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Biomechanical Analysis of the Brachioradialis as a Donor in Tendon Transfer

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Anatomic and biomechanical properties of the passive brachioradialis muscle were investigated to understand the limited excursion of this muscle seen during tendon transfer surgery. First, architectural measurements were performed on three fiber bundles obtained from four regions of the brachioradialis (10 specimens) chosen to represent the range of muscle fiber lengths across the brachioradialis. Next, in separate specimens (eight specimens), passive excursion was measured by securing the distal tendon stump to a servomotor. A constant load of 4.9 N was applied to the tendon, while the distal tendon was released from the surrounding tissue in 3-cm increments. Within the four regions studied, muscle fiber length varied significantly from 104.2 ± 6.2 mm to 179.8 ± 6.1 mm. As the brachioradialis was released, an average of 3 mm of mobility was obtained for each interval whereas for the succeeding three intervals, an average of 5.3 mm of mobility was obtained. This resulted in 22.2 ± 2.3 mm of mobility when each specimen was fully released. These data show that there is no intrinsic muscle fiber length limitation to excursion, but that excursion is limited by other intermuscular connections to adjacent connective tissue and other muscles.

A thorough understanding of upper extremity anatomy serves as the foundation for effective surgical intervention. Anatomic studies of muscle structures can be traced to the seventeenth century where the elegant and varied arrangement of muscle fibers was appreciated easily and its functional significance inferred.[6] More recently, skeletal muscle architecture (the arrangement and number of fibers in a muscle) was investigated by Brand and colleagues,[4] who estimated the excursion and force-generating capacity of many upper extremity muscles used in tendon transfer surgery. Additional refinement of these measurements was provided to quantify differences between muscles in terms of their architectural properties.[7,8] Because muscle architecture is the most important determinant of muscle function, the authors have used these data to discriminate between potential donor muscles suitable for tendon transfer.[9]

Unfortunately, practical intraoperative experience does not always mirror theoretical predictions that are based on architectural mea-

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surements. For example, the brachioradialis muscle is reported to have a fiber length (12 cm) that would predict a functional range of at least 6 cm.[9] Typical intraoperative experience with this muscle indicates that this is not the case in that brachioradialis excursion rarely exceeds 1 cm after release of the distal insertion or 4 cm after the entire forearm component is released. Still, the brachioradialis is an attractive donor muscle that often is selected to replace lost hand function after nerve or spinal cord injury. It is widely used because it does not cross the finger or wrist joints and therefore is expendable. The lost supination and elbow flexion functions that it usually provides are replaced by other synergistic muscles.

In light of the importance of the brachioradialis as a donor muscle and the "disconnect" between anatomic values reported in the literature and most surgeons' practical experience, the authors performed a more detailed study of the brachioradialis. It was suspected that either previous architectural studies were oversimplified in terms of brachioradialis fiber length or other nonmuscle tissues were present in vivo that restricted brachioradialis excursion. Therefore, the purpose of the current study was to determine the detailed architectural properties of the brachioradialis muscle ands its mechanical attachment to surrounding tissues in an effort to understand its minimal excursion even after relatively complete release.

MATERIALS AND METHODS

Skeletal Muscle Architecture

Muscle architecture was determined according to the methods developed by Sacks and Roy[14] as implemented previously.[8,9] At the time of dissection, elbow extension moment arm of the brachioradialis was estimated by measuring excursion of the brachioradialis tendon while the elbow was rotated through an arc of 1 radian.[1] Muscle mass was recorded immediately after dissection. Muscles were fixed by immersion in 10% buffered formaldehyde for 72 hours, and rinsed in phosphate buffered saline. Muscles were fixed in a flat position corresponding to the supinated forearm and extended elbow. Fixation quality was very good as ascertained based on the sharpness and intensity of the lines within the laser diffraction pattern. Muscle length (L_m) was measured as the distance from the origin of the most proximal muscle fibers to the insertion site of the most distal muscle fibers. Muscle fiber surface pennation angle was determined using a goniometer. Muscle fiber bundles (consisting of five to 50 muscle fibers) were isolated under 6 to 20 magnification and fiber bundle length (L_f) was measured using a calibrated rule (accuracy, 0.5 mm). Three fiber bundles were obtained from each of four regions of the brachioradialis (Fig 1) as shown in Table 1. The goal was not to sample representatively across the entire muscle, but to obtain fiber samples from regions thought to have different fiber lengths and thus, to represent the range of muscle fiber lengths within the brachioradialis. Regions 1 and 3 had their origin at the most proximal humeral border of the brachioradialis and extended to the radial insertion site, Region 1 on the dorsal insertion border and Region 3 on the palmar insertion border. The Region 3 origin was on the deep muscle surface (dotted lines on Fig 1). Region 2 originated on the deep aspect of the humeral border apex and inserted on the deep aspect of the most proximal extension of the insertion tendon. Region 4 originated on the deep aspect of the brachioradialis at the midpoint along the humeral border and inserted along the palmar margin of the insertion tendon. In five muscles, this ended on the deep aspect of the muscle, in three muscles, the insertion was on the superficial aspect of the muscle, in two muscles, the insertion was right on the muscle border. Because the insertion was so close to the muscle border, deep and superficial were very close at this point.

