Shoulder and Upper Arm Muscle Architecture

Steven L. Peterson, MD, Ghazi M. Rayan, MD

Purpose To examine the architecture of the shoulder and upper arm muscles and generate data that could serve as a guide for comparison, compatibility, and relative performance among these muscles for use in transfer.

Method Eleven shoulder and arm muscles were dissected bilaterally in 5 fresh cadavers. Of these 110 potentially available muscles, 107 were suitable for evaluation and were grouped according to similarities in architecture. Resting muscle length, required excursion, muscle fiber length, pennation angle, and mass were determined. Physiologic cross-sectional area (PCSA) was then calculated from these parameters using a standard formula.

Results Based on the gross appearance of muscle fiber orientation, the 11 muscles were subdivided into 3 groups. Required excursion was found to be less than fiber length in all muscles except for the teres major and middle deltoid with abduction. The middle deltoid muscle was found to have a short fiber length, complex multipennate structure, and high PCSA. Comparison showed the biceps and posterior deltoid to have fiber lengths greater than any portion of the triceps; however, neither demonstrated architectural features that would generate the force (represented by PCSA) determined for the combined triceps.

Conclusions Data presented in this study offer the opportunity for direct comparison of architectural features of select shoulder and arm musculature.

Clinical relevance This information might help in the evaluation of compatibility of various musculotendinous transfers around the shoulder and elbow. *(J Hand Surg 2011;36A:881–889. Copyright © 2011 by the American Society for Surgery of the Hand. All rights reserved.)*

Key words Muscle architecture, musculotendinous transfer, shoulder muscles.

Despite advancements in nerve reconstruction by grafting and nerve transfers, musculotendinous transfer remains a valuable option for the treatment of devastating neurological injury to the upper extremity.[1,2] Most frequently, such transfers have been applied to restore motion to the wrist and hand.[3] In tetraplegia, however, stabilization of the elbow by transfer of the deltoid or biceps to the triceps can be essential to facilitate more distal transfers using the brachioradialis or extensor carpi radialis longus. Transfers around the shoulder have been performed less frequently and have been largely confined to latissimus dorsi and trapezius muscle transfers.[4,5] However, recently, more complex transfers involving multiple shoulder muscles have been proposed for restoration of shoulder motion in patients with brachial plexus injury.[6] Information on basic mechanical characteristics of the muscles available for such complex reconstructions is limited.[7,8]

Each muscle has different characteristics and is uniquely designed for a specific function; therefore, musculotendinous transfer cannot fully duplicate the normal capability of the nonfunctioning muscle. Ideally, transferring a muscle with characteristics as close as possible to those of the nonfunctioning muscle would give the most accurate approximation of lost function. Defining the architecture of upper extremity muscles facilitates logical choices of muscles for transfer.

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Muscle architecture is the macroscopic arrangement of skeletal muscle fibers and is a major determinant of muscle function.[9] Exploration of the relationship between muscle architecture and function has been carried out for more than a century.[10,11] The foundation of modern exploration of forearm and hand muscle functional anatomy, architecture, and compatibility assessment first appeared in the article authored by Brand et al in 1981.[12] Data presented by these investigators on relative tension and potential excursion of forearm muscles have been used to make logical choices for tendon transfers in the hand. Lieber and associates[13–16] have further examined the architecture of select muscles of the hand, forearm, and arm, and similar investigation has been conducted by others on the lower extremity musculature.[17] Specific parameters that were examined include fiber length, pennation angle, and physiologic cross-sectional area (PCSA). Various aspects of shoulder and arm muscle architecture have been investigated, but not comprehensively.[7,8,18,19] Comparison of the architectural parameters of these muscles might help in determining the most appropriate musculotendinous transfers around the shoulder and elbow.

The purpose of this study was to examine the architecture of the shoulder and upper arm muscles and generate data that could serve as a guide for comparison, compatibility, and relative performance among these muscles for use in transfer.

