Mechanical Feasibility of Immediate Mobilization of the Brachioradialis Muscle After Tendon Transfer

Jan Fridén, MD, PhD, Matthew C. Shillito, MD, Eric F. Chehab, BS, John J. Finneran, BA,
Samuel R. Ward, PhD, Richard L. Lieber, PhD

Purpose Tendon transfer is often used to restore key pinch after cervical spinal cord injury. Current postoperative recommendations include elbow immobilization in a flexed position to protect the brachioradialis–flexor pollicis longus (BR-FPL) repair. The purpose of this study was to measure the BR-FPL tendon tension across a range of wrist and elbow joint angles to determine whether joint motion could cause repair rupture.

Methods We performed BR-to-FPL tendon transfers on fresh-frozen cadaveric arms (n = 8) and instrumented the BR-FPL tendon with a buckle transducer. Arms were ranged at 4 wrist angles from 45° of flexion to 45° of extension and 8 elbow angles from 90° of flexion to full extension, measuring tension across the BR-FPL repair at each angle. Subsequently, the BR-FPL tendon constructs were removed and elongated to failure.

Results Over a wide wrist and elbow range of motion, BR-FPL tendon tension was under 20 N. Two-way analysis of variance with repeated measures revealed a significant effect of wrist joint angle ($p<.001$) and elbow joint angle ($p<.001$) with significant interaction between elbow and joint angles ($p<.001$). Because the failure load of the repair site was 203 ± 19 N, over 10 times the loads that would be expected to occur at the repair site, our results demonstrate that the repair has a safety factor of at least 10.

Conclusions Our tendon force measurements support the assertion that the elbow joint need not be immobilized when the BR is used as a donor muscle in tendon transfer to the FPL. This is based on the fact that maximum passive tendon tension was only about 20 N in our cadaveric model and the failure strength of this specific repair was over 200 N. We suggest that it is possible to consider performing multiple tendon transfers in a single stage, avoiding immobilization, which may adversely affect functional recovery. These results must be qualified by the fact that issues unique to living tissues such as postoperative edema and tendon gliding cannot be accounted for by this cadaveric model. *(J Hand Surg 2010;35A:1473–1478. © 2010 Published by Elsevier Inc. on behalf of the American Society for Surgery of the Hand.)*

Key words Tendon transfer, early mobilization, spinal cord injury, muscle, tendon transfer.

Surgical tendon transfers are used commonly in the upper extremity to restore lost function and to correct joint deformities.[1,2] The choice of a donor muscle for tendon transfer is based primarily on availability, route of transfer, donor site morbidity, functional synergy, and architectural design.[3,4] The brachioradialis (BR) muscle is a valuable donor muscle, based on its expendability as an elbow flexor; its long

From the Departments of Orthopaedic Surgery and Radiology, University of California San Diego, San Diego, CA; and the Department of Hand Surgery, Sahlgrenska University Hospital, Gothenburg, Sweden.

Received for publication March 26, 2010; accepted in revised form June 1, 2010.

The authors acknowledge Mr. Robert Healey for help with the data collection.

This study was funded by Swedish Research Council grant 11200 and by National Institutes of Health grant HD050837.

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

Corresponding author: Richard L. Lieber, PhD, Department of Orthopaedic Surgery, University of California and VA Medical Centers, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0863; e-mail: rlieber@ucsd.edu.

0363-5023/10/35A09-0013$36.00/0
doi:10.1016/j.jhsa.2010.06.003

and stout distal tendon, which allows large tendon-to-tendon attachment overlap; and its high excursion when properly released.[5–7] In addition, because the BR is innervated over the C5-C6 levels, its function is often preserved in cervical spinal cord–injured patients with lesions up to the C6 level.