Sarcomere length (L_s) of the isolated fiber bundles was determined by laser diffraction according to the method previously described[7] using the zero to first order diffraction angle and the zero to second order when it was available.

In addition to the measured parameters, the following parameters were calculated: L_f/L_m ratio and physiologic cross-sectional area (PCSA) according to the following equation:[14]

$$\text{PCSA}\ (\text{mm}^2) = \frac{M(g) \cdot \cos\theta}{\rho\ (\text{g/mm}^3) \cdot L_f\ (\text{mm})}$$

where ρ represents muscle density (1.056 g/cm^3)[12] and θ represents surface pennation angle. Values for fiber bundle length were averaged for the three bundles from each region. Muscle length and fiber bundle length values were normalized by the measured sarcomere length to a standard L_s = 2.7 μm to compensate for variations among specimens in muscle length during fixation.

Passive Mechanical Tensile Experiments

The goal of the mechanical experiments was to simulate the effect of an assistant holding a tendon as a surgeon released the brachioradialis from surrounding tissue. Arms from cadavers that were amputated at the midhumeral level (eight specimens, different from those used in the architectural measurements described above) were secured to a board by Steinmann pins (Zimmer, Warsaw, IN) placed through the humerus, proximal to the elbow, and the ulna proximal to the wrist. The brachioradialis insertion then was released from the radius at the point where the distal tendon fans into the radial styloid. This tendon stump was secured into the jaws of a clamp attached to a servomotor that could

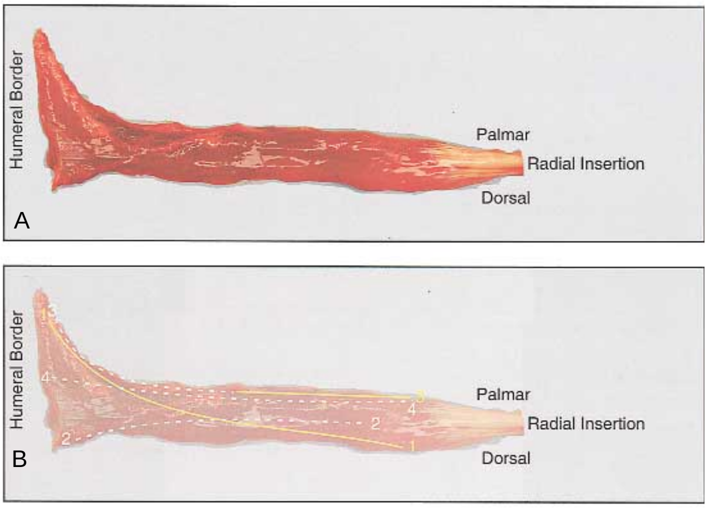

Fig 1A–B. Gross anatomy of a superficial view of the brachioradialis muscle showing the four regions from which muscle fibers were sampled. Region definitions are shown in Table 1. Solid yellow lines represent superficial fibers and white dotted lines represent deep fibers. (A) Muscle overview with anatomic directions. (B) Lines represent the major fiber bundles isolated in the current study.

