

Fiber Length Variability Within the Flexor Carpi Ulnaris and Flexor Carpi Radialis Muscles: Implications for Surgical Tendon Transfer

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Purpose: The purpose of this study was to understand the detailed architectural properties of the human flexor carpi radialis (FCR) and flexor carpi ulnaris (FCU) muscles and their implications for tendon transfer surgery.

Methods: Muscle fiber length was measured in 6 separate regions of the FCU and FCR from 10 cadaveric specimens. Sarcomere length was measured by laser diffraction for normalization. Moment arms were estimated by measuring tendon excursion with respect to joint angle. The position of entry of the motor nerve branches into each muscle also was measured to establish limits for the safe length of muscle mobilization.

Results: Muscle fiber length varied significantly along both the FCU and FCR. Fiber length variability in the FCU was twice that of the FCR. Although the average fiber length for both muscles across all regions was similar (62.6 ± 2.1 mm for the FCR and 63.1 ± 4.0 mm for the FCU), the proximal fibers of the FCU were longer compared with the proximal fibers of the FCR and the distal fibers of the FCU were shorter compared with the distal fibers of the FCR. The 99% confidence interval for the second nerve branch entry into the muscles was located ~ 69 mm distal to the medial epicondyle for the FCU and approximately 73 mm distal for the FCR.

Conclusions: These data show different designs of both the FCU and the FCR. The functional significance of fiber length variability is not clear but imply that, when used in tendon transfer, the properly mobilized FCU has a much greater excursion. (*J Hand Surg* 2004;29A:909–914. Copyright © 2004 by the American Society for Surgery of the Hand.)

Key words: Hand surgery, muscle, muscle architecture, tendon transfer.

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Received for publication December 10, 2003; accepted in revised form April 20, 2004.

Supported by the Department of Veteran's Affairs, Rehabilitation Research and Development, National Institutes of Health grant AR40539, The Swedish Research Council grant 11200, and Göteborg University. Travel supported by the International Society for Biomechanics and National Institutes of Health grant T32-AR07592 (R.M.L.).

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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0363-5023/04/29A05-0020\$30.00/0

doi:10.1016/j.jhsa.2004.04.028

Skeletal muscle architecture profoundly influences function.¹ Previous measurements of upper-extremity architecture showed a wide range of muscle designs across the arm and forearm.²⁻⁴ Based on this understanding specific recommendations have been made regarding the use of donor muscles that are appropriate to restore lost function.⁵ Because the experimental method of determining architecture relies on the relatively tedious method of microdissecting individual fibers or fiber bundles from fixed tissue, most architectural studies base their conclusions on just a few samples across the entire muscle.^{6,7} If fiber dimensions are consistent along and across a muscle this probably is acceptable. There are, however, reasons to be concerned about this practice: first, muscles with relatively broad origins, such as the pectoralis major and even the teres minor, have tremendous fiber length variation, presumably owing to the multifunctional nature of these muscles.⁸ Even in the forearm, the brachioradialis muscle, with its broad humeral origin, shows fiber length variation ranging from 100 mm to 180 mm,⁹ although the average fiber length was reported as 121 mm³. Fiber length heterogeneity has considerable implications not only for understanding muscle function but also for choosing which muscles should be selected for transfer.

Major donor muscles include the flexor carpi ulnaris (FCU) and the flexor carpi radialis (FCR).^{10,11} These synergistic muscles are reported to have complementary architectural designs, with the FCR having a higher excursion and lower force potential compared with the FCU with its lower excursion and higher force potential.^{2,4} Because both the FCU and FCR originate at the medial epicondyle and act on the wrist in 2 planes (flexion-extension and radial-ulnar deviation), one might suspect that their architectural properties would be more complex than previously appreciated. On the other hand because these muscles do not have a broad origin their architecture may be simplified compared with muscles with fan-like origins such as the brachioradialis, pectoralis major, and teres minor. Unfortunately, detailed architectural analysis of human upper extremity muscles, with the exception of the brachioradialis⁹ has never been performed; thus it is currently impossible to address this issue of fiber length variability for most upper extremity muscles.

