

Magnetic Resonance Imaging of Congenitally Deficient Upper Limbs

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Introduction

Knowledge of the anatomic location, size, and contractility of muscles within a person's congenitally deficient upper limb is useful in prescribing and fitting a myoelectric prosthesis. In 1998, at University of Texas' Hermann Hospital, magnetic resonance imaging (MRI) was used to image both arms of five volunteers with congenital unilateral below elbow upper limb deficiencies. Imaging both arms of each subject enables a direct comparison of normal and residual limb anatomy. The volunteers included one adult and four teenagers (Table 1). This paper summarizes findings on residual versus sound side musculature size, limb size, and selected residual limb features.

Table 1: Five volunteers with **congenital** upper limb below elbow limb deficiencies participated in this study.

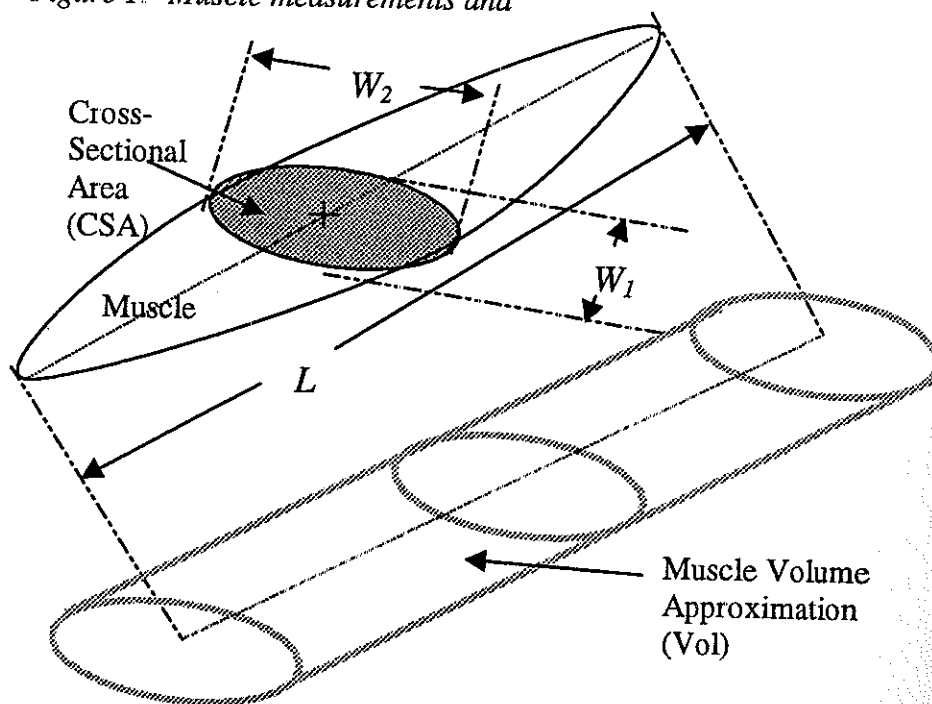
Study ID	Sex	Age	Residual Side	Residual Length	Comments
A	Female	32	Right	6.0 cm	Regular body-powered hook user since early childhood. Occasional body-powered hand use.
B	Male	12	Left	18.4 cm	No prosthesis use since age 6. Cannot fully straighten elbow of residual limb. Some carpal bones present. Residual forearm radius and ulna fused in pronated position. Sound and residual side humerus bones not equal in length.
C	Female	12	Right	7.0 cm	Moderate myoelectric user, hand only. Mother's ultrasound at 14-16 weeks of pregnancy showed two hands developing normally.
D	Male	13	Right	9.6 cm	Moderate myoelectric user, hand only.
E	Male	12	Left	10.4 cm	Occasional myoelectric user, hand only.

