Variability in Surgical Technique for Brachioradialis Tendon Transfer

Evidence and Implications

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Background: Transfer of the tendon of the brachioradialis muscle to the tendon of the flexor pollicis longus restores lateral pinch function after cervical spinal cord injury. However, the outcomes of the procedure are unpredictable, and the reasons for this are not understood. The purpose of this study was to document the degree of variability observed in the performance of this tendon transfer.

Methods: The surgical technique used for the brachioradialis tendon transfer was assessed in two ways. First, the surgical attachment length of the brachioradialis was quantified, after transfer to the flexor pollicis longus, with use of intraoperative laser diffraction to measure muscle sarcomere length in eleven individuals (twelve limbs) with tetraplegia. Second, ten surgeons who regularly performed this procedure were surveyed regarding their tensioning preferences. Using a biomechanical model of the upper extremity, we investigated theoretically the effect of different surgical approaches on the active muscle-force-generating capacity of the transferred brachioradialis in functionally relevant elbow, wrist, and hand postures.

Results: The average sarcomere length (and standard deviation) of the transferred brachioradialis was 3.5 ± 0.3 μm. That length was significantly correlated to the in situ sarcomere length ($r^2 = 0.53$, $p < 0.05$). Surgical tensioning preferences varied considerably; however, six of the ten surgeons positioned the patient's elbow between full extension (0° of elbow flexion) and 50° of flexion when selecting the attachment length, and six of the ten stated that their goal was to tension the transfer slightly tighter than its resting tension. The computer simulations suggested that a "tighter" brachioradialis transfer would produce its peak active force in an elbow position that is more flexed than the elbow position in which a "looser" transfer would produce its peak active force.

Conclusions: This study provides evidence that experienced surgeons perform this tendon transfer differently from one another. Biomechanical simulations suggested that these differences could result in substantial variability in the active force that the transferred brachioradialis can produce in functionally relevant postures.

Clinical Relevance: The surgical attachment length and the position of the patient's limb at the time of tendon transfer are both controllable and measurable parameters. Understanding the relationship between surgical technique and postoperative muscle function may provide surgeons with more control of clinical outcomes.

Loss of hand function is a debilitating consequence of cervical-level spinal cord injury. Tendon transfer surgery, which involves attaching the tendon of a nonparalyzed muscle (the donor muscle) to that of a paralyzed muscle, is one of the few means available for restoring aspects of voluntary hand function to tetraplegic individuals. The brachioradialis is the donor muscle most commonly used for this purpose[1]. Functional outcomes of transfers of the distal tendon of the brachioradialis to the proximal portion of the distal tendon of the flexor pollicis longus to restore lateral pinch function to quadriplegic patients have ranged from excellent to poor[2-6]. Quantitative assessments of pinch force have been reported to vary as much as tenfold among subjects with these transfers[6-9]. While brachioradialis tendon transfer does result in functional gains for many individuals with cervical spinal cord injuries, the basis for the variability in the outcomes requires additional study in order to optimize this valuable reconstructive procedure.

It is commonly accepted that surgical technique influences the functional outcome of a tendon transfer. This is a reasonable assumption as the surgeon maintains complete control of the donor muscle's length intraoperatively when attaching it to the paralyzed muscle. Because muscle force is highly dependent on muscle length[10], surgical outcomes could easily be compromised by an inadequate choice of surgical attachment length. It has been postulated that the choice of surgical attachment length influences postoperative strength[11,12], the range of motion of the joint[13], and the integrity of the transfer[14,15].

Surgeons select attachment lengths during tendon transfers by subjective means. The most commonly employed technique is based on tactile feedback, in which the surgeon relies on the relationship between muscle length and passive muscle force. The desired level of passive tension in the donor muscle (and the resulting surgical attachment length) is selected by the surgeon on the basis of his or her experience, and this choice of tension level is not easily taught or described. It is likely that this approach leads to variability in the attachment lengths preferred by different surgeons. For example, the surgical tensioning preferences of thirty-four hand surgeons were evaluated with use of a surgical simulator that was developed to mimic the relationship between passive tension and muscle length[16]. When instructed to indicate the level of tension that they preferred when performing a brachioradialis transfer, the surgeons chose a wide variety of surgical attachment lengths[16].

