles in the same specimen.

Across specimens, peak moment arms were strongly correlated to D_s for brachioradialis, biceps, and ECRL. D_s explained 55–88% of the interspecimen variation in peak moment arms for these three muscles (Fig. 3, filled bars). The relationship between D_s and peak moment arm was much weaker for brachialis, pronator teres, and triceps. Peak moment arms were more strongly correlated to anterior–posterior dimensions than to D_s for these three muscles, which was not true for brachioradialis, biceps, and ECRL (Fig. 3, open bars; also see Table 2). Interspecimen variation in the anterior–posterior dimension of the ulna measured at the olecranon explained 61% of the variation in triceps peak moment arm.

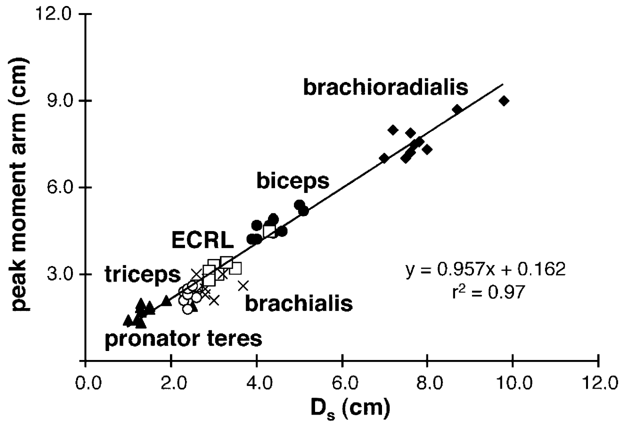

Fig. 2. Magnitude of peak moment arm vs. the shorter distance (D_s) between the axis of rotation and a muscle's attachment sites for the 58 muscles in this study. Peak moment arm is significantly correlated to D_s, which accounts for 97% of the variation in peak moment arm across muscles.

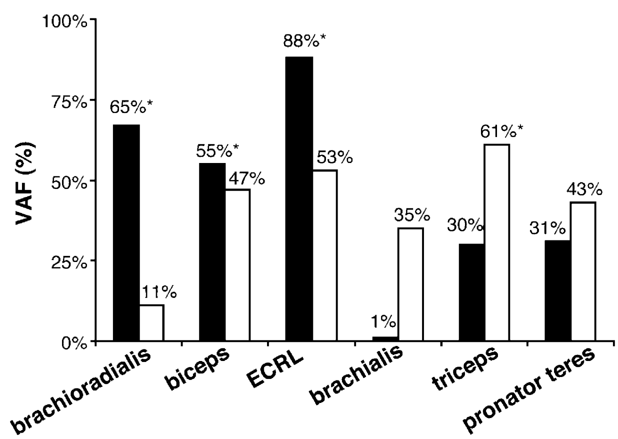

Fig. 3. Results of regression analysis between peak moment arm and D_s (filled bars), and peak moment arm and anterior–posterior dimensions (open bars). Asterisks indicate significant correlations. The results shown in the figure are for the anterior–posterior dimension with the strongest correlation for each muscle (i.e., largest VAF; see Table 2). D_s explained more interspecimen variation than anterior–posterior dimensions for brachioradialis, biceps, and ECRL. Anterior–posterior dimensions explained more variation than D_s for brachialis, triceps, and pronator teres.

The peak moment arms of the three muscles that scaled with D_s were also strongly correlated to radius length. Radius length was significantly correlated to peak moment arms of brachioradialis and ECRL (Fig. 4). While radius length explained 51% ($p = 0.021$) of the interspecimen variation in peak moment arms of biceps, this fell just outside the 90% significance level ($p<0.017$) when adjusted for multiple comparisons. Notably, radius length was also highly correlated to D_s for brachioradialis ($r^2 = 0.78$; $p = 0.001$), biceps ($r^2 = 0.83$; $p<0.0001$), and ECRL ($r^2 = 0.62$; $p = 0.007$). Humerus length explained a

