

Passive Muscle–Tendon Amplitude May Not Reflect Skeletal Muscle Functional Excursion

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Purpose: To quantify the gain in muscle mobility with progressive release of surrounding connective-tissue structures and to compare this property with the known architecture of each muscle.

Methods: Each of 5 different muscle tendon units (extensor carpi radialis brevis, extensor carpi radialis longus, flexor carpi ulnaris, flexor digitorum superficialis, pronator teres) was released from its insertion and secured into the jaws of a clamp attached to a servomotor that could be operated under length or force control to simulate the load placed on the tendon by a surgical assistant. A constant load of 5 N was applied to the tendon while the muscle–tendon unit was released surgically from the surrounding tissue in 1-cm increments. Mobility was plotted against release distance and analyzed by linear regression to yield mobility gain, the slope of the regression equation. One-way analysis of variance was used to compare mobility gain among muscles.

Results: In contrast to previous results from the brachioradialis muscle in which the mobility gain was large and highly nonlinear, mobility gain was small, consistent, and linear for all muscles studied. The smallest mobility gain was for the flexor digitorum superficialis and was highly linear. The largest gain was for the pronator teres and again was highly linear. In general, the mobility gain for the extensor carpi radialis brevis was similar to that of the extensor carpi radial longus. The flexor carpi ulnaris muscle was difficult to mobilize, and its gain was modest. There was no significant correlation between mobility gain of the forearm muscles during progressive release and the length of their fibers.

Conclusions: The small mobility and complete lack of correlation with fiber length provide strong evidence that mobility gain does not accurately reflect muscle excursion as it is typically described. This calls into question the general practice of tensioning muscles by first passively extending the muscle and then choosing the attachment length as a particular portion of that passive relationship. (J Hand Surg 2006;31A:1105–1110. Copyright © 2006 by the American Society for Surgery of the Hand.)

Type of study/level of evidence: Prospective basic science.

Key words: Tendon transfer surgery, tendon excursion, forearm biomechanics.



Tendon transfers are challenging surgical procedures that require integration of muscle–tendon anatomic properties and joint mechanics to restore upper-extremity function after injury. A necessary step in performing a tendon transfer is the mobilization of the donor muscle–tendon unit.^{1–3} This is required (1) to optimize the line of muscle

action so that the original line of action is approximated and (2) because it is believed that adequate mobilization improves donor muscle function. In some cases optimizing excursion for the transfer is relatively straightforward. For example, the extensor carpi radialis longus (ECRL) muscle requires almost no mobilization because division of the distal tendon

releases the muscle at least to the midbelly. At the other extreme is the brachioradialis (BR), which requires extensive mobilization and can actually be dysfunctional if not adequately mobilized.⁴

In addition to donor muscle mobilization during the transfer, knowledge of donor muscle architectural properties is considered important in planning the transfer.^{5,6} Both of these aspects of the transfer are intended to optimize a muscle's excursion. It is known that the excursion of a muscle depends on its fiber length, but there is often a disconnect between this anatomically derived parameter and general surgical experience. Again, the BR provides a good example in that its fibers are relatively long (~100 mm) but its excursion is not exploited unless it is released almost to its origin.⁷ Thus, the BR illustrates the importance of considering the intrinsic architectural properties of a muscle and the intimate relationships with the surrounding connective-tissue environment. Such interrelationships between muscles and surrounding connective tissues have been shown experimentally to be functionally important.^{8,9}

Although skeletal muscle architecture is established for all the muscles of the forearm^{5,10} and the general principles of tendon transfer are well established,¹¹ the specific release strategy needed for each of the common donor muscles used in tendon transfers is unknown. One might simply argue that all muscles should be completely released; however, extensive release is both time consuming and carries a risk to neurovascular structures. Therefore, releases should be performed only insofar as functional gain is achieved. The relationship between release distance and functional gain (mobility) often is nonlinear. For example, the BR has been shown to gain limited mobility for the first 9 cm of the release, with mobility increasing as the release proceeds proximally. For other common donor muscles (flexor carpi ulnaris [FCU], ECRL, extensor carpi radialis brevis [ECRB], pronator teres [PT], and flexor digitorum superficialis [FDS]), this effect is unknown. Both Z-lengthening of the tendon and aponeurotomy are commonly used in upper-extremity surgery to increase muscle-tendon unit mobility and can be used for comparative purposes. Therefore, the purpose of this study was to determine the relationship between the magnitude of muscle release and the magnitude of mobility gained for 5 common donor muscles and to compare mobility gain—in the case of the FCU, from mobility gain by Z-lengthening and aponeurotomy.