MATERIALS AND METHODS

Five fresh cadaver torsos, with an average age at death of 73 years, were the subject of this study. Eleven shoulder and arm muscles were examined in each cadaver. The muscles studied included the deltoid, supraspinatus, infraspinatus, teres minor, pectoralis major, latissimus dorsi, teres major, coracobrachialis, brachialis, biceps, and triceps. Three of these muscles, the deltoid, biceps and triceps, are commonly involved in restoration of elbow extension in tetraplegia and consist of distinct anatomical subunits. Due to this complex architecture and potential clinical implications, these 3 muscles were examined based on their anatomical and functional components: the deltoid's anterior, middle, and posterior portions; the short and long heads of the biceps; and the long, medial, and lateral heads of the triceps. Both right and left sides were examined. In 1 cadaver, a right-sided, full-thickness rotator cuff tear was identified during dissection, so the supraspinatus, infraspinatus, and teres minor were not evaluated. We assessed a total of 107 muscles.

The cadaver torsos were skinned, and the subcutaneous tissues overlying the muscles were removed to allow the best visualization of fiber orientation. The gross anatomy of these muscles was observed, and muscles were grouped based on similarities of their architecture. Five objective parameters were then assessed for each muscle, and averages were calculated:

1. Resting muscle length from origin to insertion was determined with the shoulder adducted and the elbow flexed 45°. Measurements were made in millimeters with a calibrated tape and a goniometer before any muscle mobilization.
2. Required excursion was determined by detaching the muscle origin and moving the joint crossed by that muscle through a full physiologic range of its primary axis of motion measured in degrees, using a goniometer. The excursion of the muscle was then measured in millimeters with a ruler by determining change in distance between origin and insertion as the joint was again taken through its full primary range of motion. This maneuver simulated the maximum required excursion that would be required by that muscle to move the joint through the tested motion.
3. Muscle fiber length, a measure of potential excursion, was determined. In flat muscles with a broad origin and longitudinally oriented fibers, fiber length was measured at the 2 borders, and the average length was determined. For pennate muscles, the method of Brand et al was used to unfurl the fusiform muscle between its tendons or bony origin and its tendon of insertion, and the exposed muscle fibers were measured in millimeters.[12] To facilitate the evaluation of the complex multipennate middle deltoid, 3.5× loupe magnification was used. The anterior and posterior deltoid muscle fibers were measured in the same way as flat muscles.
4. Pennation angle was measured with a goniometer in the same position that allowed determination of fiber length. We then detached the muscle from the cadaver and measured its weight in grams.
5. The PCSA was determined according to the following equation:[20]

$$\text{PCSA (cm}^2) = \frac{\textit{Muscle mass}\ (g)\ x \cos(0)}{P(\text{g/cm}^2) \times \text{L}_\text{f}(\text{cm})}$$

Where p = muscle density (1056 g/cm^2), 0 = surface pennation angle, and L_f = fiber length.

RESULTS

Based on the gross appearance of muscle fiber orientation, the 11 shoulder and arm muscles were subdivided into 3 groups (Table 1). Group 1 (Fig. 1) was characterized by muscles originating over a large surface area

TABLE 1. Muscle Grouping Based on Fiber Arrangement

Group 1	Group 2	Group 3
Supraspinatus	Coracobrachialis	Deltoid anterior
Infraspinatus	Biceps long	Deltoid middle
Teres minor	Biceps short	Deltoid posterior
Pectoralis major	Triceps medial	
Latissimus dorsi	Triceps lateral	
Teres major	Triceps long	
Brachialis		

and having longitudinally oriented fibers that coalesced in a cone-like fashion toward their insertion. With the exception of the brachialis, all muscles in this group originated predominantly from the spinous processes, thorax, or scapula. Group 2 consisted of muscles that appeared on superficial inspection to be either fusiform or strap-like (Fig. 2A). However, when the origin was elevated, the muscle could be spread out as a sheet between the tendinous or periosteal origin and the tendon of insertion (Fig. 2B). The muscles of this group were all located in the arm; originated on the scapula and humerus; and inserted on the humerus, radius, or ulna. Group 3 consisted of the 3 anatomical divisions of the deltoid muscle, with anterior and posterior portions resembling group 1 and a middle portion made up of fibrous bands interconnected by short multipennate fibers (Fig. 3), a property more like that of group 2.