In light of the importance of the FCU and FCR as donor muscles and the lack of information regarding fiber length heterogeneity, the purpose of this study

was to measure the detailed architectural properties of the FCU and FCR.

Materials and Methods

Ten fresh cadaveric specimens ($n = 10$ for each of the FCR and FCU) were used for this study and muscle architecture was determined as described previously.^{4,9} At the time of dissection the wrist and elbow flexion moment arms of the FCR and FCU were estimated by measuring the excursion of the respective tendon while the appropriate joint was rotated through an arc of 1 to 2 radians.¹² Joint angle was measured with a goniometer and tendon excursion was measured with a ruler. By using this method the tendon excursion corresponding to 1 radian joint rotation is equal to the moment arm.¹² Muscles then were harvested, weighed, and immersion-fixed in 10% buffered formaldehyde for 72 hours in a flattened position corresponding to the supinated forearm and extended elbow. After fixation the muscles were rinsed in phosphate-buffered saline and stored in fresh phosphate-buffered saline at 4° C until needed. Muscle length (L_m) was measured as the origin of the most proximal fibers to the insertion of the most distal fibers. Surface muscle fiber pennation angle was measured with a goniometer. Although fiber pennation typically is measured for superficial fibers, many of the fiber bundles originated superficially but inserted into deep tendon aponeurosis. Such fibers were excluded from this analysis.

Muscle fiber bundles were isolated under a dissection microscope ($\times 10$ to $\times 20$) and fiber bundle length (L_f) was measured using digital calipers to the nearest hundredth of a millimeter. To define fiber length heterogeneity the muscles were divided arbitrarily into 6 equal regions from proximal to distal. Fiber bundles were dissected from each of the 3 proximal regions (denoted P1, P2, P3) and from each of the 3 distal regions (denoted D1, D2, D3). The muscular origins of these 2 muscles are at similar anatomic levels so regions P1, P2, and P3 were located at about the same anatomic level. In contrast, because the FCU musculature extends more distally, regions D1, D2, and D3 extended approximately 2 cm more distally for the FCU compared with the FCR. Approximately 9 separate fiber bundles were isolated from each region. Fiber length coefficient of variation within a region ranged from 5% to 12%. Sarcomere length (L_s) was measured in 3 locations along each bundle by laser diffraction using the 0 to first order diffraction angle and also the 0 to second order when possible.¹³ This method has been used

previously to measure sarcomere length in fixed upper-extremity specimens and relies on the constructive interference that occurs between incident laser light and skeletal muscle sarcomeres.^{3,4} To provide guidelines regarding safe limits for muscle mobilization the motor nerves were traced as distally as possible under the dissecting microscope to determine the point at which they entered the muscle (denoted L_n). This was expressed as the distance from the muscle origin for the 1 or 2 nerve branches observed.

In addition to the measured data the following parameters were calculated: the L_f/L_m ratio and the physiologic cross-sectional area according to the following equation⁶:

Physiologic cross-sectional area (mm^2)

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

where M represents muscle mass, ρ represents muscle density ($1.056 \text{ g}/\text{mm}^3$), θ represents fiber pennation angle, and L_f represents fiber length. Muscle length and fiber bundle length were normalized to a standard ($L_s = 2.7 \mu\text{m}$) to compensate for variation among specimens in muscle length during fixation with joints in different configurations. The actual sarcomere length value chosen for normalization is not critical in making comparisons between muscles. We chose $2.7 \mu\text{m}$ because this is the sarcomere length in human muscle that results in maximum force generation.¹⁴

Data Analysis

Fiber length was analyzed by 2-way analysis of variance (ANOVA) with repeated measures using muscle and region as grouping factors. The significance level was set to $\alpha = .05$ and statistical power was not calculated because all differences were statistically significant and thus no potential for type II error existed.¹⁵ Statistical power is only an important consideration when the null hypothesis is accepted, that is, when a study concludes no significant difference existed. Because we observed significant effects the sample size and thus the statistical power of the study was adequate. Coefficient of variation was used to quantify fiber length variability for each specimen and was calculated as:

$$\text{Coefficient of variation} = (s/\bar{X}) \cdot 100\%$$

where \bar{X} is the sample mean and s is the sample SD. To define the safe limits for surgical muscle release