In general, there are almost no objective criteria for defining surgical tensioning preferences. The few specific descriptions of brachioradialis tendon transfers in the literature suggest variability in approaches. For instance, surgeons have reported positioning the patient's elbow during brachioradialis transfers over a range from full extension[16] to 90° of flexion[13]. A critical step in understanding the relationship between surgical technique and clinical outcome is to establish an adequate description of the current techniques.

The purpose of this study was to document the degree of variability in surgical technique observed during transfers of the tendon of the brachioradialis muscle to the tendon of the flexor pollicis longus. To do this, we (1) quantified the sarcomere length of the brachioradialis chosen at the time of tendon transfer in eleven patients (twelve limbs), (2) compared the tensioning preferences of ten different surgeons for the same brachioradialis transfer, and (3) implemented a biomechanical model of the upper limb to evaluate theoretically the effect of different surgical approaches on the active muscle-force-generating capacity of the transferred brachioradialis in functionally relevant elbow, wrist, and hand postures.

Materials and Methods

Sarcomere length was measured in vivo with laser diffraction[17] in eleven individuals (twelve limbs) with tetraplegia who were undergoing tendon transfer of the brachioradialis to the flexor pollicis longus. All procedures were performed with the full approval of the institutional review boards at the centers where the study was conducted. All patients provided informed consent. One surgeon (V.R.H.), with more than twenty-five years of experience in the surgical reconstruction of the upper limbs of tetraplegic patients, performed six of the procedures, and another surgeon (J.F.), with more than ten years of such experience, performed the other six procedures. Sarcomere length was measured both in situ and after transfer in nine limbs and following transfer only in three limbs. In situ measurements were performed with the elbow positioned in extension (in approximately 0° to 20° of elbow flexion), the forearm in neutral rotation, and the wrist in neutral. Measurements following tendon transfer were performed in the same elbow, forearm, and wrist positions, with the thumb and hand passively positioned in a lateral pinch posture. Six of the limbs in this study were included in a previous study in which the average in situ sarcomere length of the brachioradialis was reported[16].

The preferences, with regard to surgical tensioning during transfer of the brachioradialis to the flexor pollicis longus, of ten surgeons who regularly performed the procedure were documented with use of an e-mailed survey. The survey asked the surgeons to describe the positions in which they placed the patient's elbow and wrist at the time of tensioning of the transfer. It also asked them to state their goal with regard to the pressure between the thumb and the lateral aspect of the index finger, as demonstrated by qualitative intraoperative assessment, resulting from the transfer. In a follow-up survey, the same surgeons were asked to answer the following multiple-choice question:

In the elbow and wrist position that you normally choose, when you "set" the tension is it your intention to:

a. set the tension much looser than the normal state of the brachioradialis muscle?
b. set the tension slightly looser than the normal state of the brachioradialis muscle?
c. set the tension at the normal state; i.e., the so-called "resting" length?
d. set the tension slightly tighter than the normal state of the brachioradialis muscle?
e. set the tension much tighter than the normal state of the brachioradialis muscle?

The surgeons were also asked if they set the tension differently in one patient compared with another and, if so, to briefly describe what guided their thinking. Finally, the surgeons were asked to report the number of years that they had been performing surgical transfer of the brachioradialis to the flexor pollicis longus and approximately how many such transfers they had performed in the last two years. The two surgeons who performed the tendon transfers and the measurements of intraoperative sarcomere length in this study also participated in this survey.

Finally, using a computer-graphics-based model of the upper extremity[18], we simulated the active isometric force-generating capacity of the brachioradialis-to-flexor pollicis longus tendon transfer for a range of surgical attachment lengths at various functionally relevant elbow, wrist, and hand postures. Individuals with tetraplegia tend to grasp objects with use of lateral pinch[19] and an extended wrist[20]. We estimated the active muscle force produced by the transfer over the full range of motion of the elbow (0° to 130° of elbow flexion), over the full range of motion of the wrist, and with the fingers and thumb positioned in a lateral pinch posture.