The average required excursion for all muscles is shown in Table 2. The average resting lengths, fiber lengths, pennation angles, and PCSA are listed in Table 3. Specific interpretation of these values is as follows:

- Resting length. Muscle length in group 1 closely approximated fiber length. In contrast, in group 2, the resting length always exceeded fiber length. This characteristic was accentuated in muscles, such as the biceps, that had both a long tendinous origin and insertion. In group 3, the resting length approximated the fiber length in the anterior and posterior deltoid components. However, in the middle deltoid, the arrangement of short muscle fibers between fibrous bands resulted in muscle length greatly exceeding fiber length.
- Required excursion. In group 1, the supraspinatus and infraspinatus had maximum required excursion with abduction, as did the pectoralis major, teres major, and latissimus dorsi. For the same arc of motion, the pectoralis major, teres major, and latissimus dorsi had greater required excursions, resulting from their more distal insertion on the humerus and resultant longer moment arms. The teres minor, in contrast to the other muscles of this group, showed its maximum required excursion during shoulder rotation. The brachialis also had gross characteristics that led to its classification as a group 1 muscle, and it demonstrated maximal required excursion during elbow motion.

In group 2, both the biceps and triceps demonstrated their maximal required excursion during elbow motion. The coracobrachialis required shoulder flexion and extension for evaluation. Required excursion for the triceps ranged from a high of 82 mm for the long head to a low of 46 mm for the medial head. Required excursions of the long and short heads of the biceps were comparable at 65 to 70 mm. The coracobrachialis was evaluated with both shoulder flexion and extension and demonstrated required average excursion of approximately 40 mm for both motions.

For group 3, the required excursion for each of the 3 anatomical divisions of the deltoid were measured with different shoulder motions based on muscle vector. This protocol demonstrated that excursions for the anterior, middle, and posterior divisions were comparable for shoulder flexion, abduction, and extension, respectively.

- Fiber length. In group 1, the longest fiber length was found for the latissimus dorsi, followed by the pectoralis major. The infraspinatus had a fiber length comparable to that of the teres major and slightly longer than the supraspinatus.

In group 2, the coracobrachialis and medial triceps had similar muscle fiber lengths. The short head of the biceps had a longer fiber length than the long head. Based on fiber length, the long head of the triceps more closely correlated with the short head of the biceps, and the lateral head of the triceps more closely correlated with the long head of the biceps.

For group 3, the anterior and posterior portions were comparable in fiber orientation; however, the fibers in the posterior deltoid were consistently longer than in the anterior portion. The middle deltoid muscle fibers ran between fibrous bands and were notably shorter than the anterior and posterior segment fibers.

Comparison of maximal required excursion and fiber length for each muscle by group is shown in Figure 4. With the exception of the middle deltoid and the teres major measured in abduction, the maximal required excursion was consistently less than the measured fiber length for all muscles evaluated.