Materials and Methods

These biomechanical experiments were performed essentially as previously described in detail for the BR muscle.⁷ Our goal was to mimic the effect of an assistant holding a tendon as a surgeon progressively released a selected muscle from its surrounding tissue. Arms from cadavers that were amputated at the midhumeral level (N = 10) were thawed, secured to a board by Steinmann pins placed through the humerus proximal to the elbow and through the ulna proximal to the wrist (Table 1). Each of 5 different muscle insertions (ECRB, ECRL, FCU, FDS, PT) was released and secured by the jaws of a clamp attached to a servomotor that could be operated under length or force control (Model 310B; Aurora Scientific, Richmond Hill, Ontario, Canada). The testing order was randomized with the exception of the ECRL and ECRB. In this case, dissection proceeded from superficial to deep and distal to proximal. A constant load of 5 N was applied to the tendon while the muscle-tendon unit was released surgically from the surrounding tissue in 1-cm increments. The line of force measurement was aligned with the muscle's natural line of force generation by judiciously positioning the motor and by using a clamp with 2 degrees of freedom in the dorsal-volar and radial-ulnar planes, thus eliminating nontensile moments from being recorded. Muscle-tendon unit length was recorded to 0.04-mm resolution from the output of the servomotor that was used during each release. Servomotor output voltage was directly proportional to the muscle-tendon unit length (calibration factor = 3.9 mm/V, $r^2 = 0.96$). Because forearm length was variable among specimens (Table 1), releases of between 8 and 16 cm were permitted. The muscle-tendon unit length achieved after release was the value recorded 1 minute after each 1-cm release (allowing for creep). Muscle fiber lengths and BR release data previously published from our laboratory were integrated with data obtained in the current study because the methodology in both studies was identical.^{7,10}

Table 1. Subject Demographics

Characteristic	Value*
Age, y	80 ± 4
M:F ratio	3:7
R:L ratio	8:2
Ulnar length, mm	255 ± 7
Epicondylar width, mm	68 ± 3

*Values represent mean ± standard error unless noted; n = 10.

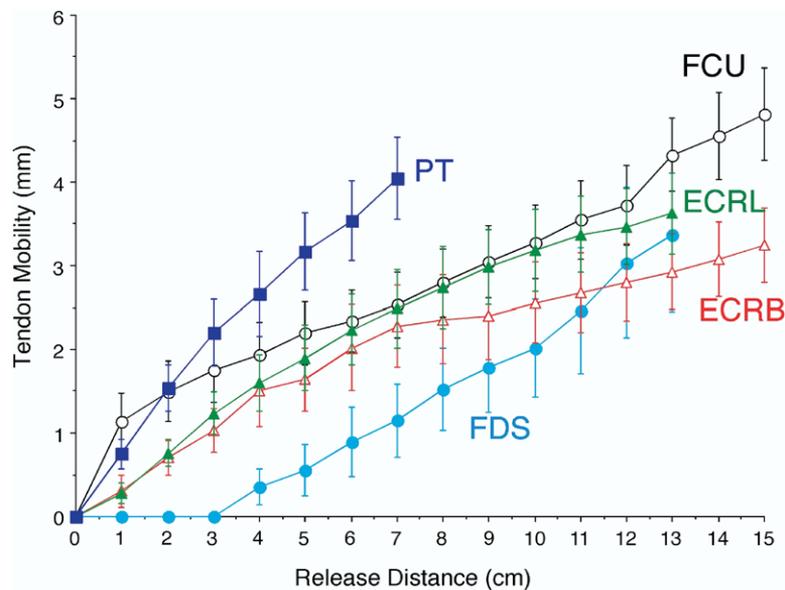


Figure 1. Relationship between mobility versus release distance determined experimentally for each of 5 forearm muscles. Values represent mean \pm standard error of the mean for the 10 specimens studied. In some cases, the increased standard error of the mean as release progresses represents a decrease in sample size because of shorter specimen length. The slope of these lines (in mm/cm) is defined as mobility gain and plotted in Figure 3.

