# Pronator Teres Is an Appropriate Donor Muscle for Restoration of Wrist and Thumb Extension

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**Objective:** To compare the detailed architectural properties of the pronator teres (PT), extensor carpi radialis brevis (ECRB), and extensor pollicis longus (EPL) muscles to evaluate the suitability of PT-to-ECRB and PT-to-EPL surgical procedures.

**Methods:** Muscle physiologic cross-sectional areas and region-specific muscle fiber lengths were measured in cadaveric PT, ECRB, and EPL muscles (n = 10 muscles of each type). One-way repeated-analyses of variance measures and *post hoc t* tests with Bonferroni corrections were used for statistical comparisons.

**Results:** The ulnar head of the PT was present in 8 of 10 specimens. The average PT fiber length was similar to that of the ECRB (7.02 ± 0.49 cm vs 6.17 ± 0.27 cm) but was significantly longer than that of the EPL (5.44 ± 0.25 mm). Fiber length in the humeral head of the PT was longer compared with the ulnar head (7.19 ± 0.52 cm vs 4.14 ± 0.25 cm). The average physiologic cross-sectional area of the PT was similar to that of the ECRB (3.5 ± 0.4 $cm^2$ vs 3.3 ± 0.3 $cm^2$) but was significantly larger than that of the EPL (3.5 ± 0.4 $cm^2$ vs 1.1 ± 0.1 $cm^2$).

**Conclusions:** From an architectural point of view the PT is an excellent donor choice for transfer to the ECRB for restoration of wrist extension or to the EPL for restoration of thumb extension. Because there is fiber length heterogeneity within the PT, however, when the ulnar head is present it may limit the total excursion of the donor muscle. These data suggest that releasing the ulnar head of the PT before transfer may result in larger excursions of this important motor in tendon transfer surgery. (J Hand Surg 2005;30A:1068–1073. Copyright © 2005 by the American Society for Surgery of the Hand.)

**Key words:** Muscle architecture, tendon transfer surgery, pronator teres, extensor carpi radialis brevis, extensor pollicis longus, biomechanics.

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Comprehensive knowledge of upper-extremity muscle architecture (ie, the number and orientation of fibers within a muscle) is critical for the planning and execution of successful surgical interventions.[1] This is because muscle architecture is an excellent predictor of muscle function[2] and thus provides surgeons with an understanding of a muscle's design and allows them to choose appropriate donor muscles for use in tendon transfer surgery.

The application of muscle architecture to surgical planning was first highlighted by Brand and colleagues,[3] who estimated the excursion and force-generating capacity of many muscles of the hand and forearm. These results appeared to explain previous degrees of success or failure in specific tendon transfer procedures. Subsequently more quantitative analyses were performed to define architectural differences among upper-extremity muscles.[4,5]

Because of the tedious nature of determining muscle architecture most previous studies have based their conclusions on only a few fibers sampled across the entire muscle.[3–6] If fiber dimensions are consistent across the entire muscle this is an acceptable methodology. Recent investigations, however, have shown that fiber length often is inconsistent across an entire muscle.[7,8] The proximal fibers of both the flexor carpi ulnaris and flexor carpi radialis were found to be longer compared with the distal fibers within the same muscle.[7] Fiber length heterogeneity within a muscle has important implications for a muscle's operating range. For example, a muscle with greater fiber length heterogeneity may have a more robust operating range but produce less relative force compared with a muscle with homogenous fiber lengths.

The pronator teres (PT) is used as a donor muscle in many tendon transfer surgeries. In particular the PT often is transferred to the extensor carpi radialis brevis (ECRB) to restore wrist extension in patients with tetraplegia or radial nerve palsy.[9,10] Additionally, PT-to–extensor pollicis longus (EPL) also has been used to restore thumb extension in patients with similar injuries (Fridén, unpublished observations, July 2005). The architecture of the PT, however, has not been studied in detail so it is not possible to determine definitively the suitability of this muscle as a donor to replace either the ECRB or EPL. Therefore, we compared the key architectural features of these muscles to provide a recommendation on the use of the PT as a donor muscle in tendon transfer surgery.