Technique

For each volunteer, the residual limbs were imaged from about 6 cm proximal of the elbow to the limb's distal end. Axial (transverse), coronal, and sagittal sections were imaged using an extremity coil on the first volunteer, subject A. Since the MRI process requires that the subject remain motionless for long periods in a small space through loud noises, the younger subjects' (B-E) imaging was limited to transverse sections, with other views synthesized. Sound limb images were limited to a length corresponding to their residual limb.

Working from the MRI films, University of Texas--Houston Health Science Center radiologists identified and measured the volunteers' forearm muscles. It was not possible to exactly measure muscle length for those muscles originating above the elbow joint or terminating beyond the field of view. This occurred on the sound limb only, where the volunteer's residual limb was short and only one extremity coil placement was done on both sides (subjects A, C-E). Muscles originating at the common flexor or extensor origin were measured from these

Figure 1: Muscle measurements and



origins. Muscles that terminate in a long tendon were measured only to the last visible muscle tissue. Cross-section dimensions (width of a minor axis, W_1 , and width of a major axis, W_2) were measured at maximal cross-sectional mass, as Figure 1 shows. At this point,

$$CSA = \pi(W_1/2)(W_2/2) \tag{1}$$

approximates the cross-sectional area (CSA) as an ellipse.

$$Vol = (CSA)(L) \tag{2}$$

approximates the muscle volume (Vol).

Maximum and minimum limb diameters and skin thicknesses were measured at a transverse plane including the radial head. Figure 2 shows these limb cross-sections

Results

Tables A-E (Appendix) show dimensions of each volunteers' residual musculature and their corresponding sound limb musculature. Table 2 summarizes all the volunteers.

For the most part, all muscles that could be identified and measured in the sound limb (within the length of the residual limb) could also be identified in the residual limb. The exception was *palmaris longus*. This muscle is missing in 10% of normal limbs [1], so its absence or presence in these volunteers' limb may not be related to their limb deficiencies. All muscles on the residual side were located approximately in their normal location with respect to other muscles. Muscles not originating in the common flexor or extensor tendons originated closer to the elbow in the residual limbs than in the sound limbs, suggesting shortened rather than truncated forearm bones. The residual limb muscles were considerably less developed than their sound limb counterparts. The average total residual limb muscle cross-sectional area was 15.7 cm², compared to 34.2 cm² (Table 7). Also interesting is the fact that the overall diameter of the residual limbs varies much less than that of the sound limbs--the standard deviation of the residual limbs' diameters is 0.26 cm versus 0.48 cm for the sound limbs.

The residual limb muscles were also separated from the skin surface by more electrically inactive tissue than their sound side counterparts (at a plane transversing the radial head, an average of 0.82 cm on the residual limbs versus 0.64 cm on the sound limbs). Toward the distal end of the residual limbs of subjects A and C-E, the thickness of the inactive tissue (apparently scar tissue as well as fat) increased greatly. This has implications for myoelectric prosthesis control, since this inactive tissue filters out the higher frequencies of the myoelectric signal [2]. Simulations by Farry [3] show that 0.8 cm of tissue attenuates a muscle action potential's amplitude by 80-90%. The action potential is almost undetectable through 1.5cm of tissue. The MRIs suggest that electrodes placed on the most distal 3-4 cm of the residual limb will not record useful myoelectric activity.