Based on the relatively complex muscle–tendon unit routing, tendon repairs, and in some cases tenodeses, postoperative rehabilitation after tendon transfer involves specific immobilization and activity limitations. Postoperative recommendations for movement largely depend on the strength of the repair method. For example, in surgical restoration of elbow extension using the posterior deltoid-to-triceps (PD-TRI) transfer, patient immobilization to prevent elbow flexion and shoulder flexion and adduction is necessary to protect the relatively fragile tendon graft/deltoid repair.[8] Similarly, in transfers involving the BR, it is often recommended that the elbow be immobilized in the flexed position to minimize tension across the repair site and permit healing.[9] However, this general recommendation, although logical, is not supported by objective data. Furthermore, immobilization itself is not completely benign. For example, immobilized repaired tendons are vulnerable to peritendinous adhesions[10–13] and immobilization may limit a muscle group's ability to be retrained, based on neural detraining.[14–16] Immobilization is also known to produce muscle atrophy, and therefore weakness.[17,18] Finally, in the cervical spinal cord–injured patient, a PD-to-TRI transfer often precedes a BR transfer as a separate surgery precisely because these 2 transfers are believed to require different postoperative immobilization strategies. As described previously, PD-to-TRI transfers require immobilization with the elbow extended, whereas traditional guidelines for BR transfer recommend that the elbow be flexed. As a result, procedures involving both PD and BR transfers typically are staged procedures.

To avoid the potential complications of immobilization, there is growing acceptance of early mobilization of tendon repairs. These studies, primarily performed on flexor tendons,[12,19,20] have demonstrated that early mobilization decreases adhesions[10] (thus improving function), increases intrinsic[20] and extrinsic[19] tendon healing and therefore repair strength, decreases soft tissue swelling,[21] and potentially improves recovery from the neural inhibition that results from immobilization.[16]

Based on our desire to provide early mobilization after restoration of key pinch by transfer of the BR into the flexor pollicis longus (FPL), it was necessary to evaluate BR-FPL tendon tension at varying degrees of elbow and wrist position after transfer. We suspected that it might be possible, based on the judicious choice of wrist and elbow joint angle, to unload the BR sufficiently, thereby decreasing the risk of repair rupture and permitting early mobilization. In making such tension measurements, it was important to define BR-FPL tendon tension as a function of the joint angle in the context of the failure stress of the repair itself, as well as the force generated by the BR muscle during physiological activation. Therefore, the purpose of this study was to measure BR tendon tension with wrist and elbow joint manipulation, using a simulated BR-to-FPL tendon transfer.

TABLE 1. Physical Properties of Experimental Specimens

Parameter	Value
Age (y)	62 ± 15
Gender	7 M/1 F
Ulnar length (cm)	28.4 ± 1.9
Suture overlap region length (cm)	5.6 ± 0.3
Range of motion	
Elbow (°)	140 ± 17
Wrist (°)	147 ± 22
Thumb metacarpophalangeal joint (°)	91 ± 34

Data are presented as mean ± SD (n = 8).

MATERIALS AND METHODS

Experimental subjects

We performed experiments on fresh-frozen cadaveric arms (n = 8) transected at the midhumeral level. The average age of the specimens was 62 ± 15 years (mean ± SD) (Table 1). All specimens were free from obvious musculoskeletal defects (although one had an ulnar plate) and underwent BR-to-FPL tendon transfer according to standard procedures.[2] After exposing the distal BR, the tendon was released from its insertion at the distal radius and carefully dissected and freed from the bone proximally to the elbow joint, to allow full excursion.[5] The BR tendon was inserted through the FPL at the myotendinous junction so that it lay on the volar aspect of the FPL tendon and tension was set roughly to its original level with the elbow extended. We set the tension of the FPL tendon to give the thumb a firm grasp pressure and used a 3-0 braided polyester suture (TevdekII 3-0; Deknatel, Research Triangle Park, NC) to create a 5-cm-long repair region that consisted of a running suture on either side of the

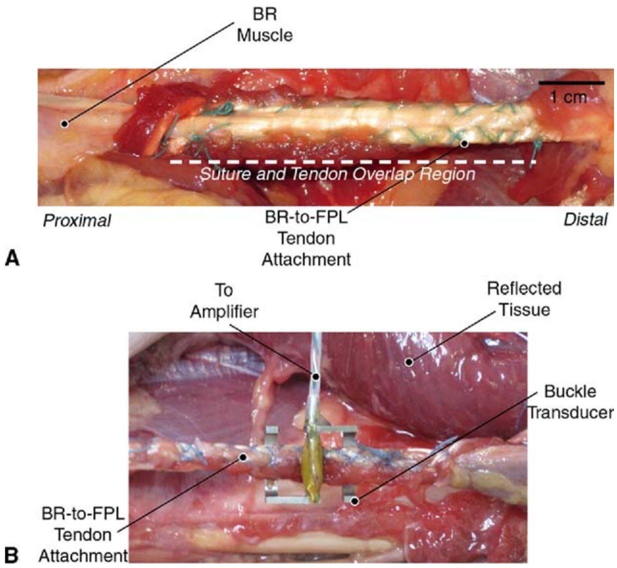

FIGURE 1: A Example of the BR-to-FPL repair. Note that the running suture extends proximally and distally along both sides of the tendons, creating a strong fixation. The dashed line represents the range over which the BR and FPL tendon overlap and are sutured. Scale bar = 1 cm. **B** Buckle transducer placed on the BR-FPL tendon to enable tendon tension measurement as a function of wrist and elbow joint angle.