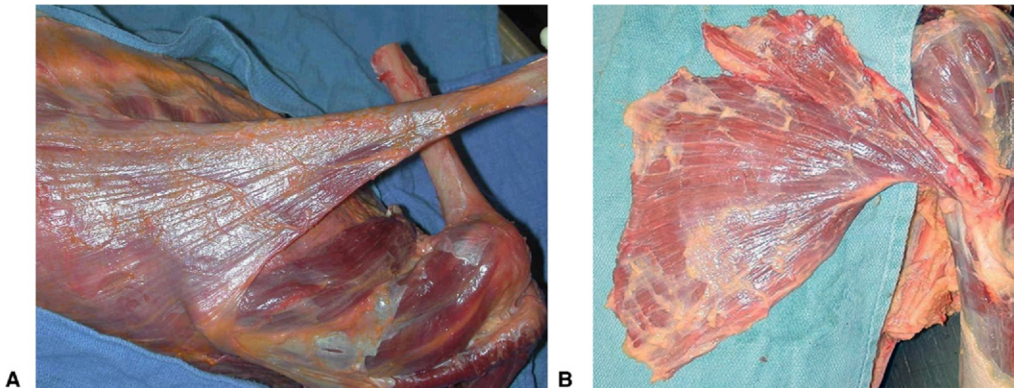

FIGURE 1: Examples of group 1 muscles. **A** Latissimus dorsi, demonstrating broad origin from the trunk. **B** Pectoralis major detached from its broad origin on the chest wall, demonstrating longitudinally oriented fibers coalescing in a cone-like fashion to its insertion on the humerus.

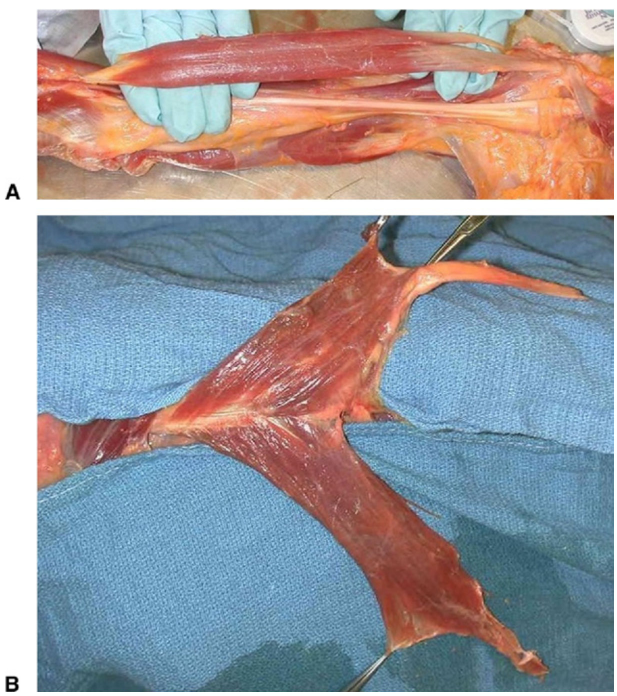

FIGURE 2: Example of group 2 muscles. **A** Fusiform appearance of the long and short heads of the biceps. **B** Long and short heads after detachment from their origin, demonstrating the characteristic of unfolding into a broad sheet between the tendinous or periosteal origin and their tendon of insertion.

FIGURE 3: Close-up view of the dissected middle head of the deltoid, demonstrating the short fiber length and interconnecting fibrous bands.

- Pennation angle. All muscles of group 1 demonstrate a muscle fiber pennation angle of 0°, except the brachialis muscle fibers, which had an angle of 28°. In group 2, pennation angle varied from 35° to 50°, whereas in the deltoid (group 3), it varied from 0° to 30°.
- Physiologic cross-sectional area. In group 1, the largest muscle mass was encountered in the latissimus dorsi, followed by the pectoralis major. Because of differences in fiber length, the infraspinatus had a PCSA greater than any other muscle in group 1.

In group 2, all components of the triceps showed considerably higher PCSA than the coracobrachialis or either component of the biceps. A shorter fiber length and greater triceps mass compared to the biceps influenced this difference. Although the coracobrachialis had a fiber length similar to that of the medial triceps, the increased mass of the medial triceps resulted in a PCSA of nearly twice that of the coracobrachialis.

The deltoid PCSA was similar for the anterior and posterior portions. However, the short fiber length of the middle deltoid, coupled with a mass greater than either the posterior or anterior portions, resulted in a PCSA that was greater than any other muscle measured in this study.