## Materials and Methods

### Skeletal Muscle Architecture

Fresh-frozen upper-extremity specimens from 6 male and 4 female cadavers with an average age of 79 ± 3.2 years were used. Arms were skinned and deep fascia overlying the muscles was excised. They then were fixed in 10% formalin for 48 to 72 hours in a position of full elbow extension and forearm supination. After fixation arms were rinsed 3 times in 0.2 mol/L phosphate-buffered saline (PBS) for approximately 24 hours for each rinse and the PT, ECRB, and EPL were removed. The ECRB and EPL were isolated easily from their adjacent muscles. In contrast it was necessary to release the PT from the bone after separation from the median nerve proximal–laterally and the flexor carpi radialis distal–medially. Given that accurate determination of architectural parameters requires sharp dissection of muscles from adjacent tissues it is important to understand that *in situ* fascial connections that impose excursion limitations to a muscle would not be captured by these data. In cases in which strong fascial connections were observed, however, qualitative descriptions of these connections were documented.

Muscle architecture was determined according to methods developed previously[11] and implemented in the upper extremity.[5,6] Briefly, muscle mass was recorded immediately after excision. Muscle length (ML) then was measured as the distance from the origin of the most proximal muscle fibers to the insertion of the most distal fibers. Surface pennation angles then were measured at 4 predetermined regions of each muscle using a goniometer. Muscle fascicles (fiber bundles) were isolated from each of these regions (Fig. 1) and their lengths (FL) were measured with a digital caliper (accuracy, 0.01 mm). The aim of this method was to sample fibers randomly from the entire PT, ECRB, and EPL to reflect accurately the true architectural properties of these muscles and identify region-specific architectural differences (if any). Regions 1 and 2 of the PT (Fig. 1A) were located on the humeral head ($PT_H$) and regions 3 and 4 of the PT (when present) were located on the ulnar head ($PT_U$). The 4 regions sampled for the ECRB and EPL are illustrated in Figures 1B and C.

Isolated fascicles then were immersed in 15% $H_2SO_4$ for 30 minutes to digest some of the connective tissue before being returned to PBS for storage. Smaller muscle fiber bundles (consisting of 5–20 muscle fibers) were separated from the harvested fascicles under a dissection microscope (8 × – 20 ×

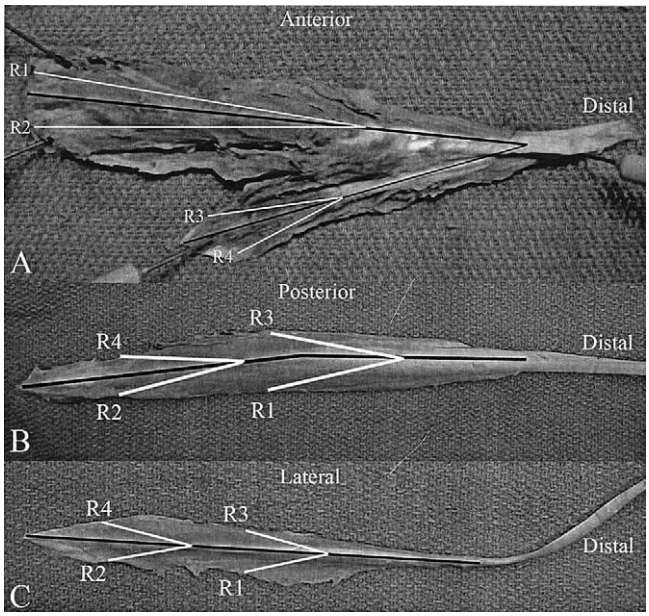


**Figure 1.** (A) Oblique view of the medial surface of left PT, (B) lateral view of a left ECRB, and (C) anterior view of EPL. Location of fiber sampling regions (R1–R4) for each muscle. Regions 1 and 2 of PT (A) were located on the $PT_H$ and regions 3 and 4 of the PT (when present) were located on the $PT_U$.

magnification). Separated fiber bundles were mounted on slides with Permount (Fischer Scientific, San Diego, CA) and allowed to dry for 24 to 48 hours. Sarcomere length ($L_s$) then was determined using laser diffraction (zero to first order) according to previously developed methods.[5] Measurement of $L_s$ allowed fiber length to be normalized to an optimal standard length of 2.7 $\mu$m to compensate for variations in specimen joint angles during fixation.[5]

In addition to the above measurements the FL/ML ratio and physiologic cross-sectional area (PCSA) were calculated according to the following equation[12]:

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

where $\rho$ represents muscle density (1.112 g/cm$^3$)[13], M represents muscle length, $L_f$ represents fiber length, and $\theta$ represents surface pennation angle. The FL/ML ratio is an index of the excursion design. For example, if muscles contain fibers that span the entire length of the muscle (FL/ML ratio = 1.0) they are designed more specifically for excursion than muscles that have fiber spanning half of the muscle's length (FL/ML ratio = 0.5). This ratio is a useful parameter to consider because it is independent of the absolute magnitude of muscle fiber length. The PCSA is, of course, related to the maximum force-producing capacity of a muscle.