tendons extending proximally and returning distally, as previously described (Fig. 1A).[22] To make accurate buckle transducer measurements and avoid the confounding mechanical effects of the surrounding tissues, the adjacent flexor muscles and tendons were reflected (see later).

Experimental method

We determined the effect of several elbow and wrist joint angles on BR-FPL tendon tension by first mounting the arm to a breadboard using external fixator components. Briefly, a pin was placed through the distal ulna into the radius with the forearm in neutral position to prevent forearm rotation, and another was placed in the proximal ulna to secure the forearm. A final pin was placed across the little finger metacarpal into the hand to permit controlled wrist flexion and extension. We used multiple 3-mm (0.056-in) K-wires to immobilize the thumb interphalangeal joint at 20° of flexion and the metacarpophalangeal and carpometacarpal joints in the neutral position. A rod was fit snugly into the distal humerus medullary canal to control elbow flexion angle. A 6 df hinge placed at the wrist joint allowed the wrist to be fixed in any position by connecting the metacarpal-based pin and locking the fixator bolts.

We used a strain gauge-based buckle transducer to measure tendon tension at the site of the BR-to-FPL repair (Fig. 1B). This transducer, used on wrist flexor tendons and flexor tendons in previous hand surgical experiments,[23,24] was nominally calibrated before the experiment using both strings and rubber tubing, and after the experiment with actual BR-FPL tendon constructs. Transducer output was linearly correlated with tension for all calibrations (r^2 = 0.984–0.998), with a nominal calibration factor of about 3 N/V.

Tendon biomechanical testing

We measured wrist joint flexion and extension angles manually with a goniometer and defined them as the included angle between the shaft of the radius and the long finger metacarpal. Elbow joint angle was measured manually with a goniometer and was defined as the angle between the ulnar and distal humerus shafts. With the wrist locked in 45° of flexion and the elbow placed in full flexion so the tendon was under no tension, the transducer was zeroed. The elbow joint was then extended to 90° of flexion and tension was measured. Then, the elbow was extended to elbow angles of 75°, 60°, 45°, 30°, and 15°, and full passive extension (which varied among specimens and as a function of wrist joint angle). We recorded buckle tension at each angle after stabilization (approximately 5 seconds after reaching the selected joint configuration). This experiment was repeated measuring tension at each elbow angle with the wrist fixed at 0°, 23° of extension, and 45° of extension, taking care to prevent wrist radioulnar deviation.

The complete tendon repair was removed along with its native unsutured proximal and distal tendon. The distal FPL and proximal BR tendon end regions were clamped into a materials testing device (Model 5565A; Instron, Inc., Grove City, PA) and were calibrated on a specimen-by-specimen basis at 0, 1, 2.5, 5, 10, 15, 20, and 25 N. Transducer output was linearly correlated with tension applied independently for each BR-FPL construct (r^2 = 0.985 –0.999), yielding an average calibration factor of 3.1 ± 0.4 N/V. We based calibration of the actual specimens tested on pilot projects that demonstrated dependence between specimen elasticity and transducer calibration factor, as previously described.[25,26] Finally, specimens were returned to their initial preload force of 1 N and then linearly elongated to failure, during which tendon force was recorded at 100 Hz, as previously described.[27,28]

Statistical analysis

In addition to the metadata from each specimen for which only descriptive statistics were calculated (Table 1), we recorded tension values across 4 wrist and 7