Table 1. Descriptive Properties of Wrist Flexor Muscles

Parameter	FCR	FCU
Forearm length (mm)	262.7 ± 7.3	262.7 ± 7.3
Muscle length (L_m , mm)	158.5 ± 10.0	236.5 ± 5.4
Muscle mass (M , g)	20.2 ± 2.5	25.9 ± 2.4
Tendon length (L_t , mm)		
External	149.6 ± 6.3	147.5 ± 10.1
Internal	101.7 ± 4.9	88.0 ± 8.1
Moment arm (mm)		
Elbow	3.0 ± 0.4	0.0 ± 0.0
Wrist	12.4 ± 0.6	10.6 ± 0.6
Motor branch entry point (L_n)*		
First	46.6 ± 4.4	29.7 ± 1.9
Second	56.8 ± 3.8	50.4 ± 4.1

Values are presented as mean ± SEM, $n = 10$.

*Measured as the distance from muscle origin near the medial epicondyle to the point where the nerve branch enters the muscle belly.

the 99% confidence intervals were calculated for the nerve branches of both the FCU and FCR.¹⁶

Results

Because both the FCU and FCR were harvested from the same specimens, any differences measured between muscles were not caused by interspecimen size variation but were true differences between the muscles (Table 1). Much more fiber length variation was observed for the FCU compared with the FCR. Specifically the coefficient of variation for the FCU was more than twice that of the FCR ($p < .001$; Fig. 1). For both muscles studied a notable fiber length variation was observed along the entire muscle length, with fibers in the distal regions being markedly shorter compared with fibers in the proximal regions (Fig. 2). Two-way ANOVA revealed no significant main effect of muscle ($p > .9$), but a highly significant muscle × region interaction ($p < 0.0001$). In other words although average fiber length for both muscles across all regions was similar (reflected by the main effect of the ANOVA being insignificant: $62.6 \pm 2.1 \text{ mm}$ for the FCR and $63.1 \pm 4.0 \text{ mm}$ for the FCU) the proximal fibers of the FCU were longer compared with the proximal fibers of the FCR and the distal fibers of the FCU were shorter compared with the distal fibers of the FCR (Fig. 2). Because the fiber length variation of the 2 muscles was opposite from proximal to distal, this yielded the highly significant interaction term mentioned ($p < .001$).

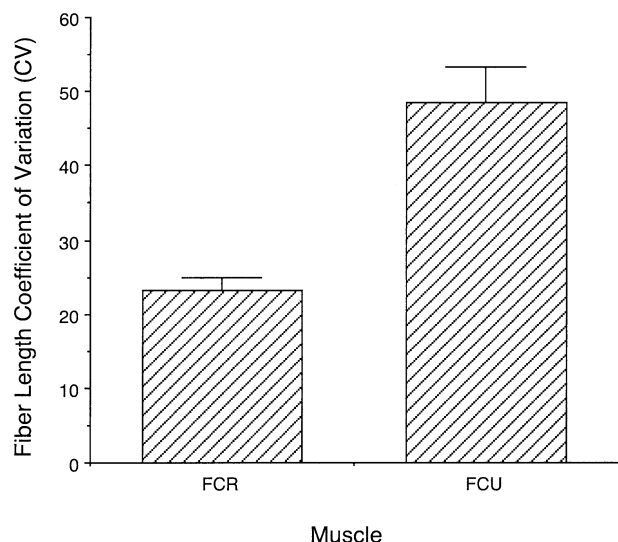


Figure 1. Fiber length variability observed in the FCU and FCR as expressed by coefficient of variation (see Materials and Methods section). Note that the FCU fiber length variability is more than twice that of the FCR.

Two main nerve branches were observed for all of the FCUs and 7 of 10 of the FCRs (Fig. 3). The proximal nerve branch entered the muscle significantly closer to the medial epicondyle for the FCU (29.7 ± 1.9 mm) compared with the FCR (44.0 ± 4.1 mm, $p < .005$). For the 7 paired specimens in which the second branch always was observed, they entered the muscle at nearly the same location (FCU at 50.9 ± 4.8 mm compared with FCR at 56.3 ± 4.3 mm, $p > .4$). The 99% confidence interval for the second nerve branch was located approximately 69-mm distal to the medial epicondyle for the FCU and approximately 73-mm distal for the FCR. Based on the number of regions within each muscle and the overall muscle length (Table 1) both nerve branches in both muscles would enter the muscle belly proximally in regions P1 and P2.