The biomechanical model represents the bone geometry,

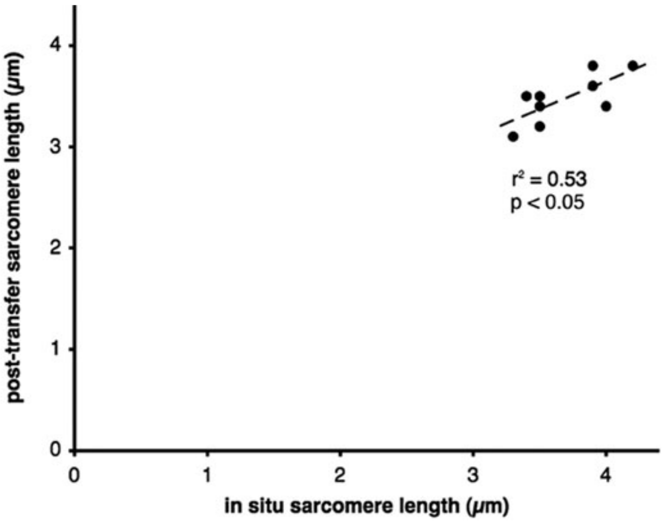

Fig. 1
Sarcomere length measured intraoperatively after surgical transfer of the brachioradialis to the flexor pollicis longus was significantly correlated with in situ sarcomere length of the brachioradialis measured prior to transfer in the nine limbs in which both measurements were performed. Thus, the surgeons chose a transferred muscle length that was comparable with that found in situ.

joint kinematics, origin-to-insertion paths, and architectural parameters of fifty muscles (or muscle compartments) of the upper extremity. The model characterizes the mechanical actions of the muscles of the upper extremity, as determined by comparisons with experimentally measured moment arms[18]. The force-generating characteristics of the muscles were derived from detailed anatomical studies of muscle architecture[18]. Total isometric joint moments estimated with use of the model are comparable with the isometric moments produced by healthy adult subjects during maximum voluntary effort[18]. Muscle-tendon paths can be altered interactively to simulate various surgical procedures, and muscles can be "paralyzed" by turning off their active properties[11,13,21].

We simulated surgical transfer of the brachioradialis to the flexor pollicis longus, with use of the computer model, by altering the muscle-tendon path of the brachioradialis to reflect the procedure. In the simulation, the muscle-tendon path of the transferred brachioradialis was identical to the path of the brachioradialis at the elbow joint and identical to the path of the flexor pollicis longus at the wrist and thumb joints. Thus, the simulated transfer had the elbow flexion moment arm of the brachioradialis and the wrist flexion and thumb flexion moment arms of the flexor pollicis longus. The peak active muscle force of the transferred brachioradialis was assumed to be equal to the peak force of the non-transferred brachioradialis, which we calculated by multiplying the cross-sectional area of the non-transferred brachioradialis (1.8 cm^2)[22] by muscle specific tension[2] (22.5 N/cm^2)[23]. In all simulations, we assumed that the strengths of the elbow extensors and the wrist extensors were adequate to stabilize these joints during hand function powered by a brachioradialis transfer. Specifically, we assumed that the maximum isometric moment that