Table 2
Peak moment arms vs. selected bone dimensions: correlation coefficients, p-values, and VAF[a]

		D_s	Radius of capitulum	Radius of trochlear groove	A–P dimension of the ulna
Brachioradialis	r	*0.818**	0.338	0.249	0.311
	p	*0.004**	0.340	0.487	0.382
	[VAF]	*67%**	11%	6%	10%
Biceps	r	*0.744**	0.344	0.000	0.688
	p	*0.014**	0.330	1.000	0.028
	[VAF]	*55%**	12%	0%	47%
ECRL	r	*0.936**	0.728	0.300	0.558
	p	*0.0001**	0.026	0.432	0.118
	[VAF]	*88%**	53%	9%	31%
Brachialis	r	0.115	0.567	0.119	0.588
	p	0.768	0.111	0.760	0.096
	[VAF]	1%	32%	1%	35%
Pronator teres	r	0.555	0.655	0.621	0.387
	p	0.096	0.040	0.055	0.269
	[VAF]	31%	43%	39%	15%
Triceps	r	0.552	0.348	0.301	*0.782**
	p	0.098	0.325	0.398	*0.008**
	[VAF]	30%	12%	9%	*61%**

[a] Correlations were considered significant at the 90% confidence level ($p<0.017$ when adjusted for multiple comparisions). Significant correlations are italicized and marked with an asterisk.

maximum of 40% of interspecimen variation in peaks (brachioradialis; $p = 0.049$). Bone lengths explained a maximum of 17% of interspecimen variation in peaks for brachialis, triceps, and pronator teres (brachialis vs. ulna length; $p = 0.264$). The relationships between anterior–posterior bone dimensions and bone lengths were not as strong as the relationships between bone lengths and D_s. Interspecimen variations in bone lengths explained less than 43% (radius of the capitulum vs. radius length; $p = 0.038$) of the interspecimen variation in anterior–posterior bone dimensions quantified in this study.

The maximum difference in peak moment arms between specimens ranged from 2.0 cm in brachioradialis to 0.7 cm in pronator teres (Table 3). For pronator teres, the average peak of the male specimens (1.9 ± 0.1 cm) was significantly larger ($p<0.019$) than the average peak of the female specimens (1.5 ± 0.2 cm). Peak moment arms were not significantly different between males and females in the other five muscles. The magnitudes of the moment arms of the elbow flexors and extensors vary with elbow position (Fig. 5).

4. Discussion

The objective of this work was to identify the source of variation in peak moment arms of the elbow flexors and extensors. Moment arm is a geometric measure which characterizes the distance between the joint center and the muscle path. Therefore, we investigated how peak moment arms of the elbow muscles scale with bone dimensions that reflect the distances between the elbow flexion axis and the muscle path. Our data indicate that D_s explains a substantial portion of intermuscular differences in peak moment arm. In addition, we evaluated interspecimen variations and found that peak moment arms scale with D_s for brachioradialis, biceps, and ECRL. Anterior–posterior dimensions explain more of the interspecimen variation in peak moment arms for brachialis, triceps, and pronator teres than D_s. Strong linear relationships between radius length and D_s indicate that radius length can provide a good measure of the interspecimen variation in peak moment arms for brachioradialis, biceps, and ECRL. Weaker relationships between bone lengths and the anterior–posterior dimensions of the bones suggest that bone lengths may not fully reflect interspecimen variation in the triceps moment arm.

None of the bone dimensions studied explained a significant amount of the interspecimen variation in peak moment arms of brachialis and pronator teres. Scaling relationships may exist for these two muscles that we could not identify from this data. A weakness of this study is the relatively small number of specimens; the statistical power of the regression analysis could have been improved by testing more specimens (McClave and Dietrich, 1991).