There was no elbow flexion moment arm for the FCU (0 ± 0 mm; Table 1) whereas the FCR moment arm was 3.0 ± 0.36 mm, showing that the sole action of the FCU was at the wrist and even the FCR had a very small influence on elbow joint function. (The zero FCU elbow moment arm calls into question the practice of immobilizing the elbow after surgery involving the FCU.) The wrist flexion moment arms of the 2 muscles were similar at 11 to 12 mm (Table 1).

Discussion

The purpose of this study was to quantify the detailed architectural properties of 2 synergistic wrist flexors: the FCR and the FCU. Although the FCU showed greater fiber length variability compared with the

FCR (Fig. 1), both muscles showed significant fiber length variability from proximal to distal, with the proximal fibers being significantly longer than the distal fibers (Fig. 2). Although the average fiber length of the FCU and FCR was the same the distribution of fiber lengths along the muscles was significantly different. Specifically, the proximal FCU fibers were longer than the proximal FCR fibers, but the distal FCU fibers were shorter than the distal FCR fibers. Because the general consensus seems to be that the FCU has shorter fibers than the FCR,^{2,4,17} apparently most investigators preferentially sampled the distal musculature. This is likely owing to the fact that the proximal flexor mass is very difficult to separate into discrete muscles and thus the proximal musculature is studied less often.

The reason that fiber length distribution is so important for hand surgeons to take into account is that fiber length is the primary determinant of skeletal muscle excursion.^{2,18} Taken at face value the longer fibers of the proximal FCU and FCR would be predicted to have a greater excursion compared with the distal fibers. The rules that govern the intramuscular interactions among fiber populations, however, are unknown at this time. With regard to whole-muscle function it is not clear whether skeletal muscle fibers in various regions of the same muscle act completely in parallel, completely in series, or some combination of the two. If muscle fibers were acting completely in parallel then the proximal portion of the muscle would have a greater excursion than the distal portion of the muscle and this would result in various portions of the muscle "fighting" against one another. The shorter fibers even might restrict the range of the

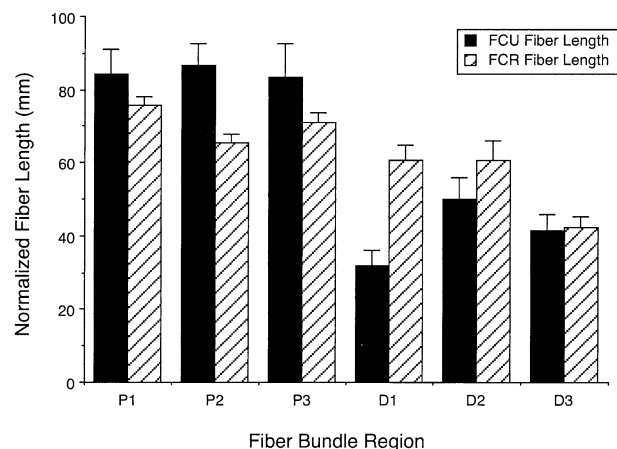


Figure 2. Fiber length distribution in the FCU (■) and FCR (▨) muscles along their length. Each region represents one sixth of the muscle from the proximal origin (regions P1, P2, P3) to the distal insertion (regions D1, D2, D3).