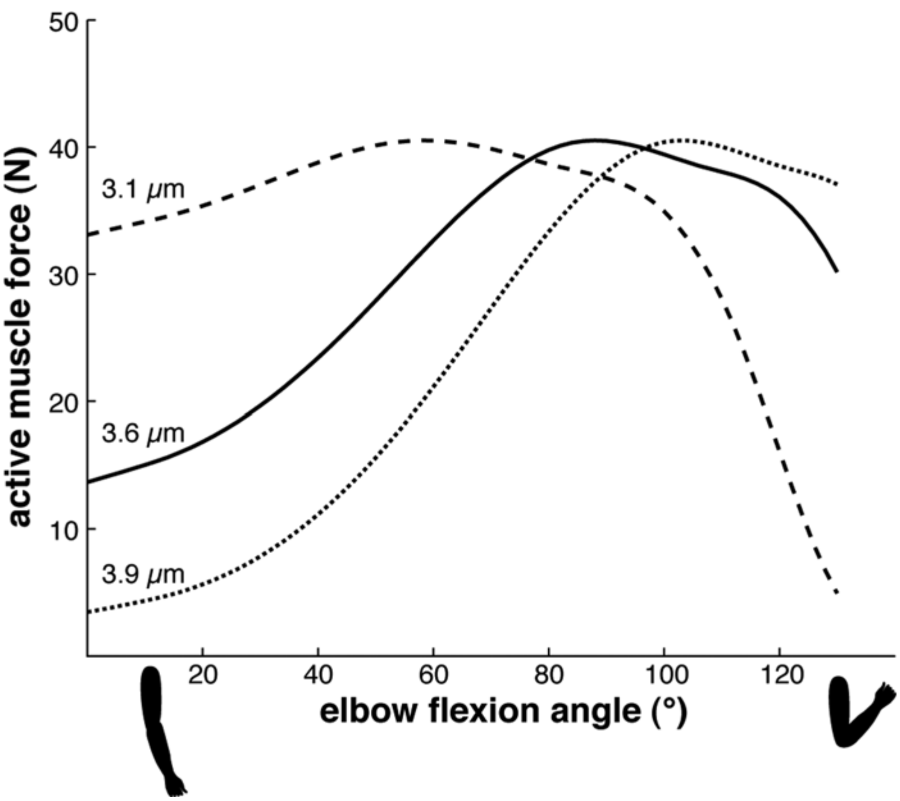

Fig. 2
Computer simulation of active brachioradialis muscle force as a function of elbow position with the wrist in 55° of extension and the hand in a lateral pinch posture. The dashed line indicates active force following use of a surgical attachment length of 3.1 μm (the shortest measured length), the dotted line indicates active force following use of a surgical attachment length of 3.9 μm (the longest measured length), and the solid line indicates active force following use of a surgical attachment length of 3.6 μm (between the two measured extremes). These simulations demonstrate that differences in intraoperative tensioning that result in variable sarcomere length dramatically affect active muscle force.

TABLE I Surgeons' Preferences When Transferring the Brachioradialis to the Flexor Pollicis Longus Tendon

Surgeon	No. of Yr Surgeon Performed Transfers	No. of Transfers Performed in Past 2 Yr	Elbow Position	Wrist Position	Pressure Between Thumb and Finger	Goal Relative to Resting Tension of in Situ Brachioradialis	Sets Tension Differently From Patient to Patient
1	30	Retired	Full extension	Neutral	Mild touch	Slightly tighter	Yes
2	11	17	Full extension	45° extension	Fairly tight	Slightly tighter	Yes
3	30	8	30° flexion	Neutral	Light touch	Resting tension	No
4	23	15-20	30° flexion	Full extension	Moderate pressure	Slightly tighter	Yes
5	11	7	45° flexion	Neutral	Light touch	Slightly tighter	Yes
6	*	*	50° flexion	Neutral	Firm touch	Slightly tighter	Yes
7	10	25	90° flexion	10° extension	Moderate pressure	Much looser	No
8	*	*	90° flexion	Neutral	Light touch	Does not compare with in situ resting tension	Yes
9	40†	24	90° flexion	Neutral	Light touch	Slightly tighter	No
10	28	6	90° flexion	30° flexion	Light touch	Resting tension	No

*The surgeon did not respond to this question. †The surgeon responded that the transfer has been performed at the medical center for more than forty years.

could be produced by the elbow extensors (whether generated by residual triceps function or augmented by the tendon transfer) was greater than the elbow flexion moment produced by the brachioradialis during maximum voluntary effort for all elbow positions. Likewise, we assumed that the maximum isometric moment produced by the wrist extensors was greater than the wrist flexion moment produced by the brachioradialis, after transfer to the flexor pollicis longus, during maximum voluntary effort.