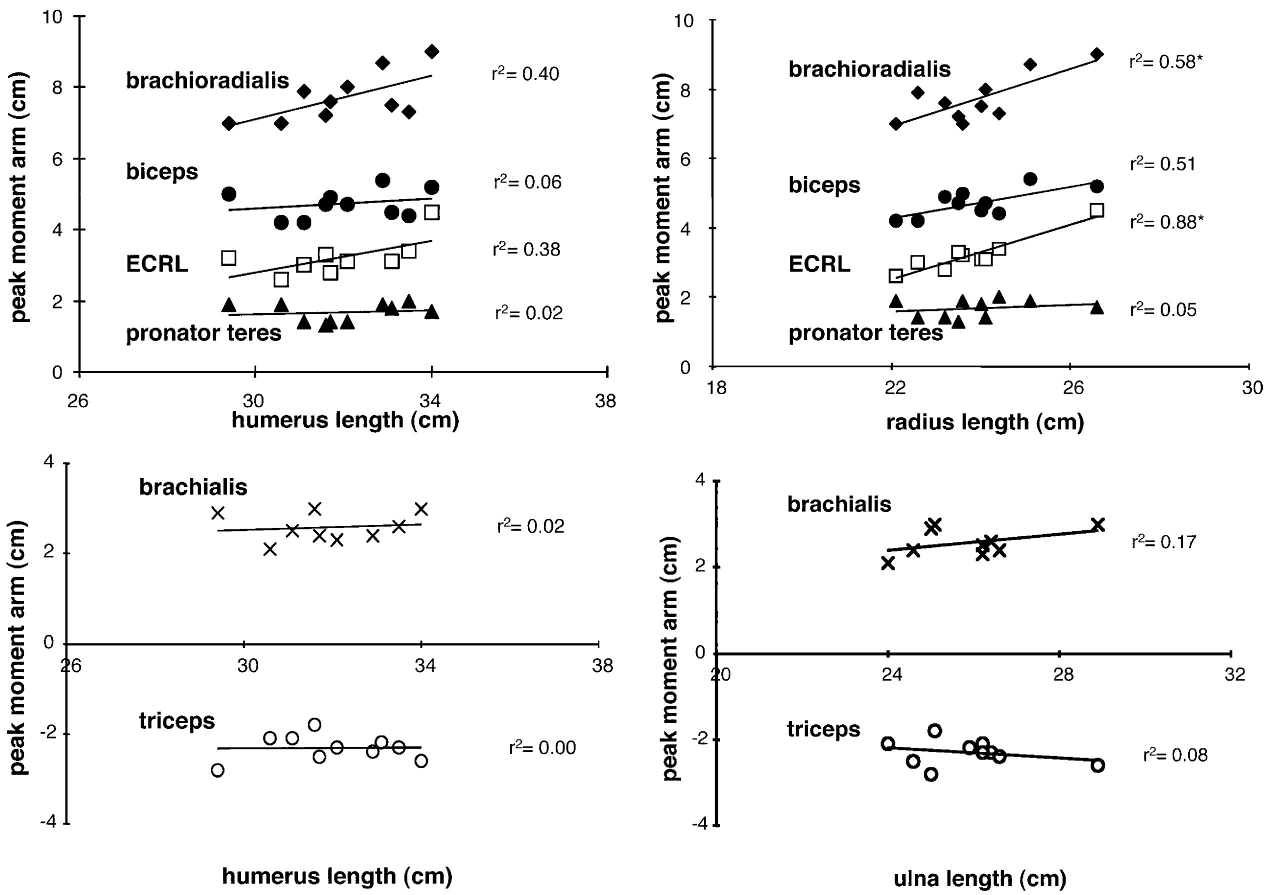

Fig. 4. Peak moment arms and bone lengths for the 10 upper extremity specimens in this study. Asterisks indicate significant correlations. Radius length was significantly correlated to peak moment arm in brachioradialis and ECRL. Radius length accounted for 51% of the variation in biceps peak moment arms ($p = 0.021$), which fell just outside the desired significance level ($p<0.017$).