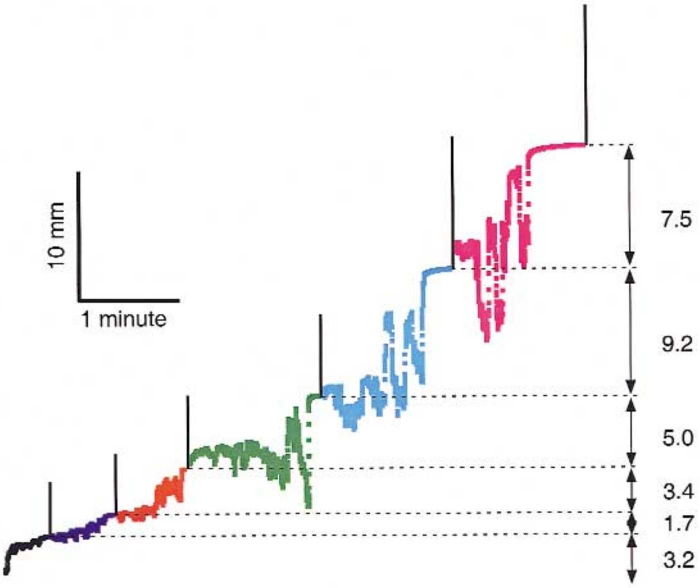

Fig 2. The length-time records measured during progressive release of brachioradialis muscle from the radius and surrounding tissues are shown. Each color represents a 3 cm release with the overall release length obtained for each segment is shown to the right of the panel. Vertical lines separating colors represent the excursion magnitude after each release and correspond to the values obtained from the curves shown in Figure 3A.

TABLE 1. Muscle Region Definitions

Region	Origin	Insertion
1.	Superficial proximal humeral border	Superficial distal dorsal tendon
2.	Deep aspect of the humeral border apex	Deep aspect of the most proximal extension of the insertion tendon
3.	Deep proximal humeral border	Superficial distal palmar tendon
4.	Deep aspect of the brachioradialis at the midpoint along the humeral border	Palmar margin of the insertion tendon

be operated under length or force control (Model 310B, Aurora Scientific, Richmond Hill, Ontario, Canada). A constant load of 4.9 N was applied to the tendon, while the distal tendon was released surgically from the surrounding tissue in 3 cm increments. The forearms were long enough to permit four to six steps of 3-cm releases (see below).

Muscle-tendon unit length was recorded online at 25 Hz during each release, resulting in a series of length-time records that corresponded to each 3 cm-release increment (Fig 2). To estimate the mechanical properties of the released tissue, after each release, the muscle-tendon unit was loaded linearly to 9.8 N over 2.5 seconds and the load-excursion relationship was recorded (Fig 3; vertical lines in Fig 2). This sequence of tests was repeated until the brachioradialis was released to the elbow.

Statistical Analysis

Mean fiber length, excursion during release, and elongation during linear loading were compared by one-way analysis of variance (ANOVA) (StatView

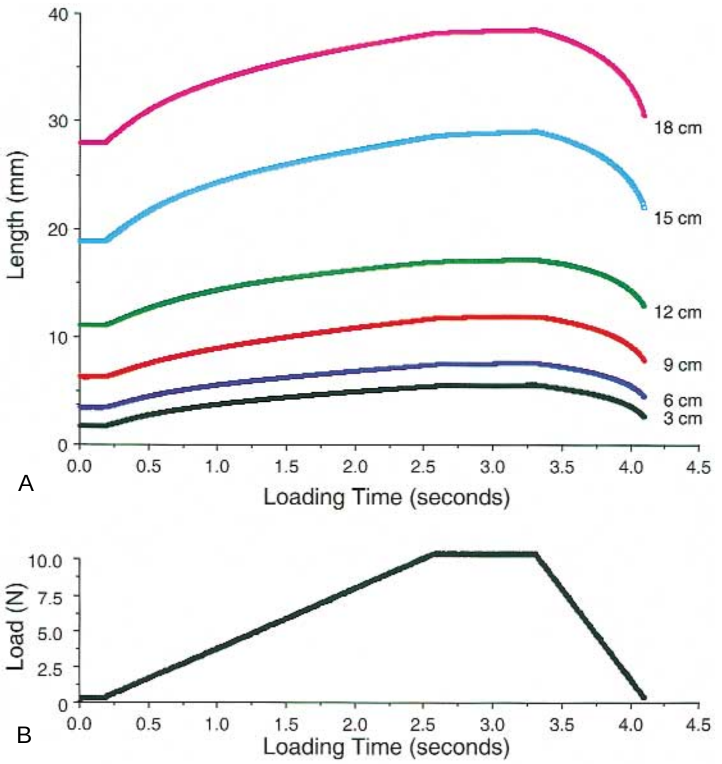

Fig 3A–B. (A) Load-extension curves obtained after progressive release of the brachioradialis from the radius and surrounding tissues are shown. The curves shift vertically based on the length gained after each release, the magnitude of which is shown to the right of each curve. (B) Load-time ramp imposed on the muscle-tendon unit is shown. The peak excursion values for each curve are shown as a vertical line separating successive color shown in Figure 2.