To provide an internal positive control for this experimental approach and to compare these mobility gains with the more commonly performed Z-lengthening and aponeurotomy, after the FCU was released Z-lengthening of the distal tendon and aponeurotomy of the superficial fascia were performed at the midbelly, again with the distal tendon loaded to 5 N.

Statistical Analysis

Data were analyzed by linear regression to quantify the mobility gain (in mm/cm release), which was the slope of the mobility gain–release linear regression equation. To determine whether significant nonlinearities existed with respect to mobility gain with release, both first- and second-order regression models were examined, and their respective coefficients of determination (r^2) were compared. Finally, regression slopes among muscles were compared by 1-way analysis of variance (StatView 5.0; Abacus Concepts, Berkeley, CA). The significance level (α) was set at .05 and statistical power ($1 - \beta$) exceeded 80% for all comparisons that were not significantly different.

Results

In contrast to a previous experiment⁷ on the BR muscle (in which mobility gain = 1.6 ± 0.2 mm/cm), mobility gain was small, extremely consistent, and linear for the ECRB, ECRL, FCU, FDS, and PT muscles. Based on the length of the specific muscle

tested, the release amount ranged from 8 to 16 cm (Fig. 1). In some cases the nature of the mobility gain was predictable. For example, the FDS, with its distinct distal tendon insertions, gained zero mobility until it was freed about 3 cm, essentially to the distal muscle–tendon junction (Fig. 1, circles). From that point, the mobility gain was a highly linear 0.3 ± 0.1 mm/cm released. At the other extreme was the PT, which gained mobility on initial release from the radius (Fig. 1, squares) and thereafter gained 0.6 ± 0.1 mm/cm, again in a highly linear fashion. Distally, it was necessary to release the PT from its association with radial periosteal connections and the adjacent flexor carpi radialis muscle belly to achieve mobility. Most of the mobility gain for the radial extensors was achieved distally, with release of the insertion and then continuing along the passage through the second dorsal tendon sheath compartment (Fig. 1, open and filled triangles for ECRB and ECRL, respectively). In general, the mobility gain for the ECRB (0.2 ± 0.02 mm/cm) was similar to that for the ECRL (0.3 ± 0.03 mm/cm). The ECRB, however, had the most nonlinear release pattern of all muscles studied. This was consistent with the fact that the ECRB analysis produced the largest difference in r^2 between the linear fit ($r^2 = 0.82$) and the quadratic fit ($r^2 = 0.96$). (For other muscles, this difference was less than 0.06, suggesting highly linear mobility gain). The FCU muscle was difficult to mobilize because of its

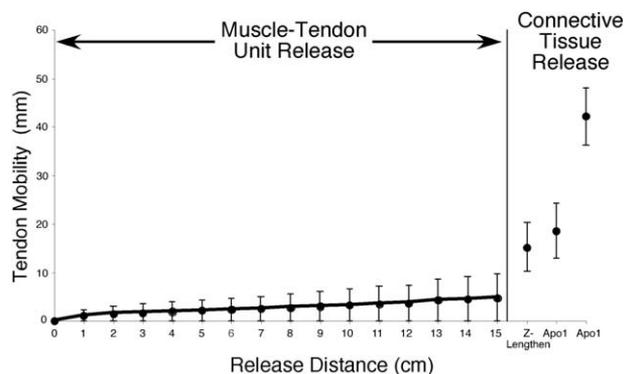


Figure 2. Relationship between mobility versus release distance determined for the FCU during progressive release of the muscle (left) and then with connective-tissue release (right). Z-lengthen: Z-lengthening of the most distal portion of the tendon; Apo1, Apo2: sequential aponeurotomy of the proximal connective-tissue sheath. (This procedure is illustrated in the online video that can be viewed at the *Journal's* web site: www.jhandsurg.org)