To evaluate the effect of variability in surgical technique on postoperative muscle function, the sarcomere length of the transferred brachioradialis was altered in the model to reflect the range of surgical attachment lengths measured intraoperatively and the stated surgical preferences reported in the survey. For each measured sarcomere length, the intraoperative data were first normalized by the optimal sarcomere length (2.7 μm), and this ratio was then used to define either (1) the muscle fiber length at elbow, forearm, wrist, and hand postures comparable with the postures of these joints during intraoperative data collection (0° of elbow flexion, a neutral wrist position, a neutral forearm position, and a lateral pinch hand posture) or (2) longer or shorter lengths, to reflect a range of "tensions" given the results of our surgeon survey. On the basis of previous studies, muscle fiber length was defined as 173 mm at optimal sarcomere length[22,24].

All surgical attachment lengths were prescribed in the model with the muscle under passive conditions (i.e., assuming zero muscle activation) to be consistent with intraoperative conditions. To simulate maximum isometric force-generating capacity, we then assumed full muscle activation; the model estimated the change in muscle fiber length with activation[25]. The change in fiber length with joint rotation was calculated on the basis of the muscle moment arm[26], optimal muscle fiber length, and tendon compliance[25]. Strictly speaking, fiber length actually refers to muscle fascicle length since there is evidence that brachioradialis fibers do not extend the entire length of the fascicle[27]. For each surgical simulation, the active muscle force produced by the transferred brachioradialis was calculated as a function of elbow and wrist positions on the basis of fiber lengths estimated for that surgical attachment length.

Results

The mean sarcomere length (and standard deviation) of the brachioradialis following transfer to the flexor pollicis longus was 3.5 ± 0.3 μm (range, 3.1 to 3.9 μm, or approximately ±11%). The difference between the longest and shortest surgical attachment lengths was 30% of the optimal length (2.7 μm). In the subgroup of nine limbs in which sarcomere length was measured both in situ and after tendon transfer, the length after the transfer was significantly correlated with the in situ length (r^2 = 0.53, $p < 0.05$; Fig. 1). The paired in situ and transferred lengths indicated that the chosen surgical attachment lengths (mean, 3.5 ± 0.2 μm) were slightly shorter than the in situ lengths (mean, 3.7 ± 0.3 μm; p = 0.018). On the average, the transferred sarcomere length was 95% (range, 85% to 103%) of the in situ length. The in situ sarcomere lengths ranged from 3.3 to 4.2 μm.

The differences in surgical attachment lengths observed among the twelve limbs in this study could result in substantial variability in the active force that the transferred brachioradialis can produce. For example, computer simulations of the brachioradialis-to-flexor pollicis longus tendon transfer demonstrated that, with the elbow near full extension (0° to 20° of elbow flexion) and with a functional hand and wrist posture, the active force-generating capacity associated with a surgical attachment