### Data Analysis

Initially, whole-muscle comparisons between the PT, ECRB, and EPL were made with 1-way repeated-measures analyses of variance (ANOVAs) after confirmation that the assumptions of normality and homogeneity of variances were met. *Post hoc t* tests with Bonferroni corrections were used to distinguish between muscle differences when main effects were identified. Given that the PT has 2 distinct heads whole muscle values for mass, muscle length, and PCSA represent sums whereas pennation angles represent averages. Fiber lengths, however, are averages weighted by the PCSA. These within- muscle, between-head comparisons were performed using paired *t* tests on the 6 specimens that contained ulnar head muscle fibers.

After the initial whole-muscle comparisons separate within-muscle comparisons were performed using 1-way repeated-measures ANOVAs and *post hoc t* tests to identify regional fiber length differences. All values are reported as mean ± standard error unless otherwise noted. Statistical tests were performed with statistical software (SPSS version 11.5; SPSS Inc., Chicago II) with p values set at .05 except for *post hoc* tests, for which the experiment-wise p value of .05 was adjusted according to the Bonferroni correction.

## Results

Specimen age and skeletal dimensions enable comparison of the current study with existing and future architectural data and therefore are presented in Table 1. Although the larger $PT_H$ always was present

**Table 1. Specimen Demographics (Pronator Teres)**

| Characteristic | Value |
|---|---|
| Age (y) | 79 ± 3 |
| Male/female ratio | 6/4 |
| Humeral epicondylar width (mm) | 62.7 ± 7.3 |
| Ulnar length (mm) | 251.6 ± 16.7 |
| Radial length (mm) | 234.1 ± 14.2 |
| Pronator insertion length (mm) | 33.4 ± 10.1 |
| Motor branch (mm from medial epicondyle) | 54.1 ± 10.1 |

Values provided are mean ± SD of n = 10 independent specimens unless otherwise noted.

**Table 2. Muscle Architectural Properties**

| Muscle | Mass (g) | Muscle Length (cm) | $L_f$ (cm) | Pennation Angle (°) | PCSA ($cm^2$) | $L_f/L_m$ Ratio§ |
|---|---|---|---|---|---|---|
| PT | 25.2 ± 3.7 | 15.96 ± 0.46 | 7.02 ± 0.49 | 9 ± 2 | 3.5 ± 0.4 | 0.44 ± 0.03 |
| $PT_H$ | 23.1 ± 3.1* | 15.96 ± 0.46* | 7.19 ± 0.52* | 10 ± 2 | 3.3 ± 0.3* | 0.45 ± 0.03* |
| $PT_U$ | 2.7 ± 0.8 | 6.33 ± 0.54 | 4.14 ± 0.25 | 8 ± 4 | 0.4 ± 0.1 | 0.95 ± 0.08 |
| ECRB | 23.1 ± 2.5 | 15.85 ± 0.42 | 6.17 ± 0.27 | 8 ± 1 | 3.3 ± 0.3 | 0.39 ± 0.02 |
| EPL | 6.8 ± 0.7†‡ | 14.72 ± 0.38†‡ | 5.44 ± 0.25†‡ | 7 ± 1 | 1.1 ± 0.1†‡ | 0.37 ± 0.02† |

Values provided are mean ± standard error of 10 independent specimens, except for $PT_U$, for which only 6 specimens were obtained (see Results).
*Significant difference between $PT_H$ and $PT_U$.
†Significantly different from PT.
‡Significantly different from ECRB.
§Fiber length : muscle length ratio.

the $PT_U$ was present in only 8 out of 10 specimens. In 2 of these 8, there were no muscle fibers associated with the humeral head but rather only a small tendon extending from the coronoid process of the ulna into the humeral head tendon. Thus, the sample size from which $PT_U$ fiber data were obtained is n = 6 despite the fact that 8 ulnar heads were identified (Table 2). Diffraction patterns were obtained on all fiber specimens to enable calculation of $L_s$ and therefore computation of normalized fiber length, $L_f$.