intimate and firm association along the ulna (Fig. 1, open circles). Although mobility was gained with each successive release, the magnitude was modest (0.3 ± 0.03 mm/cm). In contrast, a tremendous mobility increase was achieved for the FCU with stair-step lengthening (Z-lengthening) of the distal tendon (Fig. 2) and even more pronounced mobility after aponeurotomy of the proximal connective-tissue sheath (Fig. 2; see supplemental online video at the *Journal's* web site: www.jhandsurg.org).

The low mobility gain for some of these muscles was surprising in light of previous demonstrations of their relatively long muscle fibers. This was most vividly illustrated by comparing ECRL and ECRB (Fig. 3). Although ECRL muscle fibers are nearly 70% longer than those of the ECRB, the 2 muscles have about the same mobility gain during release. In fact, there appears to be no correlation between passive mobility achieved for forearm muscles during progressive release and the length of their fibers (Fig. 3).

Discussion

The purpose of this study was to measure the mobility gained by progressive release of several forearm muscles used in tendon transfer surgery. The most important finding was the consistently small mobility gained for all muscles studied (ECRB, ECRL, FCU, FDS, PT), even though many of them are traditionally considered to have high excursion based on their long muscle fibers. In fact, mobility was 10% to 30% of that previously measured for the BR muscle using the same methodology.

The small mobility and lack of correlation with fiber length is clearly seen in Fig. 3, in which forearm flexors and extensors with markedly different architectural designs have almost the same mobility, ranging from about 0.2 to 0.3 mm/cm. The only muscle with a sizeable mobility gain was the PT (~ 0.6 mm/cm). These data provide strong evidence that mobility gain, measured by passive elongation in cadaveric specimens and that we believe mimics intraoperative mobilization, does not accurately reflect muscle excursion as it is typically considered. Muscle excursion, strictly speaking, refers to the range over which a muscle can actively generate force. In isolated systems, excursion is directly proportional to muscle fiber length.^{12,13} There is very little evidence to suggest that passive tension provides a good estimate of either excursion or fiber length. Consequently, mobility gain measured by passive tension should not necessarily correlate with fiber length. This calls into question the general practice of tensioning muscles by passively extending the muscle and then choosing the attachment length based on that passive relationship. Several surgical texts explicitly state that the length at which a muscle is sutured to a recipient tendon should be chosen based on the length that occurs when a muscle is subjected to passive loading.^{14,15} We suggest that this will not necessarily provide optimal function. This is because there is apparently no correlation between passive load and fiber length in these muscles. If there were such a correlation, then muscles with longer fibers such as the ECRL would have

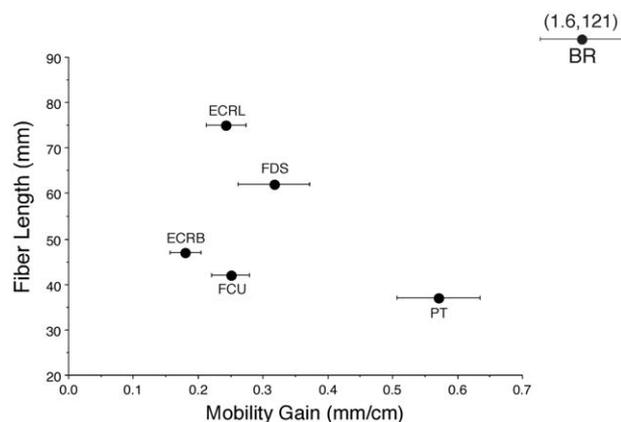


Figure 3. Relationship between mobility gain (defined as the slope of the mobility versus release distance graphs in Fig. 1) and muscle fiber length determined for these muscles in a previous study.^{10,22} Note that the mobility gain for all muscles except the PT are about the same, even though there is a 2-fold variation in fiber length. Data for the BR are shown for comparison based on data from a previous study.⁷

greater mobility gains on release compared with muscles with shorter fibers such as the FCU.