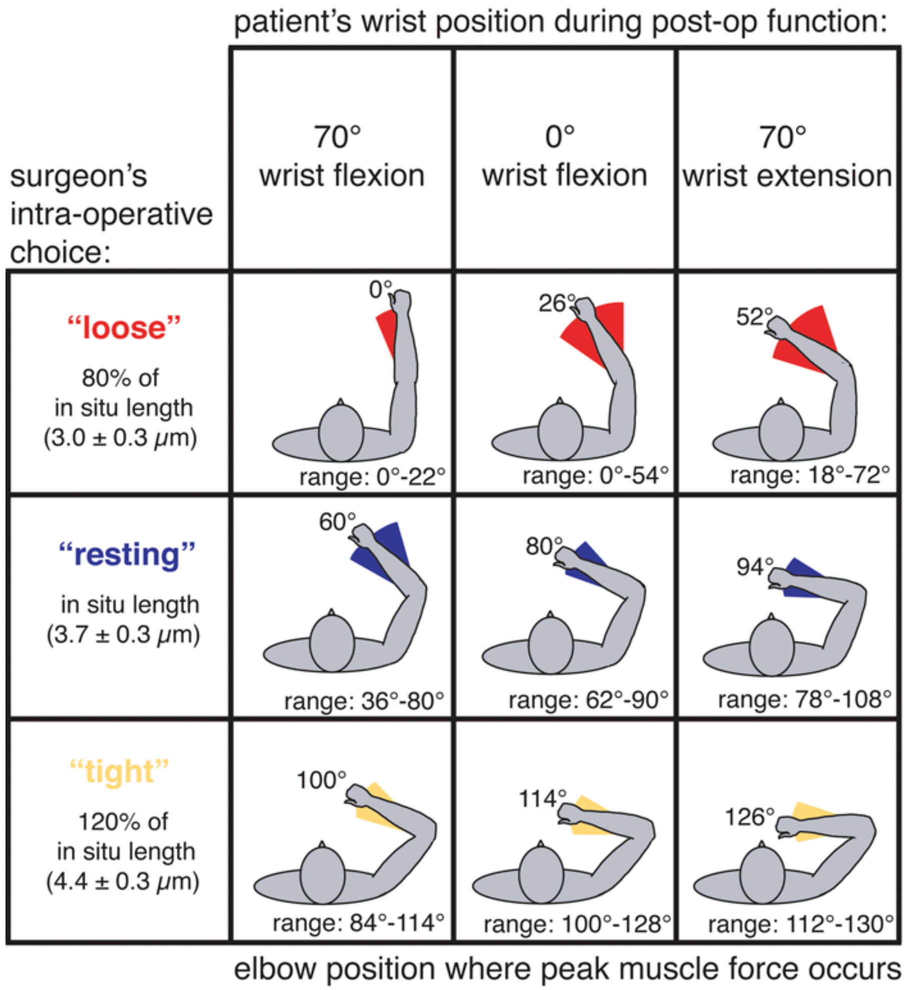

Fig. 3

Computer simulation results illustrating the elbow positions at which peak active muscle force occurs as a function of surgical attachment length and the patient's wrist position during postoperative function. Surgical attachment length was prescribed with the elbow fully extended, the forearm in neutral, the wrist in neutral, and the hand in a lateral pinch posture. While the specific elbow positions and sarcomere lengths indicated here are for a single surgeon's preference with regard to the elbow, forearm, wrist, and hand postures during the transfer, the general observation derived from these simulations (that is, that longer surgical attachment lengths cause peak active force to occur in more flexed elbow postures) can be extended to the other surgical preferences for elbow and wrist positions that are described in Table I.

length of 3.1 μm (the shortest attachment length measured in this study) was at least seven times greater than that associated with a surgical attachment length of 3.9 μm (the longest attachment length measured in this study). The computer simulation also suggested that peak muscle force occurred in more flexed elbow postures when the longer attachment lengths had been used. For instance, a surgical attachment length of 3.1 μm yielded a transfer that produced peak active muscle force at 58° of elbow flexion (Fig. 2, dashed line) while an attachment length of 3.9 μm yielded a transfer that produced peak active force at 104° of elbow flexion (Fig. 2, dotted line) in the simulated functional hand and wrist posture.

The ten surgeons who were surveyed regarding their performance of this procedure reported different preferences for tensioning of the transfer. These surgeons differed from one another with regard to their positioning of the limb when they tensioned the muscle (Table I), with their preferred elbow position ranging from full extension to 90° of flexion and their preferred wrist position ranging from 30° of flexion to 45° of extension. The most common single elbow position that they selected when attaching the brachioradialis to the flexor pollicis longus was 90° of flexion (selected by four of the ten surgeons); however, the majority (six) of the surgeons positioned the elbow between full extension (0° of elbow flexion) and 50° of flexion. When more than one surgeon preferred a particular elbow position (e.g., two surgeons prefer 30° of flexion), those surgeons often preferred different wrist positions. The majority (six) of the ten surgeons reported that their goal was to tension the transfer slightly tighter than its resting tension, with resting tension evaluated in their preferred elbow and wrist positions. Six of the ten surgeons also reported altering their choice of surgical attachment length from patient to patient. The factors that influenced their choice of attachment length for a particular patient included thumb stability, thumb positioning relative to the index finger, the degree of thumb extension or opening, the range of wrist extension available to the patient, and an evaluation of brachioradialis tension in multiple elbow and wrist positions.