5.0, Abacus Concepts, Berkeley, CA). The significance level was set at 0.05 and statistical power exceeded 75% for all comparisons that were not significantly different.

RESULTS

General Anatomy

The brachioradialis originated at the lateral supracondylar ridge of the humerus as a broad (66 ± 3 mm) fan-shaped cluster of fibers and inserted at the styloid process of the distal radius with a long tendon (Table 2). The distance between insertion and the muscle-tendon junction was 80 ± 4 mm on the superficial side, whereas deep tendon length was significantly longer, ranging from 115 ± 5 mm at the peripheral muscle borders to 138 ± 5 mm in the center.

Within the four regions studied, muscle fiber length varied significantly from a low value of approximately 100 mm in Region 2 to a high value of approximately 180 mm in Region 4 (Table 3, Fig 4).

Biomechanical Attachments

A nonlinear relationship was observed between the length of muscle surgically released and the amount of mobility measured (Fig 5). As the brachioradialis was released over the first three intervals (3, 6, and 9 cm release distances), an average of 3 mm of mobility were obtained for each interval whereas for the succeeding three intervals (12, 15, and 18 cm release distances),

TABLE 2. Brachioradialis Descriptive Statistics

Parameter	Value*
Forearm length	241.0 ± 3.0 mm
Elbow extension moment arm	41.3 ± 3.2 mm
Muscle length (normalized to 2.7 μm)	199.3 ± 8.2 mm
Origin length	66.0 ± 3.2 mm
Muscle width	
Proximal	25.4 ± 1.3 mm
Middle	19.0 ± 1.6 mm
Distal	20.0 ± 1.7 mm
Tendon length	
Superficial	79.8 ± 3.8 mm
Deep (peak)	137.8 ± 5.4 mm
(base)	114.9 ± 4.5 mm

*Values presented are mean ± standard error of the mean (n = 10).

TABLE 3. Brachioradialis Muscle Architectural Properties

Parameter	Value*
Muscle mass	29.3 ± 3.7 g
Muscle length (normalized to 2.7 μm)	199.3 ± 8.2 mm
Longest fiber (superficial)	
Fiber length 1	179.8 ± 6.1 mm
FL1/ML	0.91 ± 0.02
Shortest Fiber	
Fiber length 2	104.2 ± 6.2 mm
FL2/ML	0.52 ± 0.03
Longest fiber (deep)	
Fiber length 3	176.1 ± 7.0 mm
FL3/ML	0.89 ± 0.02
Intermediate fiber (typical?)	
Fiber length 4	149.6 ± 6.4 mm
FL4/ML	0.75 ± 0.02
PCSA (using fiber 4)	1.9 ± 0.3 cm^2

*Values presented are mean ± standard error of the mean (n = 10); FL = fiber length; ML = muscle length; PCSA = physiologic cross-sectional area.

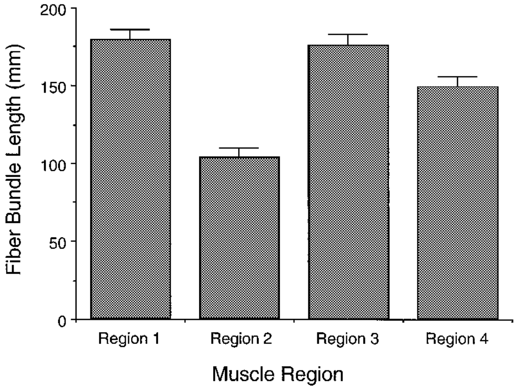

Fig 4. Bar graph showing the average muscle fiber bundle length obtained from the four regions shown in Figure 1. One-way ANOVA revealed a significant difference between regions ($p < 0.0001$) with all regions significantly different from one another ($p < 0.01$) except for Regions 1 and 3 ($p > 0.6$).