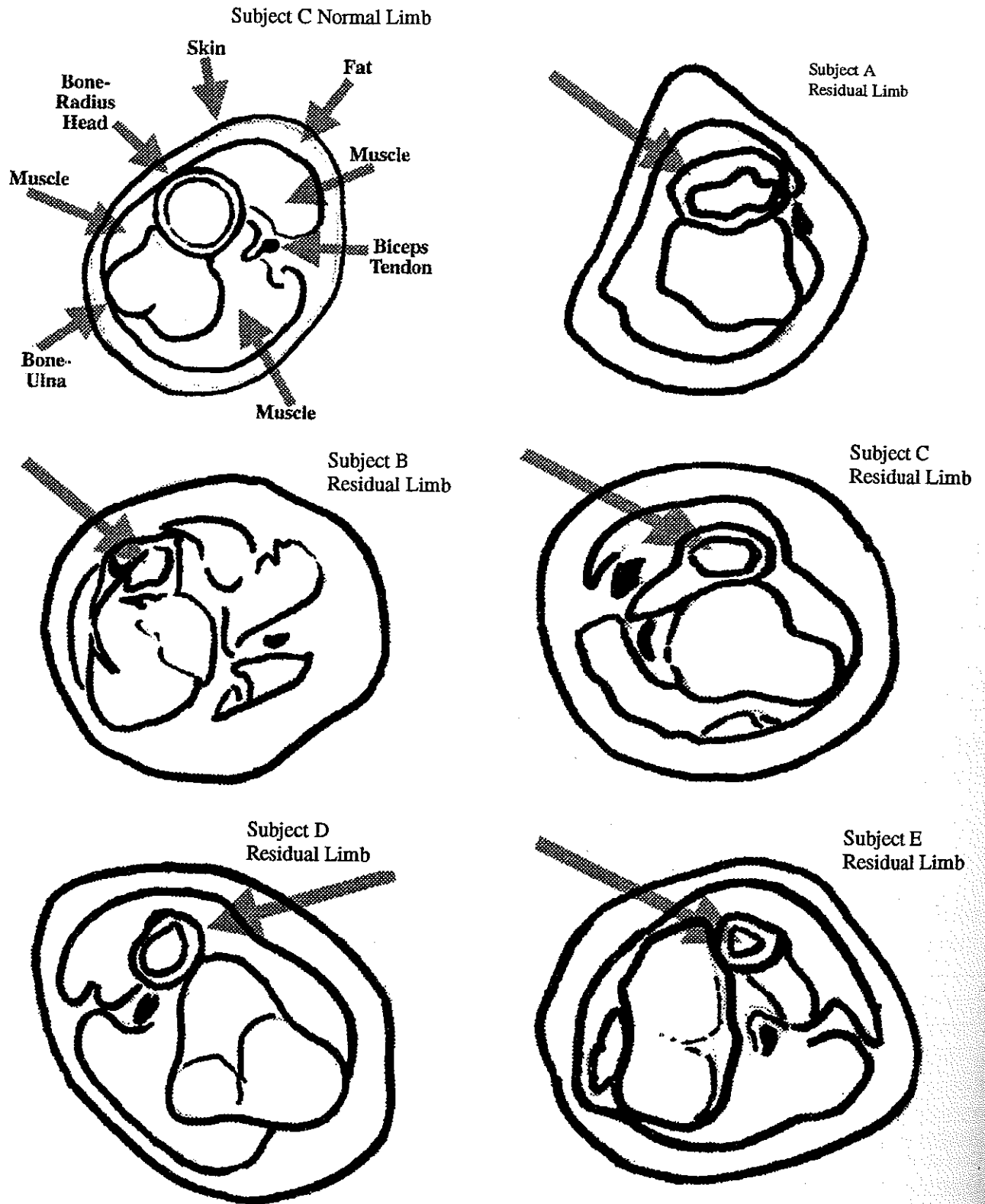
Table 2 also gives the correlation between these MRI measurements and preliminary results from a multifunction myoelectric control study, described in detail in [4,5]. The candidate controller discriminated between six motions--close grasp, open grasp, flex wrist, extend wrist, rotate palms up (supinate), and rotate palms down (pronate)--from four myoelectric signals collected from the residual limb during contra-lateral stimulation (i.e., the volunteers simultaneously moved their sound hand through these motions while imagining moving their missing hand). The best predictor of controller performance is the residual limb muscle volume. Interestingly, some sound limb characteristics correlate more highly with the controller performance than their corresponding residual limb characteristics.