The computer simulations suggested that tensioning of the brachioradialis tighter than its resting tension (i.e., choosing an attachment length that is longer than 3.7 ± 0.3 μm when the elbow is extended, the wrist and forearm are in neutral, and the hand is in a lateral pinch posture) tends to produce peak muscle force when the elbow is flexed (Fig. 3). In contrast, the computer simulations suggested that "looser" transfers (i.e., an attachment length that is shorter than 3.7 ± 0.3 μm in these same joint positions) are strongest in more extended elbow positions. The exact elbow position in which peak muscle force occurs postoperatively (i.e., the elbow position in which the restored function will be strongest) depends on the surgical attachment length as well as on the wrist position that the patient uses during postoperative function.

The specific functional results and sarcomere lengths illustrated in Figure 3 are for a given surgical preference concerning the elbow, forearm, wrist, and hand postures of the patient during tensioning; the predicted elbow positions and the chosen sarcomere lengths described above are sensitive to the surgical preference for these joint postures. However, the general results of these simulations extend to the other surgical preferences for elbow and wrist positions that are described in Table I. For any given subset of preferred joint positions, our biomechanical simulations predicted that a brachioradialis transfer with a longer attachment length will produce its peak active force in a more flexed elbow position compared with the elbow position if the same transfer were performed with a shorter attachment length. The preference of surgeons to tension the brachioradialis transfer "slightly tighter" than the resting tension suggests that they are biasing the outcome for a given patient toward peak function in a more flexed elbow posture compared with the position if they chose a "looser" transfer for that patient. Predicting a more specific outcome for a given surgeon or a given patient would require more quantitative assessment of surgical technique. Because the surgeons surveyed in this study preferred such a wide variety of elbow and wrist positions and because the survey results reflect only qualitative assessments of surgical tensioning, no specific conclusions about how surgical outcomes would vary among different surgeons can be drawn from this study.

Discussion

The functional success of tendon transfers is variable, with donor muscles generally losing at least one grade of muscle strength after transfer[28]. The physiological and mechanical basis for the variability in outcomes as well as for the reduction in function postoperatively remains unknown. This study provides evidence that experienced surgeons perform this particular tendon transfer differently from one another. The computer simulation results demonstrate that, on the basis of scientifically established muscle properties (specifically, muscle force is highly dependent on muscle length and joint properties (muscle length changes with joint position), differences in surgical approach reported by surgeons may alter functional outcomes in a quantifiable way. The surgical attachment length and the position of the patient's limb at the time of the tendon transfer are both controllable and measurable parameters. Establishing and understanding the relationship between surgical technique and postoperative muscle function are a priority in order to allow surgeons greater control of clinical outcomes.

As illustrated by the results of our survey of ten surgeons, the decision-making process by which a surgeon "tensions" a muscle is complex. Surgeons often rely on experience and anecdotal information to make these important decisions. Previously, we tested thirty-four hand surgeons with a mechanical device that simulated the "feel" of the brachioradialis muscle and documented substantial variability in the simulated choice of "tension" of the transferred brachioradialis[16]. Neither the surgeon's grip strength nor the number of transfers performed (an index of "experience") was a significant predictor of the choice of tension with the simulator. The results from the survey performed in the current study suggest that at least some of the variability observed in the previous study is intentional—that is, different surgeons choose different attachment lengths because of their distinct intraoperative goals and paradigms (Table I).