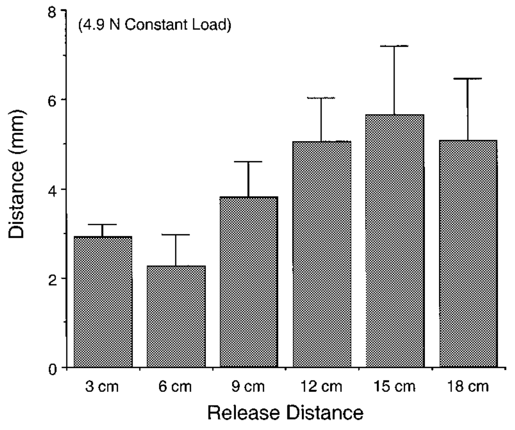

Fig 5. Bar graph showing the average distance gained after successive releases from 3 to 18 cm. Release magnitude was relatively small (3 mm) for the first three release intervals and larger (5 mm) for the succeeding three release intervals. The change in sample size with increasing release magnitude attributable to size differences between forearms is shown.

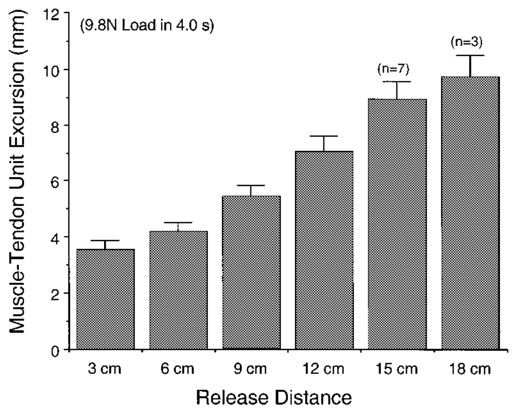

Fig 6. Bar graph is showing average excursion measured on loading of muscle-tendon unit to 9.8 N after release from 3 cm to 18 cm. The change in sample size with increasing release magnitude attributable to size differences between forearms is shown.

an average of 5.3 mm of mobility was observed. This resulted in 22.2 ± 2.3 mm of mobility in all eight specimens when each specimen was released fully. This average mobilized length was influenced slightly because not all specimens were long enough to perform six releases. However, at least four releases were performed in all eight specimens, five releases were performed in six specimens and six releases were performed in five specimens, dependent on the length of the brachioradialis.

Not surprisingly, as more tissue was mobilized from surrounding tissues, the excursion measured on passive loading increased proportionately (Fig 6). In contrast to the incremental mobility increases measured above, the excursion progressively increased because the released regions were arranged in series. After the initial release of 3 cm, an excursion of 3.6 ± 0.3 mm was measured and after five releases (15 cm) an excursion of 8.9 ± 0.7 mm was measured. In the three specimens that were long enough to perform six releases, the final excursion that was measured was 9.7 ± 0.8 mm. The amount of mobility was significantly but weakly correlated with the excursion that was measured ($r^2 = 0.15$, $p < 0.02$).

DISCUSSION

Brachioradialis Architecture

The purpose of the current study was to understand the anatomic and mechanical basis for the limited excursion observed during tendon transfers in which the brachioradialis is used as a donor muscle. The authors previously reported a brachioradialis fiber length of 121 mm, which represented a gross average across the muscle.[9] In the current study, which was performed in much greater detail, a systematic variation of approximately 100 mm to approximately 180 mm across the muscle was observed depending on the region that was studied (Fig 4). Despite this variation, it is unlikely that these fiber lengths, which are among the longest in the forearm, would restrict muscle excursion. The longest fibers of the brachioradialis were those that traversed from the humeral origin to the radial insertion (Regions 1 and 3, Fig 1). The shorter fibers only traversed from the most distal humeral point of origin to the inferior aspect of the distal brachioradialis Region 2, Fig 1). The longer fibers may be required to provide adequate brachioradialis range while providing a relatively large elbow flexion moment arm.

Brachioradialis Biomechanics

In the current study, mechanical studies of the brachioradialis documented the fact that the brachioradialis muscle is strongly tethered to surrounding structures within the forearm. Distally, the insertion tendon fans into a bone-tendon junctional structure that does not permit any mobility of the insertion point. In fact, a release of approximately 3 cm was necessary to linearly load the muscle-tendon unit, providing enough free tissue on which to align the tendon clamp. Subsequent release, as much as 9 cm proximal from the insertion, provided minimal additional mobility (Fig 5). Importantly, as the release progressed toward the elbow, large increases in mobility were measured. These large increases typically were obtained at the point of muscle-muscle contact in contrast to the earlier connections that were tendon-bone and tendon-surrounding connective tissue contacts. Anatomically, the first muscle-muscle connection to be severed was that between the brachioradialis and the extensor carpi radialis longus muscle, which share a common fascial connection on the dorsoradial margin of the brachioradialis and the dorsal border of the extensor carpi radialis longus. As one progressed, successive release of the brachioradialis-pronator teres and brachioradialis-flexor carpi radialis connections also provided increased excursions, although the anatomic location and consistency of these connections was much more variable.