The volunteers' elbow joints varied considerably from sound to residual side. Note, in particular, the dysplasia of the radial heads in all five residual limbs (Figure 2)--none are circular. All the study volunteers achieve the equivalent of pronation and supination of their forearms (with or without a prosthesis) using abduction and adduction of the shoulder and humeral rotation (depending on the degree of elbow flexion) rather than moving their proximal radio-ulnar joints. This suggests that the proximal radio-ulnar joint does not develop without use. In contrast, individuals with traumatic below elbow amputations retain some mobility in the proximal radio-ulnar joint, even though it is usually not useful in moving a prosthesis where less than 50% of the forearm remains.

Table 2: A summary of sound and residual limb statistics for the five subjects. No volume averages across subjects are given since sound side muscle lengths used in volume calculations are truncated by image field of view for some subjects.

Subject	Average Limb Diameter (cm) in Plane of Radial Head (cm)		Average Thickness of Tissue between Electrode and Muscle in Plane of Radial Head (cm)		Total Muscle Cross Sectional Area (cm ²) (Sum of Areas at Maximum Mass)		Total Muscle Volume (cm ³) (Sum of Muscle Areas at Maximum Mass Multiplied by Muscle Length)	
	Sound	Residual	Sound	Residual	Sound	Residual	Sound	Residual
A	6.1	5.2	0.51	0.67	39.6	14.1	562.9	50.0
B	7.1	5.9	0.81	0.89	47.6	15.5	717.9	120.2
C	5.8	5.4	0.64	0.89	17.8	9.4	112.4	31.9
D	6.2	5.6	0.58	0.97	34.7	17.3	341.4	67.5
E	6.3	5.6	0.65	0.69	31.6	22.3	227.5	77.3
Average	6.26	5.54	0.64	0.82	34.3	15.7		
Standard Deviation	0.48	0.26	0.11	0.13	11.0	4.7		
Correlations with Controller Accuracy	0.91	0.81	0.63	0.00	0.79	0.70	0.61	0.97

Figure 2: All volunteers had elbow abnormalities in their residual limbs. Upper left tracing is of a sound limb for comparison, transverse plane through the radial head. The unmarked arrows identify the radial head.



Conclusions

This five-person MRI study:

- quantifies muscle development and location in congenitally below-elbow deficient limbs;
- reveals extensive myoelectric signal attenuating scar tissue;
- suggests ways to predict success with a multifunction myoelectric controller; and
- shows bone abnormalities far from the end of the residual limbs.

Five subjects constitute a small sample and is a starting point rather than the basis for sweeping generalizations, but this sample suggests that congenitally deficient residual limbs are quite different from traumatically amputated residual limbs. This study raises many questions. Future work should investigate a routine role for MRI in prescribing prostheses for congenitally limb deficient individuals, especially its use in locating electrodes for myoelectric control.

Acknowledgements

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Appendix

Table A: Measurements of musculature in subject A. Residual forearm length from distal humerus is 6.0 cm. Muscle dimensions: L=length; W1=minor width; W2=major width; CSA=cross-sectional area; and Vol=estimated volume. All measurements are in centimeters (cm).