TABLE 2. Required Excursion and Motion Used in Evaluation

Muscle	Motion (^{0})	Excursion (mm)	Motion (^{0})	Excursion (mm)	Motion (^{0})	Excursion (mm)	Motion (^{0})	Excursion (mm)
Group 1								
SS	Abduction 0–140	33 ± 5						
IS	Abduction 0–140	42 ± 6	Rotation 0–90	27 ± 4				
TMi	Abduction 0–140	12 ± 4	Rotation 0–90	26 ± 5				
PM	Abduction 0–140	102 ± 10	Rotation 90–0	23 ± 5				
LD	Abduction 0–140	89 ± 16	Flexion 0–160	96 ± 9	Extension 0–45	38 ± 8	Rotation 90–0	24 ± 5
TM	Abduction 0–140	125 ± 12	Flexion 0–160	61 ± 6	Extension 0–45	20 ± 6	Rotation 90–0	17 ± 4
BR	Elbow flexion 0–150	52 ± 8						
Group 2								
CB	Flexion 0–160	42 ± 4	Extension 0–45	37 ± 5				
BLg	Elbow flexion 0–150	65 ± 5	Full P/S	21 ± 3	Sh Flex 0–160	47 ± 5		
BS	Elbow flexion 0–150	70 ± 6	Full P/S	23 ± 5	Sh Flex 0–160	47 ± 5		
TLg	Elbow flexion 0–150	82 ± 4						
TMd	Elbow flexion 0–150	46 ± 9						
TL	Elbow flexion 0–150	68 ± 9						
Group 3								
DA	Flexion 0–160	50 ± 9						
DM	Abduction 0–140	47 ± 5						
DP	Extension 0–45	52 ± 6						

SS, supraspinatus; IS, infraspinatus; TMi, teres minor; PM, pectoralis major; LD, latissimus dorsi; TM, teres major; BR, brachialis; CB, coracobrachialis; BLg, biceps long; BS, biceps short; TMd, triceps medial; TL, triceps lateral; TLg, triceps long; DA, deltoid anterior; DM, deltoid middle; DP, deltoid posterior; P/S, pronation/supination.

DISCUSSION

Anatomists and physicians have been interested in muscle architecture for more than 3 centuries.[9,10] Early anatomic descriptions of skeletal muscles appeared in 17th century literature, with subsequent correlation between geometry and function. However, the clinical application of the study of structure and function to evaluation of musculotendinous transfer in the forearm and hand did not appear until the 1981 Brand et al study.[12] In this seminal work, Brand and colleagues

TABLE 3. Major Architectural Properties Measure

Muscle	Muscle Mass (g)	Muscle Length (mm)	Fiber Length (mm)	Pennation Angle (^{0})	PCSA (cm^2)	FL/ML Ratio
Group 1						
SS	30 ± 4	127 ± 7	117 ± 7	0	2.48 ± 0.94	0.92 ± 0.01
IS	76 ± 5	134 ± 5	124 ± 5	0	5.89 ± 0.32	0.92 ± 0.01
TMi	11 ± 3	95 ± 5	85 ± 5	0	1.26 ± 0.34	0.89 ± 0.01
PM	80 ± 4	203 ± 10	193 ± 10	0	4.05 ± 0.15	0.95 ± 0.01
LD	101 ± 3	287 ± 27	255 ± 17	0	3.99 ± 0.14	0.89 ± 0.03
TM	36 ± 3	136 ± 14	126 ± 14	0	2.98 ± 0.12	0.92 ± 0.02
BR	52 ± 12	150 ± 8	108 ± 7	28	3.84 ± 0.71	0.72 ± 0.02
Group 2						
CB	18 ± 2	153 ± 7	60 ± 7	35	2.41 ± 0.39	0.39 ± 0.04
BLg	36 ± 13	349 ± 10	113 ± 23	45	2.12 ± 0.62	0.32 ± 0.06
BS	30 ± 0	277 ± 18	137 ± 21	50	1.37 ± 0.0	0.47 ± 0.11
TLg	82 ± 3	285 ± 11	102 ± 16	42	6.07 ± 0.44	0.36 ± 0.05
TMd	41 ± 3	198 ± 18	65 ± 7	43	4.69 ± 0.28	0.33 ± 0.03
TL	51 ± 3	261 ± 7	81 ± 6	40	4.80 ± 0.32	0.31 ± 0.02
Group 3						
DA	40 ± 12	144 ± 8	144 ± 8	0	2.54 ± 0.59	1
DM	67 ± 12	161 ± 6	55 ± 9	31	11.18 ± 1.57	0.34 ± 0.06
DP	51 ± 3	178 ± 6	178 ± 6	0	2.73 ± 0.12	1