Gross architectural features (mass and muscle length) of the PT and ECRB were significantly larger than those of the EPL (Table 2). Specific architectural features (ie, fiber length, PCSA) also were significantly greater in the PT and ECRB than in the EPL but significant FL/ML differences were found only between the PT and EPL.

The fact that the PT architectural features tended to be greater than those of the other muscles was driven by the much larger humeral head (Table 2); $PT_U$ when present was significantly smaller in terms of mass, muscle length, fiber length, and PCSA. This held true for regional fiber length differences as well. The PT had clear differences in fiber length between regions 1 and 2 ($PT_H$) and regions 3 and 4 ($PT_U$) (Fig. 2). Although regions 2 and 3 of the ECRB were significantly different from each other they did not represent anatomically distinct muscle compartments as was true for the PT.

## Discussion

These data show that based on architecture the PT represents an excellent donor to substitute the lost function of the ECRB in tendon transfer. It is reasonable that to substitute for lost muscle function, one would choose a donor muscle with similar architectural characteristics.[6] In comparing the PT with the ECRB it is seen that fiber lengths and PCSAs in the 2 muscles are nearly identical (Fig. 3), suggesting that their force-generating capacity and excursion probably are nearly identical also. This also may help to explain why this transfer has been described in the literature in such positive terms.[10,14]

With regard to the PT-to-EPL transfer, PT muscles had significantly larger PCSAs and longer fiber lengths compared with EPL muscles (Fig. 3). These differences, however, actually would provide enhanced force production and excursion compared with the lost EPL. Although this transfer would be appropriate from an architectural standpoint other donors for the EPL also have been described.[3,15–18] From an architectural perspective the palmaris longus is more similar to the EPL.[6] This does not, however, preclude the use of the PT as a donor for the EPL should other donor muscles be unavailable.

The average fiber lengths reported here for the ECRB and EPL agree with those of previous inves-

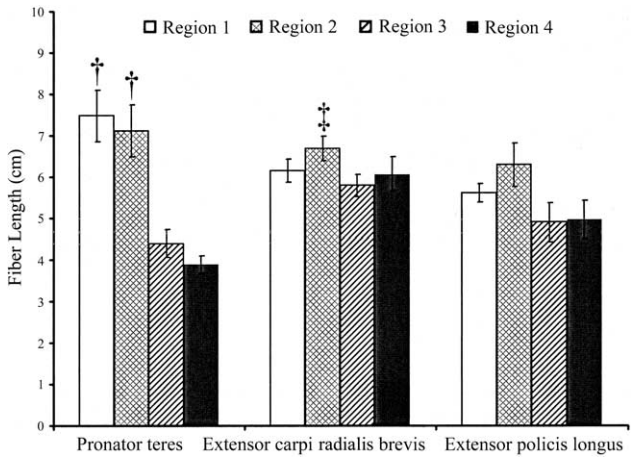


**Figure 2.** Regional fiber length differences in the PT, ECRB, and EPL. † indicates significant differences between regions 1 and 2 ($PT_H$) and regions 3 and 4 ($PT_U$). ‡ indicates significant differences between regions 2 and 3 in the ECRB.