Muscle	Sound Limb (Left)					Residual Limb (Right)				
	L*	W1	W2	CSA	Vol	L	W1	W2	CSA	Vol
<i>Extensor Carpi Ulnaris</i>	18.7	1.2	1.3	1.2	22.9	3.2	0.5	1.0	0.4	1.3
<i>Extensor Digitorum</i>	18.3	1.5	2.0	2.4	43.1	3.6	0.3	2.1	0.5	1.8
<i>Anconeus</i>	7.8	0.8	1.6	1.0	7.8	3.2	0.8	1.3	0.8	2.6
<i>Brachialis</i>	3.0	1.2	3.6	3.4	10.2	1.6	0.7	2.7	1.5	2.4
<i>Brachioradialis</i>	11.4	1.4	2.0	2.2	25.1	3.6	0.5	2.2	0.9	3.1
<i>Extensor Carpi Radialis</i>	14.1	1.3	2.4	2.5	34.6	3.6	1.4	2.5	2.7	9.9
<i>Pronator Teres</i>	11.7	0.8	2.3	1.4	16.9	4.0	0.5	2.0	0.8	3.1
<i>Supinator</i>	9.3	0.8	2.9	1.8	16.9	3.6	0.6	2.3	1.1	3.9
<i>Palmaris Longus</i>	13.0	2.3	7.0	12.6	164.4	2.1	0.6	0.8	0.4	0.8
<i>Flexor Carpi Radialis</i>	>20	1.2	2.1	2.0	39.6	4.3	0.9	1.1	0.8	3.3
<i>Flexor Carpi Ulnaris</i>	>20	1.0	2.2	1.7	34.6	2.9	0.5	1.2	0.5	1.4
<i>Flexor Digitorum Superficialis</i>	>20	1.3	3.3	3.4	67.4	5.1	1.4	1.6	1.8	9.0
<i>Flexor Digitorum Profundus</i>	>20	2.2	2.3	4.0	79.5	3.6	1.2	2.2	2.1	7.5
Totals	Sound Limb			39.6	562.9	Residual Limb			14.1	50.0

* ">" indicates that the muscle continues beyond the imaged area.

Table B: Measurements of musculature in subject B. Residual forearm length from distal humerus is 18.4 cm. Muscle dimensions: L=length; W1=minor width; W2=major width; CSA=cross-sectional area; and Vol=estimated volume. All measurements are in centimeters (cm).

Muscle	Sound Limb (Right)					Residual Limb (Left)						
	L	W1	W2	CSA	Vol	L	W1	W2	CSA	Vol		
<i>Extensor Carpi Ulnaris</i>	22.0	1.5	1.5	1.8	38.9	10.4	0.6	0.7	0.3	3.4		
<i>Extensor Digitorum</i>	22.0	1.3	2.2	2.2	49.4	13.4	0.8	1.6	1.0	13.5		
<i>Anconeus</i>	8.0	1.0	2.4	1.9	15.1	5.4	1.2	1.3	1.2	6.6		
<i>Brachialis</i>	4.4	1.6	4.2	5.3	23.2	5.4	0.6	2.1	1.0	5.3		
<i>Brachioradialis</i>	13.4	1.2	3.2	3.0	40.4	7.0	1.7	2.4	3.2	22.4		
<i>Extensor Carpi Radialis</i>	17.4	1.2	2.3	2.2	37.7	7.8	0.7	2.0	1.1	8.6		
<i>Pronator Teres</i>	16.6	1.1	3.4	2.9	48.8	3.2	0.8	1.0	0.6	2.0		
<i>Supinator</i>	10.0	0.9	3.6	2.5	25.4	2.0	0.7	2.7	1.5	3.0		
<i>Palmaris Longus</i>	10.0	1.2	2.2	2.1	20.7	tendon only						
<i>Flexor Carpi Radialis</i>	20.4	1.7	1.8	2.4	49.0	15	1.1	1.1	1.0	14.3		
<i>Flexor Carpi Ulnaris</i>	24.6	1.8	2.0	2.8	69.6	6.8	0.6	1.3	0.6	4.2		
<i>Flexor Digitorum Superficialis</i>	23.6	1.6	2.5	3.1	74.1	9.8	0.7	1.0	0.5	5.4		
<i>Flexor Digitorum Profundus</i>	23.2	1.5	4.9	5.8	133.9	14.2	0.8	2.5	1.6	22.3		
<i>Pronator Quadratus</i>	4.6	1.4	4.2	4.6	21.2	--	--	--	--	--		
<i>Extensor Pollicis Longus</i>	15.4	1.0	1.8	1.4	21.8	2.6	0.8	1.0	0.6	1.6		
<i>Flexor Pollicis Longus</i>	16.0	1.1	1.8	1.6	24.9	9.0	0.9	1.0	0.7	6.4		
<i>Abductor Pollicis Longus</i>	12.2	1.3	1.9	1.9	23.7	2.6	0.7	0.9	0.5	1.3		
Totals	Sound Limb					47.6	717.9	Residual Limb			15.5	120.2

Table C: Measurements of musculature in subject C. Residual forearm length from distal humerus is 7.0 cm. Muscle dimensions: L=length; W1=minor width; W2=major width; CSA=cross-sectional area; and Vol=estimated volume. All measurements are in centimeters (cm).