SS, supraspinatus; IS, infraspinatus; TMi, teres minor; PM, pectoralis major; LD, latissimus dorsi; TM, teres major; BR, brachialis; CB, coracobrachialis; BLg, biceps long; BS, biceps short; TMd, triceps medial; TL, triceps lateral; TLg, triceps long; DA, deltoid anterior; DM, deltoid middle; DP, deltoid posterior; FL/ML, fiber length/muscle length.

showed that when muscles were detached distally in the forearm and swung away from their origin on the intramuscular tendon of insertion, they assumed the shape of either a parallelepiped or a trapezoid. This technique allowed these investigators to confirm that resting muscle fiber length was constant, even for fusiform muscles that appeared to have variable fiber lengths. This concept of uniformity of fiber orientation and length was in reality a rediscovery and extension of an observation that had been documented by Steno in 1667.[11] The presence of equal fiber length means that the ratio of muscle volume to fiber length provides a good estimate of potential force. With this work as a foundation, many subsequent studies have examined forearm and hand musculature in even more detail.[13–16] New data generated from this work have helped lend scientific support to many tendon transfers commonly used today in restoration of hand function.[21]

Herzberg et al[8] evaluated 13 muscles around the shoulder to determine potential excursion and relative tension (PCSA of muscle fibers, expressed as a percentage of a group of muscles). From their data, they made recommendations on possible compatible transfers for shoulder muscle deficiencies secondary to nerve palsy and attritional rotator cuff rupture. They did not evaluate the biceps or triceps muscles, but they observed the complex anatomy of the middle portion of the deltoid. A recent detailed study of the middle deltoid combined anatomical and magnetic resonance imaging assessments and showed that this section usually consisted of 4 proximal and distal fibrous bands with muscle fibers situated between.[19]

Friden and Lieber[18] evaluated quantitatively the posterior deltoid to triceps tendon transfer based on architectural properties of these 2 muscles. They demonstrated that adequate potential excursion exists in the posterior deltoid to mimic triceps function. The PCSA of the posterior deltoid, however, was found to be notably less than that of the entire triceps, and they estimated that it would provide approximately 20% of the maximum tension of the entire triceps.

From our data, architectural comparisons can be useful for matching potential donor muscles to recipient insertions for restoration of shoulder and elbow motion.

Comparison of fiber length, which estimates potential excursion, with required excursion indicates that