Table 3
Summary of peak moment arm data

	Mean (cm)	SD (cm)	Range of peaks (cm)	SD/mean (%)	Angle of peak (°)	Range of angles (°)
Brachioradialis	7.7	0.7	7.0–9.0	9	108	100–118
Biceps	4.7	0.4	4.2–5.4	9	88	80–93
ECRL	3.2	0.5	2.6–4.5	16	106	99–115
Brachialis	2.6	0.3	2.1–3.0	12	88	76–102
Pronator teres	1.7	0.3	1.3–2.0	18	100	94–113
Triceps	−2.3	0.3	−1.8 to −2.8	13	44	31–62

With the exception of the anterior–posterior bone dimensions (see Fig. 3), we generally observed stronger relationships between bone dimensions and peak moment arms for the three muscles with larger moment arms compared to the three muscles with smaller moment arms. Because of this trend, it should be noted that measurement resolution and error sources may have a greater effect on the regression analysis for the muscles with smaller moment arms. For example, the intertrial variation of peaks of 0.1 cm is 33% of the standard deviation (i.e., interspecimen variation) in the moment arms of pronator teres, triceps, and brachialis compared to 14% of the standard deviation of brachioradialis. Similarly, our method for positioning of the forearm bones relative to the humerus affects the estimation of D_s for biceps, triceps, and brachialis. Because D_s for brachialis and triceps is smaller than D_s for biceps, errors in translational alignment represent a larger percentage of D_s for these two muscles.