Muscle	Sound Limb (Left)					Residual Limb (Right)						
	L*	W1	W2	CSA	Vol	L	W1	W2	CSA	Vol		
<i>Extensor Carpi Ulnaris</i>	>5.8	0.4	0.8	0.3	1.5	2.8	0.3	0.4	0.1	0.3		
<i>Extensor Digitorum</i>	>7.0	0.9	1.6	1.1	7.9	2.1	0.5	0.8	0.3	0.7		
<i>Anconeus</i>	6.6	0.8	1.4	0.9	5.8	2.6	0.6	1.5	0.7	1.8		
<i>Brachialis</i>	4.4	1.8	3.4	4.8	21.1	1.4	0.5	2.0	0.8	1.1		
<i>Brachioradialis</i>	>7.8	0.9	1.2	0.8	6.6	3.0	0.5	1.8	0.7	2.1		
<i>Extensor Carpi Radialis</i>	>7.8	0.3	1.9	0.4	3.5	3.0	0.4	2.2	0.7	2.1		
<i>Pronator Teres</i>	>7.8	0.7	2.7	1.5	11.6	4.2	0.6	1.7	0.8	3.4		
<i>Supinator</i>	5.4	0.5	2.9	1.1	6.1	3.0	0.8	2.1	1.3	4.0		
<i>Palmaris Longus</i>	>6.8	0.9	1.3	0.9	6.2	3.0	0.6	1.1	0.5	1.6		
<i>Flexor Carpi Radialis</i>	>7.6	0.7	1.8	1.0	7.5	5.0	0.4	1.3	0.4	2.0		
<i>Flexor Carpi Ulnaris</i>	>7.6	0.9	1.8	1.3	9.7	2.4	0.5	0.6	0.2	0.6		
<i>Flexor Digitorum Superficialis</i>	>7.0	1.0	1.6	1.3	8.8	5.2	0.8	1.8	1.1	5.9		
<i>Flexor Digitorum Profundus</i>	>6.6	1.1	2.8	2.4	16.0	3.8	0.8	2.7	1.7	6.4		
Totals	Sound Limb					17.8	112.4	Residual Limb			9.4	31.9

* ">" indicates that the muscle continues beyond the imaged area.

Table D: Measurements of musculature in subject D. Residual forearm length from distal humerus is 9.6 cm. Muscle dimensions: L=length; W1=minor width; W2=major width; CSA=cross-sectional area; and Vol=estimated volume. All measurements are in centimeters (cm).