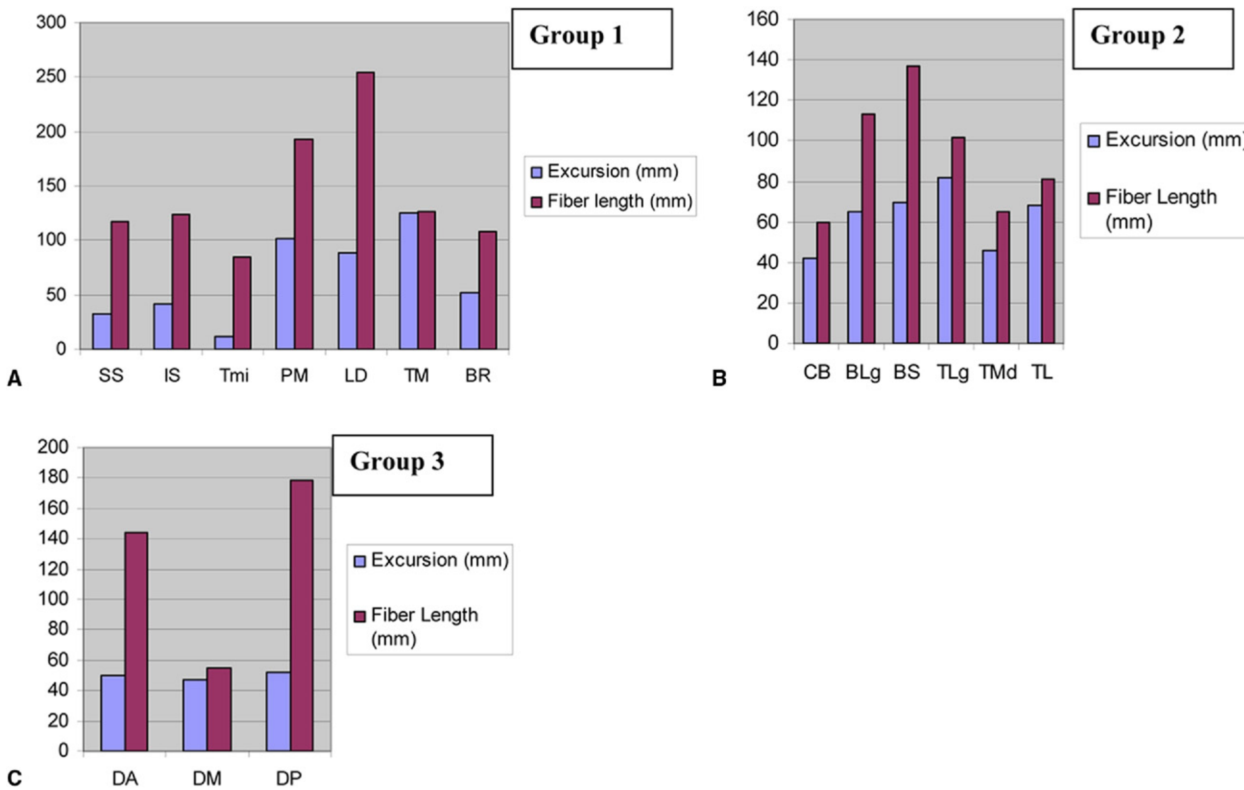

FIGURE 4: Relative excursion versus fiber length. SS, supraspinatus; IS, infraspinatus; TMi, teres minor; PM, pectoralis major; LD, latissimus dorsi; TM, teres major; BR, brachialis; CB, coracobrachialis; BLg, biceps long; BS, biceps short; TMd, triceps medial; TL, triceps lateral; TLg, triceps long; DA, deltoid anterior; DM, deltoid middle; DP, deltoid posterior.

maximum physiologic joint motion probably leaves most of the muscles examined in this study operating principally near the central portions of their Blix curves.[22] This correlation between increasing muscle fiber length and required excursion has been observed before, during muscle analysis, and has been interpreted as offering more capacity for stretch to a joint powered by these types of muscles.[23]

During abduction in 2 muscles, the teres major and middle deltoid, the motion creating maximal required excursion approximated their potential excursions. These data would support the concept that the teres major's primary function is arm rotation and that it contributes little to adduction power. This might have clinical relevance when the latissimus dorsi muscle is transferred or used for other reconstructive procedures.[24] In this situation, the teres major probably contributes little to preservation of adduction strength, but it might maintain arm rotation through its shared insertion.