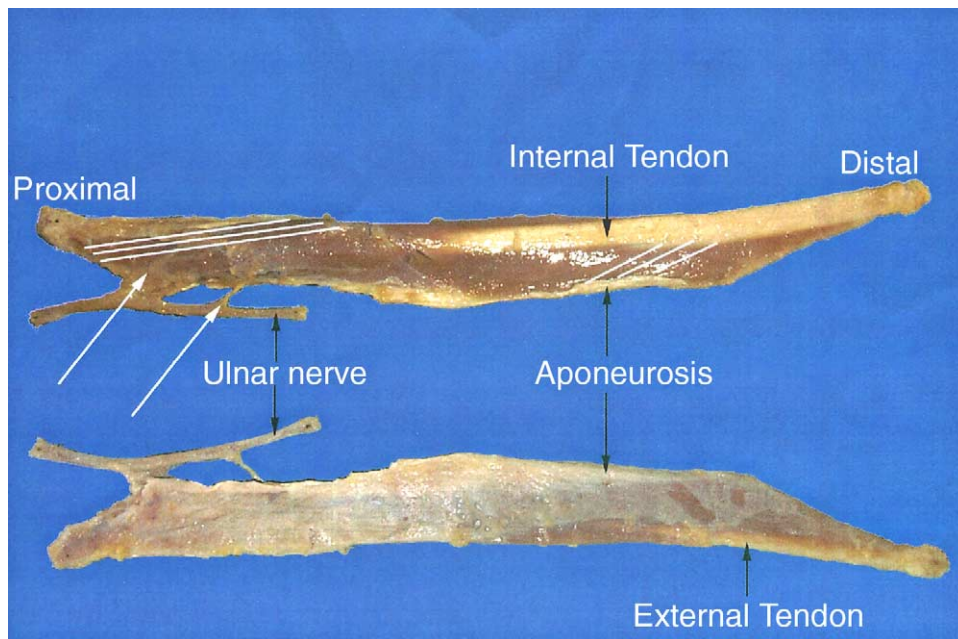


Figure 3. Representative view of a dissected FCU muscle showing fiber length heterogeneity, tendon plates, and motor nerve branching pattern. Upper figure is a deep view, the lower figure is a superficial view. Fibers in the P1 (left) and D3 (right) regions are shown with solid white lines. Arrows represent points at which the nerve branches from the ulnar nerve.

longer fibers. This is not an advantageous design but might be compensated for based on differential activation of different portions of the muscle. Should the different portions of the muscle be acting in series then the excursion of the distal portion simply would summate with the proximal portion and the overall muscle excursion would be greater than either portion alone. It only is possible to distinguish between series or parallel interactions by directly measuring the *in vivo* length-tension properties of the muscles themselves. This concept has important surgical implications. To exploit the longer proximal fibers of either muscle an extensive release of the donor muscle must be performed. Because the distal nerve branch is within approximately 75 mm of the medial epicondyle there is little risk for nerve injury with such a thorough muscle isolation.

These data suggest that the FCU and FCR actually have the same excursion potential because their average fiber length is about the same. Given that both muscles are available the choice of which muscle to use as a donor then would be based on the muscle force required and the route of transfer. With its higher mass (Table 1) the FCU will generate a higher force because average fiber length is the same. Because the FCU is tethered more tightly to the ulna and surrounding fascia the functional muscle isolation is more difficult. Additionally many surgeons prefer to use the FCU as a donor in part to remove the

deforming force of ulnar deviation as well as to restore function.

A previous study of the brachioradialis muscle revealed almost 100% variation in fiber length in different portions of the muscle.⁹ This of course was not totally unexpected because the brachioradialis has a broad humeral origin that traverses an L shape with a 90° twist before inserting into the distal radius. Therefore it functions in both elbow flexion and wrist rotation. Both the FCU and FCR, however, originate from the medial epicondyle and traverse a relatively straight path. In addition we have shown that the FCU has no elbow moment arm because its origin lies directly on the axis of elbow rotation and the FCR moment arm is limited (Table 1). Because both muscles' lines of action are straight the basis for fiber length variation within these muscles is not clear. It could be that the fiber length variation really does represent functional heterogeneity within the muscle based on unique neural activation patterns or it could be that the fiber length variation simply represents a constraint of the volume available as the muscle extends from proximal to distal. Future experiments are required to refine the subtle variation in fiber length that occurs between synergistic muscles.

Finally it was reported recently that the FCU had 2 heads.¹⁹ We were unable to confirm this observation in the 10 specimens, attempting to divide the FCU either proximally/distally or medially/laterally. It is

possible that the previous investigators reported an anomaly that would not be apparent given our limited sample size. If the FCU were innervated dually and 2-headed then it certainly would provide new opportunities regarding the choice of donor muscles for surgical reconstruction.

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