Muscle	Sound Limb (Left)					Residual Limb (Right)						
	L*	W1	W2	CSA	Vol	L	W1	W2	CSA	Vol		
<i>Extensor Carpi Ulnaris</i>	>11.4	1.0	2.7	2.1	24.2	4.8	0.6	1.0	0.5	2.3		
<i>Extensor Digitorum</i>	>13.4	1.2	2.2	2.1	27.8	7.0	0.4	1.8	0.6	4.0		
<i>Anconeus</i>	6.4	0.6	1.8	0.8	5.4	3.2	1	2.3	1.8	5.8		
<i>Brachialis</i>	4.6	2.2	3.7	6.4	29.4	1.4	0.6	2.8	1.3	1.8		
<i>Brachioradialis</i>	11.0	1.0	2.2	1.7	19.0	3.4	0.7	1.8	1.0	3.4		
<i>Extensor Carpi Radialis</i>	13.2	1.7	2.8	3.7	49.3	3.6	1.0	1.5	1.2	4.2		
<i>Pronator Teres</i>	11.0	0.7	3.6	2.0	21.8	3.2	0.8	2.1	1.3	4.2		
<i>Supinator</i>	9.8	0.8	3.7	2.3	22.8	4.0	0.8	3.2	2.0	8.0		
<i>Palmaris Longus</i>	--	--	--	--	--	--	--	--	--	--		
<i>Flexor Carpi Radialis</i>	>11.6	1.1	2.2	1.9	22.0	4.0	0.5	3.9	1.5	6.1		
<i>Flexor Carpi Ulnaris</i>	>11.4	1.2	1.8	1.7	19.3	4.4	0.4	2.7	0.8	3.7		
<i>Flexor Digitorum Superficialis</i>	>11.4	2.0	2.3	3.6	41.2	6.0	1.1	3.2	2.8	16.6		
<i>Flexor Digitorum Profundus</i>	>10.4	1.4	4.6	5.1	52.6	3.2	1.4	2.0	2.2	7.0		
<i>Flexor Pollicis Longus</i>	4.8	0.8	1.3	0.8	3.9	1.4	0.3	0.7	0.2	0.2		
<i>Extensor Digitorum Minimi</i>	>5.8	0.7	0.8	0.4	2.6	0.8	0.3	0.4	0.1	0.1		
Totals	Sound Limb				34.7	341.4	Residual Limb				17.3	67.5

* ">" indicates that the muscle continues beyond the imaged area.

Table E: Measurements of musculature in subject E. Residual forearm length from distal humerus is 10.4 cm. Muscle dimensions: L=length; W1=minor width; W2=major width; CSA=cross-sectional area; and Vol=estimated volume. All measurements are in centimeters (cm).

Muscle	Sound Limb (Right)					Residual Limb (Left)						
	L*	W1	W2	CSA	Vol	L	W1	W2	CSA	Vol		
<i>Extensor Carpi Ulnaris</i>	>7.0	1.1	1.3	1.1	7.9	3.8	0.8	0.9	0.6	2.1		
<i>Extensor Digitorum</i>	>7.8	1.2	1.6	1.5	11.8	5.0	0.5	1.7	0.7	3.3		
<i>Anconeus</i>	7.6	1.0	2.2	1.7	13.1	4.6	0.7	1.0	0.5	2.5		
<i>Brachialis</i>	4.4	1.8	4.5	6.4	28.0	1.8	1.4	3.2	3.5	6.3		
<i>Brachioradialis</i>	>8.6	1.1	3.8	3.3	28.2	3.2	0.7	3.2	1.8	5.6		
<i>Extensor Carpi Radialis</i>	>8.6	1.2	2.4	2.3	19.5	3.2	1.6	2.2	2.8	8.8		
<i>Pronator Teres</i>	>8.6	1.9	2.8	4.2	35.9	2.8	1.4	1.6	1.8	4.9		
<i>Supinator</i>	>6.2	0.8	3.4	2.1	13.2	4.0	1.1	3.3	2.9	11.4		
<i>Palmaris Longus</i>	--	--	--	--	--	1.2	0.3	0.4	0.1	0.1		
<i>Flexor Carpi Radialis</i>	>8.8	1.0	2.2	1.7	15.2	4.6	0.9	2.9	2.0	9.4		
<i>Flexor Carpi Ulnaris</i>	>7.6	1.1	2.4	2.1	15.8	5.2	0.4	2.0	0.6	3.3		
<i>Flexor Digitorum Superficialis</i>	>8.6	0.9	3.0	2.1	18.2	5.8	1.2	2.4	2.3	13.1		
<i>Flexor Digitorum Profundus</i>	>7.4	1.2	2.8	2.6	19.5	2.2	0.9	3.7	2.6	5.8		
<i>Extensor Digitorum Minimi</i>	>2.4	0.5	1.2	0.5	1.1	2.0	0.4	0.7	0.2	0.4		
Totals	Sound Limb				31.6	227.5	Residual Limb				22.3	77.3

* ">" indicates that the muscle continues beyond the imaged area.