The equality of required excursion and fiber length/potential excursion observed in the middle deltoid is open to several interpretations. Due to the short fiber length and large arc of motion required to maximally abduct the shoulder and position the hand in space, the middle deltoid would appear to have a poor mechanical advantage. However, the high muscle mass of the middle deltoid relative to this short fiber length yields a muscle with a high PCSA. The mechanical disadvantage of the short fiber length can be overcome by the ability to create a high tension across a short moment arm (ie, short origin to insertion). This configuration means that the muscle itself needs to contract less for a given arc of motion than a muscle with a long fiber length and long moment arm would.[22] Alternatively, the multiple short muscle fibers and interconnecting fibrous bands might have a role in providing power and stability after other muscles bring the arm into abduction. A third possibility for the complex arrangement of the middle deltoid is providing fine control to shoulder motion. This would be analogous to the fine control provided by the intrinsic muscles of the hand, which have been postulated to be essential for musical instrument play or keyboard use.[22] This complex structure of the deltoid implies that muscle transfer to restore its function would at best provide a gross approximation, without the fine positioning of the arm in space required for many demanding daily tasks.

Within group 2, the similarities between the coracobrachialis and medial head of the triceps were noteworthy. Both fiber length and required excursion correlated, but mass was greater for the medial triceps, resulting in a larger PCSA. The disparity in PCSA was, however, no different for these 2 muscles than between the 2 heads of the biceps and 2 other triceps heads. A profound difference in PCSA between the anterior and posterior muscles of the arm was present in this study. This difference might have clinical implications when considering use of the biceps or posterior deltoid for restoration of elbow extension.[18,25,26]

Dissection of the deltoid along with the triceps and biceps in a single study allowed for comparison of these muscles for transfers to restore elbow extension. Both the biceps and posterior deltoid would appear to have adequate fiber length to provide an effective transfer to the triceps. However, even the entire biceps would not approach the strength of the entire triceps. Experimentally, this difference in cross-sectional area has been predicted previously for deltoid transfer and has been confirmed in clinical cases.[18,26] From our data, the biceps offers no architectural advantage over the posterior deltoid for triceps transfer. Other factors can influence the choice of transfer, however, including the need for a tendon graft when transferring the posterior deltoid to the triceps.

The data presented in this study offer the opportunity for direct comparison of architectural features of select shoulder and arm musculature and could potentially be integrated into future computer modeling for proposed tendon transfers. This information might have clinical relevance in evaluating compatibility of various musculotendinous transfers around the shoulder and elbow. It is also important to acknowledge that matching architectural properties during musculotendinous transfer is a desired objective, but it is only one of several variables that determine the functional outcome. Other important prerequisites are assessing the moment arm, line of pull, and number of joints crossed by the transferred muscle. Satisfactory functional results can be obtained despite architectural mismatch, and some transfers are more forgiving than others, perhaps due to adaptation.

This investigation has the limitations of a cadaver study, which underscores the need for clinical correlation. However, previous work has shown that experimental studies of skeletal muscle architecture can have clinical implications.[21] The cadavers represented in this study were also all of a similar advanced age. The disparity in biceps and triceps PCSA might be accentuated by age and preferential premorbid use of the triceps for assistance in rising from a sitting position over biceps use for lifting heavy objects.

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A TOUCH OF HUMANITY

Hands on Stamps: Brazil 1971–Women's Basketball

Terry R. Light, MD

Scott Catalogue #1188

This stamp commemorates the Sixth World Women's basketball championship games in Sao Paulo, Recife, Niteroi, and Brasilia, Brazil. The championship is held every 4 years in non-Olympic years under the auspices of the International Basketball Federation (FIBA). The Soviet Union won the 1971 gold medal, Czechoslovakia won the silver, and the host, Brazil, won the bronze. The Soviet Union won 5 consecutive titles between 1959 and 1975. The United States has won 5 of the last 7 titles, perhaps reflecting the expansion of women's sports in American high schools and colleges. Brazil won the 1994 championship.

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