We also tested the effect of aponeurotomy and Z-lengthening on mobility gain to calibrate our methodology against more commonly used procedures. There was a significant difference in mobility achieved with muscle release compared with either Z-lengthening or aponeurotomy. Specifically, when the muscle belly fully mobilized by releasing the FCU from its ulnar connections and the surrounding fascia, the mobility gain was only about 0.2 mm/cm—a 15-cm release producing a mobility of about 5 mm. In contrast, subsequent aponeurotomy of the proximal superficial fascia resulted in a 20-mm increase in muscle–tendon unit length. The fact that the aponeurotomy or release caused such specific muscle–tendon unit length changes implies that it is these connective tissues that are being affected and sensed by the surgeon, not the muscle fibers themselves as is often stated.

Muscle mobilization is still an important facet of the tendon transfer procedure. It is imperative that the new line of action be as close to the original muscle's line of action, or unintended donor muscle function may result¹⁶ and/or the magnitude of force developed may be small. Although it has not been explicitly studied in tendon transfer surgery, a poor line of action also would presumably result in relatively high frictional force loss, which would compromise function.

Muscle mobilization is not without hazard. Extensive mobilization proximally may risk disruption of neurovascular structures. For example, we measured the location of the most distal FCU motor branch to be 89 ± 6 mm (mean \pm SD) distal to the medial epicondyle. The 99% confidence interval for the position of this nerve branch would extend 11 cm distal to the medial epicondyle, suggesting that release proximal to this point should be avoided. Similarly, the very small gain in mobility obtained for the ECRB (Fig. 1, open triangles) after 8 cm of release would not appear to be worth the risk of further release.

It is interesting to note that the 2 most mobile muscles studied in our laboratory to date are the PT (this study) and the BR.⁷ Given the fact that both muscles provide forearm rotation, perhaps the extensive interaction with adjacent connective tissue that occurs along their length is responsible for the large mobility gained on release. We speculate that extensive interaction is required to minimize shear stresses that would occur in these muscles if they were al-

lowed to either slide laterally or rotate during muscle contraction. Further studies are required to test this hypothesis. Increased BR mobility with release is consistent with previous publications by Freehafer et al.^{4,17} These researchers reported a 16-mm mobility gain with release of the BR from surrounding tissues. Based on the BR mobility gain presented here (1.6 mm/cm released), this value implies that they performed about 10 cm of release, which is consistent with common surgical experience.

We acknowledge that this study is limited by the fact that passive mechanical properties were measured in cadaveric specimens rather than in living humans. There are 3 reasons, however, why we do not believe that this limitation represents a serious flaw: (1) previous intraoperative BR measurements in living humans¹⁸ were closely approximated by the mechanical measurements made of the BR in cadaveric specimens⁷; (2) although cadaveric tissues do not recoil as do living muscles, their limited excursion implies connective-tissue restrictions as the major factor determining mechanical properties; and (3) biomechanic models generated from cadaveric specimens almost exactly mimic intraoperative laser diffraction values obtained in living humans.¹⁹ It still is important to validate these findings in living human tissue. We also acknowledge that there are a number of unknown factors related to this study that may mitigate our findings. First, we do not know the extent or the direction of muscle fiber adaptation that occurs after tendon transfer surgery. If all muscles simply optimized after tendon transfer, as has been reported for rodent soleus muscle,²⁰ the tensioning procedure itself would not be critical. We have experimental evidence, however, that optimization is not the general rule for skeletal muscles,²¹ and the extent to which human upper-extremity muscles adapt after transfer remains unknown. If upper-extremity muscles were always to optimize after transfer, the generally accepted notion that one should not put a transfer in too loosely would not be the case, because muscles would simply tighten after tenorrhaphy.

These data show that mobility gained with forearm muscle release is relatively constant and is not correlated with muscle excursion as indicated by muscle fiber length, except in the pronators. Surgeons must be cautioned that intraoperative tensioning based on passive mechanical properties alone is bound to be misleading and may lead to suboptimal functional restoration.

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