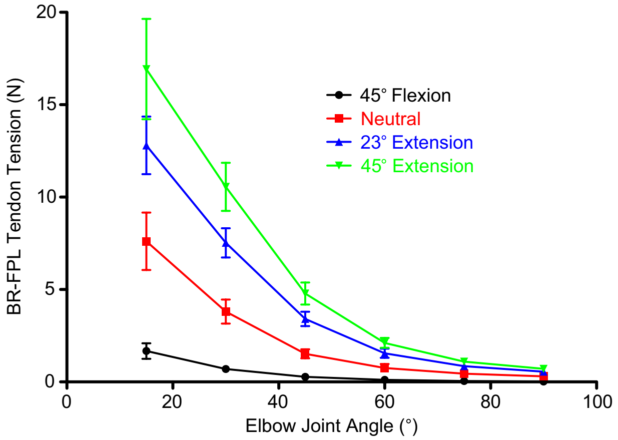

FIGURE 2: BR-FPL tendon tension as a function of elbow joint angle for 4 different wrist positions. Note that average peak tension does not exceed approximately 20 N. Two-way ANOVA with repeated measures revealed a significant effect of wrist joint angle ($p<.001$) and elbow joint angle ($p<.001$), with significant interaction ($p<.001$).

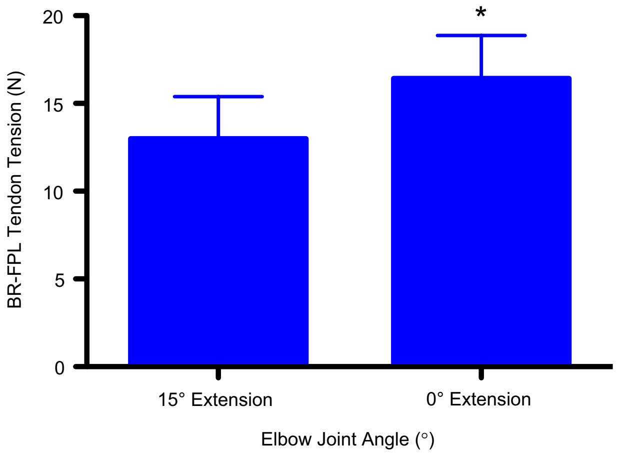

FIGURE 3: Bar graph comparing BR-FPL tendon tension at 15° and 0° of elbow extension with the wrist in 45° of extension for the 5 specimens that could achieve this configuration. A paired *t*-test revealed a significant difference between positions (*$p<.05$), which was about 20% in magnitude.

elbow joint angles (where possible), which typically yielded 28 data points per specimen. These data were screened for normality and skewed to justify the use of a parametric 2-way analysis of variance (ANOVA), with the elbow and joint angle serving as the 2 repeated measures. For the 5 specimens that could be fully extended to an elbow angle of 0°, we performed a paired *t*-test between tendon force at 15° of extension and 0°. Significance level (α) was set to 0.05 for all statistical tests. Data are presented as mean ± SEM unless otherwise noted.

RESULTS

Of the 8 specimens studied, we acquired the complete data set of 28 points for 5. For 3 of the specimens, owing to joint limitations, 0° of elbow extension could not be achieved. Thus, we performed the complete 2-way ANOVA on wrist angles ranging from 45° of extension to 45° of flexion and elbow angles ranging from 90° to 15° of flexion. Data from the 5 specimens that could be extended to 0° were analyzed separately (see later).

Over the normal wrist and elbow range of motion, tendon tension of the BR-FPL repair site was under 20 N (Fig. 2). This numerical result has important implications for the practice and rehabilitation of tendon transfer surgery (see Discussion). These numbers yield a safety factor for passive tension of 8 to 10 and active tension of 4 to 5. The failure mode for all specimens tested was disruption of the native FPL or BR tendon division near the clamp, which suggests that stress concentration at the clamp was responsible for the failure loads (3 BR tendons and 5 FPL tendons). This failure tension should thus be viewed as underestimating the true failure strength of the construct.

We defined the dependence of the tension change at the repair site on elbow and wrist motion (Fig. 2). Two-way ANOVA with repeated measures revealed a significant effect of wrist joint angle ($p<.001$) and elbow joint angle ($p<.001$), with significant interaction between elbow and wrist joint angle ($p<.001$). The interaction term was significant and both joints contributed relatively equally to tension change, with about 10-fold tension variability resulting from either joint being moved from flexion to extension. For example, with the wrist in neutral, tendon force varied from less than 1 N to about 10 N with elbow rotation. Similarly, with the elbow at 15° of flexion, tendon force varied from approximately 2 N to approximately 20 N with wrist rotation.