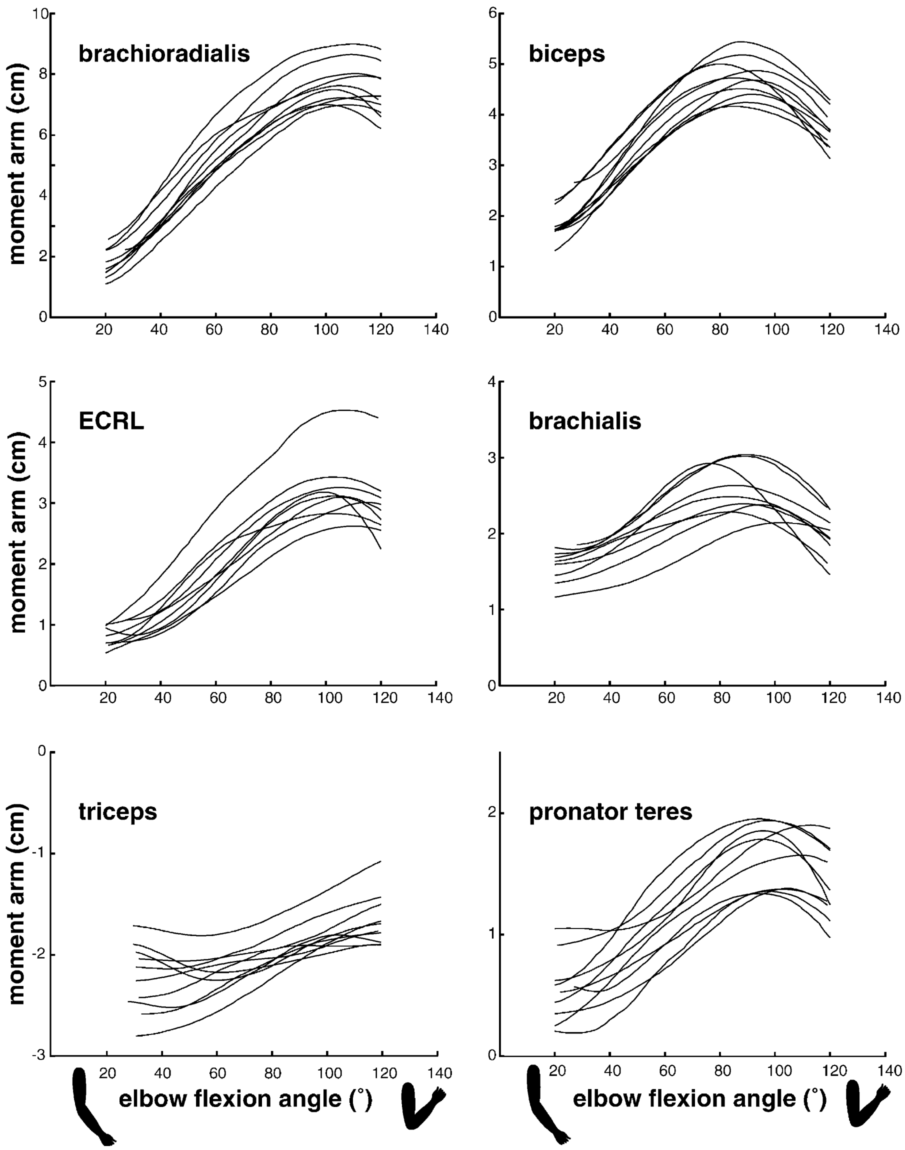

Fig. 5. Elbow flexion moment arms vs. elbow flexion angle measured in 10 upper extremity specimens. Positive values indicate flexion moment arms, negative values indicate extension moment arms. 0° flexion is full extension.

Muscle attachment sites were approximated by a single point in this study, which may inadequately represent the actions of muscles that encompass a large surface of the bone, as illustrated by Van der Helm and Veenbaas (1991) at the shoulder. The origins of brachialis and medial head of the triceps encompass a large area on the anterior and posterior surfaces of the humerus, respectively. We did not evaluate the impact these large attachment sites have on our estimate of peak moment arm. However, moment arm reflects the shortest distance between the muscle path and the joint center and even the most distal aspects of the origins of brachialis and triceps are further away from the joint center than the insertion. Also, the elbow is a more constrained joint that the shoulder, so defining a muscle's basic function at the elbow is less complicated than the shoulder.

The origins of brachioradialis and ECRL are narrow but extend over a substantial length of the humerus. We routed the wire connecting each of these muscles to the transducer through a hole drilled in the approximate centroid of the attachment site (see Methods). In one specimen, we also measured brachioradialis moment arm by routing the muscle path through holes drilled along the distal third and proximal third of the origin. As expected, we found that brachioradialis fibers that attach proximally on the humerus have a larger moment arm than fibers that attach distally. Because we carefully measured the length of the attachment sites and drilled the holes in the same relative location along the origin for each specimen, we are confident the interspecimen variation in D_s and moment arm accurately reflects anatomical differences across specimens. The attachment sites of all other muscles in this study are justifiably represented by a single point.

The position of the forearm is a source of variation in peak moment arms of the elbow muscles (Murray et al., 1995). Our previous study reports biceps peak increased by 5–7 mm when the forearm was supinated. Biceps inserts on the radius, which undergoes a large change in orientation relative to the humerus during forearm rotation. Thus, we expect the change in biceps peak elbow flexion moment arm results from a change in D_s that occurs as the forearm is rotated.

While it is often implicitly assumed moment arms scale with size and can be normalized by segment lengths or limb circumferences, quantitative scaling relationships between muscle moment arms and anthropometric dimensions are currently not available. This is the first study to quantify moment arms, muscle attachment sites, axes of rotation, and bone dimensions measured in the same cadaveric specimens. We have investigated plausible sources of interspecimen variation in peak moment arms and we have identified important trends that provide the basis for further study. A practical limitation of this study is that the parameters that we studied cannot be easily quantified from surface measurements. While all of the bone dimensions we evaluated could be accurately assessed in living subjects using medical imaging techniques, it would be more convenient if scaling relationships existed between moment arms and externally measurable anthropometric dimensions. We chose to investigate bone dimensions because we believe it is necessary to understand the source of the variation to develop accurate scaling relationships. This work substantially advances our knowledge of the degree and potential sources of variation in elbow muscle moment arms across subjects of different sizes. As a result, we believe this work provides an important foundation for establishing scaling relationships between peak moment arms and external dimensions.

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