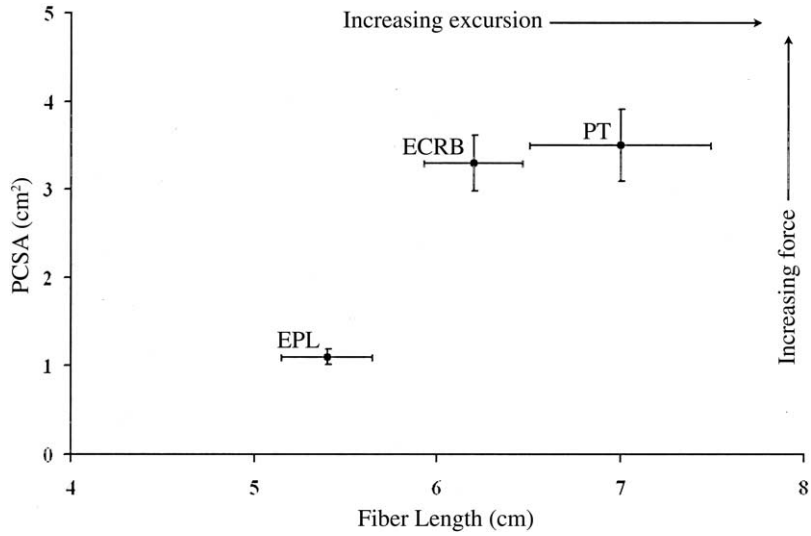


**Figure 3.** Scatterplot of muscle fiber length versus PCSA in the PT, ECRB, and EPL muscles. The location of a muscle on the plot represents its excursion and force-generating capacities relative to other muscles.

tigations.[3,6] Data for PT fiber lengths are not comparable directly to other studies because the PT exhibited significant heterogeneity in fiber length between its 2 heads. When we examine the PCSA-weighted average fiber length for the PT, however, our results do not agree with previously published data,[6] which measured an average PT fiber length of 4.40 ± 0.16 cm (vs 7.02 ± 0.49 cm for the PT total in the current study). If we calculate a nonweighted average for all zones of the PT our findings are more in agreement with—but still substantially differ from—previously published data[6] (5.80 ± 1.39 cm vs 4.40 ± 0.16 cm). Although the previous study did not describe the anatomic locations of fiber length measurements we collected data from 4 locations representing all areas of the muscle. This methodology allowed accurate characterization of the muscle's architecture and would be considered the most reliable estimate to date. We suggest that all future architectural studies use a methodology in which the anatomic location of isolated fibers is identified precisely. This will facilitate more rationale comparisons among studies and, hopefully, convergence of opinion.

The average PCSAs reported here (Fig. 2, Table 2) agree with previous data.[6] Our data also agree with previous findings of natural variations in the presence of the $PT_U$.[19] The prior study[19] reported that the $PT_U$ was present in 47 out of 60 cases (78%) and was found to be either muscular or tendinous. This corresponds to our finding of the $PT_U$ being present 80% of the time and also the characterization that the $PT_U$ could be composed of either muscle or tendon only.

A second objective of this study was to determine whether these muscles have significant fiber length heterogeneity. Although significant regional fiber length differences were observed in both the PT and ECRB, the PT is perhaps most interesting. In the PT these regional differences corresponded to separate muscular heads, providing the intriguing possibility of head-specific function. In the ECRB regional differences did not correspond to anatomic subsections of the muscle and were much smaller than the differences observed in the PT (9% vs 49%). In fact fiber length variation (9%) was smaller than in the EPL (12%) and likely reached statistical significance only because of very low within-region variability.

The presence or absence of the $PT_U$ may be important in determining the operating range of the donor/recipient muscle tendon unit. As reported the $PT_U$ has shorter muscle fibers compared with either the ECRB or EPL. Additionally the $PT_U$ often had thick fascial connections that spanned the entire muscle length. In these cases fiber length, our index of excursion, may overestimate the available operating range of the muscle because fascia ultimately could restrict muscle excursion. Because the rules that govern intramuscular interactions among fiber populations have yet to be elucidated it is not clear whether fibers in various regions of a given muscle act in parallel, in series, or in a combination of the two. Should the various regions be acting in series excursion limitations would arise because of the short nature of $PT_U$ fibers. From the hand surgeon's point of view it is reasonable to release or excise the $PT_U$ before transfer. We base this recommendation on the fact that the $PT_U$ is likely to restrict

excursion after transfer and provides only a small (~10%) portion of the total force produced by the PT (Table 2).

Previous investigations have concluded that fiber length heterogeneity does exist in other muscles of the forearm such as the flexor carpi radialis, flexor carpi ulnaris, and brachioradialis.[7,8] What is not clear, however, is whether these intramuscular variations in fiber lengths within donor muscles represent a challenge to achieving desired clinical outcomes after tendon transfer procedures. Future experiments should define the functional importance of such fiber length variations. It is possible that shorter fibers restrict the range of longer fibers or perhaps that various fiber populations function independently or even synergistically. Unfortunately, definitive primary data are not available to distinguish among these possibilities.

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