The tension change between 15° and 0° of elbow extension for 5 of the specimens, while statistically significant ($p<.05$), was relatively modest—only about 20% (Fig. 3).[29]

DISCUSSION

The purpose of this study was to quantify the tension of the reconstructed BR-to-FPL tendon repair during elbow and wrist joint rotation in a cadaveric model. Our suspicion was that elbow immobilization in flexion should not be required for protection of the tendon repair site. The results of our study support this assertion. Passive tendon tension did not exceed 20 N (Fig.

2, green line) and was typically well under 10 N. As a result, we claim that the conservative approach of imposing elbow immobilization in flexion after BR transfer is unwarranted.

The assertion that elbow immobilization is not required after surgery has several practical implications for hand surgery and postoperative rehabilitation. Most important, the multiple surgical procedures that are often required for this patient population can be performed as a single procedure. For example, for the cervical spinal cord–injured patient lacking triceps function and key pinch, the PD-to-TRI transfer could be performed in combination with the BR-to-FPL transfer because the postoperative joint configurations would no longer be considered incompatible. Previously, it had been argued that the PD-to-TRI postoperative requirement for immobilization in elbow extension would overstretch the BR-to-FPL repair site. Data from this study demonstrate that this is not the case (Fig. 2). Similar arguments could be made for other combinations of transfers. Besides the obvious advantage that the patient experiences only a single surgery, we suspect that a single-stage procedure could result in shorter total rehabilitation time, immediate return to functional retraining, and decreased cost. Postoperative treatment of these patients often includes nighttime immobilization of the elbow and wrist, to prevent overstretch of the repair site, which may not be necessary.

Even though the earlier-described argument is made for the case of passive tension only, it is relatively straightforward to extend this discussion to the case that includes active muscle contraction. This is because both the active and passive BR length-tension properties have been explicitly defined based on intraoperative sarcomere length measurements[30] and biomechanical modeling.[31] Based on known BR architecture, its active force would be predicted to be about 40 N,[32] and this muscle appears to operate in large part on the descending limb of its length tension curve.[33] Passive BR tension begins to become sizeable at lengths greater than optimum (see Fig. 4 in Lieber et al.[30]), with the net result that total muscle force (active tension plus passive tension) actually decreases with increasing BR length. Thus, whether the muscle is activated voluntarily or experiences passive tension as a result of joint rotation (or a combination of the 2), the conclusions of this study are still supported.

Our conclusions are valid only in light of the relatively high failure stress of the repair site based on the use of a running side-to-side suture that extends proximally and distally along both sides of the donor to recipient tendon. Compared with traditional weave repairs, we recently showed that this strategy increases ultimate strength by a factor of 2 to 3 (see Fig. 3 in Brown et al.[22]). A weaker repair would result in a substantially decreased safety factor, and thus the current recommendations strongly depend on the side-to-side running suture repair method implemented (Fig. 1A). Furthermore, traditional weave techniques result in a bulkier repair construct, leading to a higher risk of adhesion.

There were several limitations to this study. Most obvious is the possibility that the cadaveric muscle-tendon units used may not faithfully represent the living condition of these tissues. Fortunately, we can compare our data with intraoperative data recently collected, which demonstrate nearly identical absolute tension levels for the BR. Although we restricted the amount of BR stretch during *in vivo* experimental measurements to 3 to 5 cm, even under these conditions peak tension did not exceed 20 N (see Fig. 4 of Lieber et al.[30]). This argument depends on the fact that we performed these experiments with the BR at a length that closely approximated the *in vivo* muscle length before transfer. A second limitation of this study was that we did not include the effect of wrist pronation and supination on tendon tension. However, the BR moment arm for frontal plane motion is extremely small[34] and becomes even smaller when transferred volarly to the FPL,[35] which suggests that the effect on tendon tension would be small. However, because the natural line of pull of the BR was altered for this transfer, this comment regarding forearm rotation must still be experimentally verified.

We believe that the extensive dissection and freeing of the BR required for application of the buckle method and experimental manipulation resulted in a slight overestimation of the tendon force. This is because the extensive BR release had the effect of increasing the elbow moment arm, thus increasing BR excursion that occurred with elbow extension. During hand surgery, the more limited BR release would result in a smaller elbow moment arm than that created here. As a result, the patient's BR excursion with elbow extension would likely be lower, as would the accompanying BR-FPL tendon tension.

These experiments report relatively low tendon tensions in the repaired BR-to-FPL with elbow and wrist rotation. As a result, postoperative treatment of this patient population may be extended to include protected activity of the wrist and elbow.

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