Limitations to Excursion

The excursion values reported (Fig 6) are much lower than those observed intraoperatively even when almost the entire length of the brachioradialis is mobilized. The maximum excursion observed in the current study (approximately 10 mm) represents the extension obtained when the muscle-tendon unit is loaded to 9.8 N after taking up the slack in the system. To provide a reasonable comparison between the excursion values reported in the current study and the intraoperative condition, it is necessary to add the excursion values to the release distances to obtain the total excursion of the muscle-tendon unit after surgical release under physiologic conditions. For the data reported in the current study, this value would be approximately 32 mm, which represents the average sum of the release distances (22 mm) added to the excursion value under load (10 mm). Because the muscles did not provide a restoring force after release, the excursion values measured in the specimens from cadavers only represent the connective tissue component of excursion, without taking into account the mechanical restoring force within the muscle fibers.

Combining the architecture data with the mechanical data provides insights into the factors that limit brachioradialis mobility. If the average brachioradialis fiber length is approximately 150 mm (Fig 4), approximately 75 mm of active contraction distance would be expected. This is based on the fact that sarcomere lengths in humans can be as long as 4.25 μm and probably as short as 2.2 μm[10] during active contraction. However, the excursion measurement obtained intraoperatively represents the length corresponding to the maximum passive tension minus the length with the muscle under no tension. This would tend to be much less than the active range over which the muscle could contract. This type of argument provides strong evidence that muscle fiber length does not limit excursion in the brachioradialis muscle.

Based on the current mechanical and architectural data, the authors think that there are connective tissue constraints on brachioradialis excursion. There is no obvious sheath to the muscle that could limit such motion. However, there is a prominent internal tendon on the deep aspect of the muscle and a significant tendinous inscription along the deep border of the muscle. Should this limit excursion, one could argue for the division of this inscription as a method to increase brachioradialis functional range. This may act as an internal strut limiting the muscle fiber's longest length.

Upper Extremity Architecture

In addition to the influence of muscle architecture on the design of the brachioradialis, there also is a high degree of specialization built into other upper extremity muscles by virtue of their architecture. For example, the superficial and deep digital flexors are very similar to one another but are different from the digital extensors (Fig 7). As another example, based on its very high physiologic cross-sectional area, the flexor carpi ulnaris is expected to generate very high forces. Examination of this type of information can be used to compare functional properties between muscles that might be transferred surgically to restore lost function. Intuitively, one might consider it important to match the transferred muscle's architectural properties to the architectural properties of the muscle whose function was lost. To substitute a lost muscle function, the distal tendons of muscles often are transferred from one position to another.[2,3,5,13] It would seem reasonable to select a donor muscle with similar architectural properties as the original muscle to match the original muscle's function. Numerous other factors also influence donor selection including donor muscle availability, donor muscle morbidity, preoperative strength, integrity, expendability, synergism, transfer route and direction, and surgeon experience and preference.

Surgical Restoration of Digital Extension

Architectural differences might be useful in tendon transfer when a making choice involving multiple donors or when a combination of transfers is available for selection. For example, in the surgical restoration of digital extension after high radial nerve palsy, described and accepted, potential donor muscles (that are transferred to the extensor digitorum communis) include the flexor carpi radialis, the flexor carpi ulnaris, the

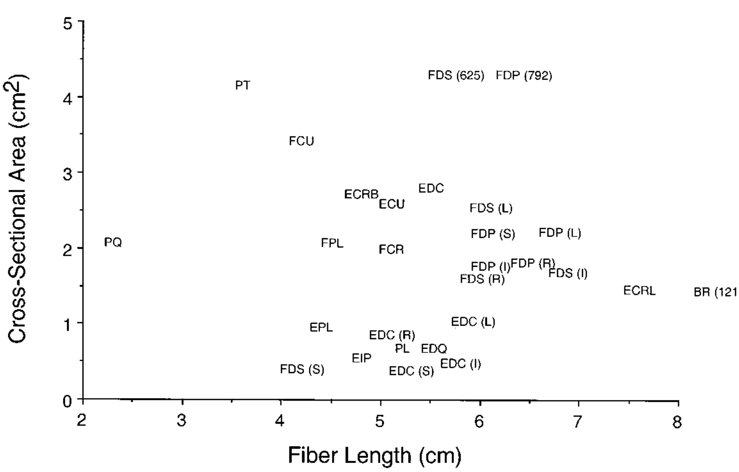

Fig 7. Scattergraph of the fiber length and cross-sectional areas of muscles in the human forearm is shown. The fiber length is proportional to muscle excursion, and the cross-sectional area is proportional to maximum muscle force. This graph can be used to compare the relative forces and excursions of arm and forearm muscles. BR = brachioradialis; ECRB = extensor carpi radialis brevis; ECRL = extensor carpi radialis longus; ECU = extensor carpi ulnaris; EDC I, EDC M, EDC R, and EDC S = extensor digitorum communis to the index, middle, ring and small fingers, respectively; EDQ = extensor digiti quinti; EIP = extensor indicis proprious; EPL = extensor pollicis longus; FCR = flexor carpi radialis; FCU = flexor carpi ulnaris, FDP I, FDP M, FDP R, and FDP S = flexor digitorum profundus muscles; FDS I, FDS M, FDS R, and FDS S = flexor digitorum superficialis muscles; FDS I (P) and FDS I (D) = proximal and distal bellies of the flexor digitorum superficialis I; FDS I (C) = the combined properties of the two bellies as if they were one single muscle; FPL = flexor pollicis longus; PQ = pronator quadratus; PS = palmaris longus; PT = pronator teres. (Figure adapted from data presented in Lieber RL, Fazeli BM, Botte MJ: Architecture of selected wrist flexor and extensor muscles. J Hand Surg 15A:244–250, 1990 and Lieber RL, Jacobson MD, Fazeli BM, Abrams RA, Botte MJ: Architecture of selected muscles of the arms and forearm: Anatomy and implications for tendon transfer. J Hand Surg 17A:787–798, 1992.)

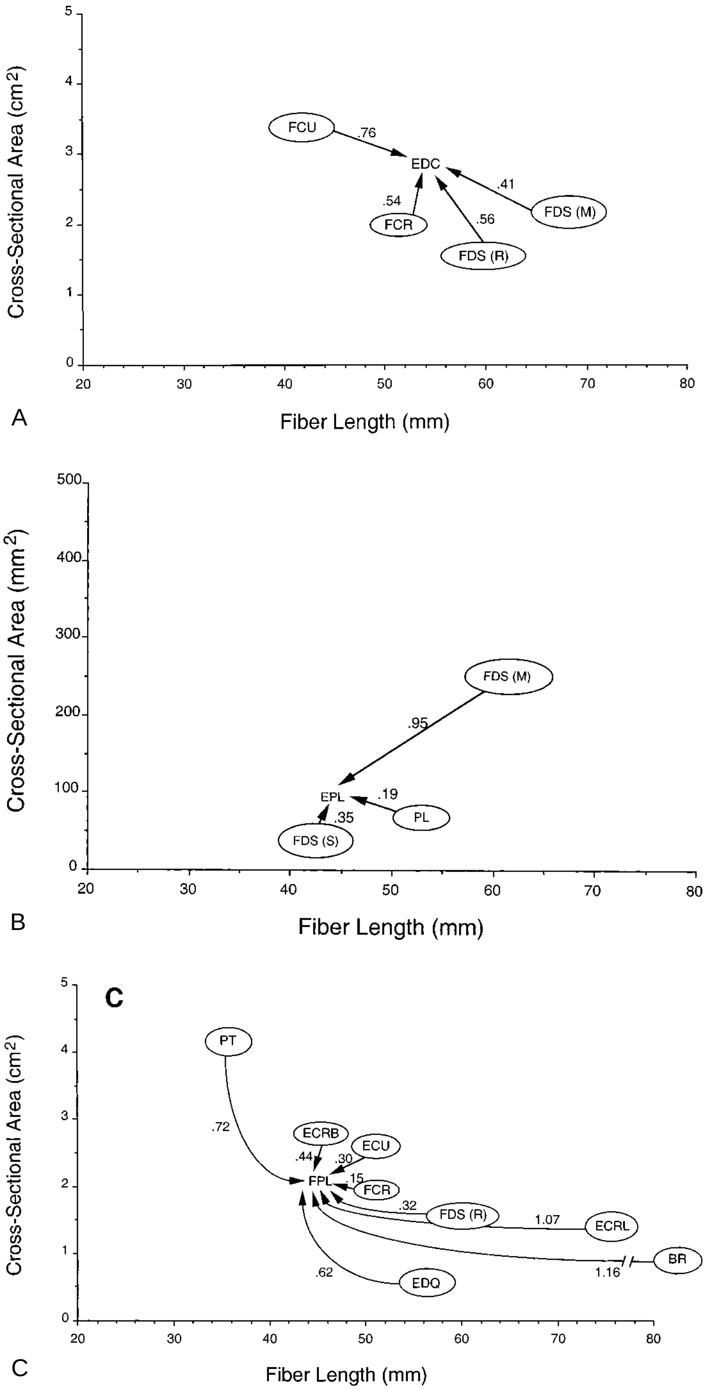

Fig 8A–C. Graphic representation of tendon transfers in the forearm from the point of view of architectural features. Each muscle is plotted as shown in Figure 7 in terms of its fiber length and physiologic cross-sectional area. Circled muscles represent potential donors for the muscle indicated. Numbers represent difference indices as calculated previously.[7] In some cases the difference index is small even though the distance on this graph is relatively large. This is because the difference index represents the combination of five variables whereas the graph presents only two of these variables. (A) The architectural representation of the tendon transfers proposed to restore digital extension is shown. (B) The architectural representation of the tendon transfers proposed to restore thumb extension is shown. (C) The architectural representation of the tendon transfers proposed to restore thumb flexion is shown. BR = brevis; ECRB = extensor carpi radialis brevis; ECRL = extensor carpi radialis longus; ECU = extensor carpi ulnaris; EDC = extensor digitorum communis; EDQ = extensor digiti quinti; EPL = extensor pollicis longus; FCR = flexor carpi radialis; FCU = flexor carpi ulnaris; FDS (R), FDS (M) = flexor digitorum superficialis to the ring and middle fingers, respectively; PL = pollicis longus; PT = pronator teres. (Figure adapted from data presented in Lieber RL, Fazeli BM, Botte MJ: Architecture of selected wrist flexor and extensor muscles. J Hand Surg 15A:244–250, 1990.)

flexor digitorum superficialis to the middle finger, and the flexor digitorum superficialis to the ring finger. From the standpoint of architecture alone, the flexor digitorum superficialis (middle) most closely resembles the extensor digitorum communis in terms of force generation (cross-sectional area) and excursion (fiber length). This is emphasized by its relatively close position in architectural space of the flexor digitorum superficialis (middle) to the extensor digitorum communis (Fig 8A). If one were to compare individual architectural properties, it is clear that the flexor digitorum superficialis (middle) has more than enough excursion compared with the extensor digitorum communis whereas the flexor carpi ulnaris has sufficient force-generating potential. If the concern were sufficient force, the flexor carpi ulnaris might be chosen whereas if the concern were excursion, the flexor digitorum superficialis (middle) might be chosen. Either way, a knowledge of muscle architecture permits an informed decision to be made. Architectural mismatch between the flexor digitorum superficialis and extensor digitorum communis has been attributed to the poor clinical result of this transfer.[11]

Surgical Restoration of Thumb Extension

To restore thumb extensor function in high radial nerve palsy, potential donors include the flexor digitorum superficialis to the middle finger, the flexor digitorum superficialis to the small finger, and the palmaris longus. Again, in terms of architecture, the flexor digitorum superficialis to the small finger and the palmaris longus are more similar to the extensor pollicis longus, and therefore should provide the force generation and excursion required to restore lost function (Fig 8B).

Surgical Restoration of Thumb Flexion

As a final example, after high median nerve palsy, anterior interosseus nerve injury, or isolated, irreparable flexor pollicis longus muscle injury, multiple potential donors for transfer to restore thumb flexion are available. These donors include the brachioradialis, the extensor carpi radialis longus, the extensor carpi radialis brevis, the extensor carpi ulnaris, the extensor digiti quinti or the flexor digitorum superficialis to the ring finger. From an architectural standpoint, the extensor carpi radialis brevis, the flexor digitorum superficialis to the ring finger, and extensor carpi ulnaris are most similar to the flexor pollicis longus (Fig 8C). A simple quantitative method for comparing architectural properties between muscles has been reported.[7]

Muscle architecture represents the most functionally important muscle anatomic feature. Studies such as those presented here should provide surgeons with the information necessary to make rational decisions regarding donor muscles for tendon transfer and for those interested in human movement, should provide insights into the design of the upper extremity muscles in humans.

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