We believe that the variability in surgical preferences for tensioning brachioradialis transfers that was documented in this study results from the fact that, currently, there is neither an accepted general theory nor a scientifically established guideline for setting the tension of any tendon transfer. The surgical literature and textbooks support this assertion. For example, a common text devoted to hand surgery[29] states that "setting the proper tension in the transfers [referring to transfers for radial nerve palsy] is a somewhat tricky task but it is very critical to the outcome of the operation. It is difficult to describe precisely how to adjust tension in tendon transfers, and a certain amount of experience is essential in being able to 'feel' the proper tension." Another text[30] states that the tendon transfers should be placed at "normal tension," but "normal tension" is not further defined. An article in the surgical literature recommends "considerable tension."[31] Some articles that discuss surgical technique point out other keys to proper tensioning, with the recommendations focusing not on how the tension "feels" to the surgeon as he or she attaches the tendon, but rather on the postural outcome that is achieved[32]. For example, recommendations for surgical transfers performed to restore opposition to the thumb following median nerve injury provide varying suggestions related to the attitude of the thumb that should be attained after attachment of the transfer[33]. Similarly, in his treatise describing the principles of tendon transfer, Littler advised that the proper tension of a transfer to restore finger flexion should allow the digits to passively extend when the wrist is passively fully flexed, as occurs in the unimpaired hand[33]. Thus, articles and texts describing surgical techniques for many different tendon transfers reflect the results from our survey: the experiential methodologies that are being implemented are based on few standardized or objective criteria, resulting in variability in technique among surgeons.

The current study provides some insight into the influence of the surgical approach with respect to the attachment length of the transferred brachioradialis. A difference in the tensioning preferences of the two surgeons who performed the transfers in this study is demonstrated by the intraoperative data. Specifically, in response to the survey, one of the surgeons stated that his goal was to tension the brachioradialis at "resting tension" (i.e., at about the same length as in situ) in all patients, and the other surgeon stated that his goal was to tension the brachioradialis "much looser" (i.e., shorter than the in situ length) in all patients. The measurements of sarcomere length in this study showed that each surgeon effectively implemented his stated surgical preference. The intraoperative data suggest that the surgeon who prefers to perform a "much looser" transfer would choose a shorter attachment length compared with the surgeon who prefers "resting tension" if these two surgeons performed the transfer in the same patient in the same limb position.

Despite this difference in tensioning preferences, it is important to note that the absolute surgical attachment lengths implemented by the two surgeons overlapped. This is primarily because of the large range of in situ sarcomere lengths observed among the nine limbs in which they were measured both in situ and after tendon transfer and because both surgeons "tensioned" the muscle with use of the resting tension of the in situ brachioradialis as a guide. This finding is supported by the strong correlation between in situ and posttransfer sarcomere length. An alternative tensioning approach would be to use the same surgical attachment length for all subjects, regardless of the in situ sarcomere length. This approach would require intraoperative measurements of either sarcomere lengths or muscle force at different lengths[34,35] to be implemented effectively.

Before altering their current surgical technique, surgeons should consider that the model predictions must first be verified with postoperative assessments of patients. To evaluate the outcomes of their surgical approach within the context of this study, hand surgeons should quantify the pinch force produced in multiple elbow positions following brachioradialis-to-flexor pollicis longus tendon transfers in their patients. We recommend externally stabilizing the elbow during such outcome assessments to reduce confounding effects of weakened elbow extensors on brachioradialis function and measurements of lateral pinch force[2,6]. The question of how brachioradialis transfers should be tensioned in order to provide optimal hand function will be most effectively addressed once such postoperative assessment data are available from multiple surgeons.

While many factors influence surgical outcomes, this study was designed to elucidate the direct effect of intraoperative surgical tensioning on the active force that the transferred brachioradialis produces in isolation from other factors. The computer simulations indicated that a primary effect of surgical tensioning is that a brachioradialis transfer with a longer attachment length produces its peak active force in an elbow position that is more flexed than the elbow position in which the same transfer with a shorter attachment length would produce its peak active force. To derive this conclusion, we made a number of assumptions, including that the transferred brachioradialis is fully and uniformly activated throughout the range of elbow and wrist motion during lateral pinch, patients undergoing a brachioradialis transfer have sufficient elbow extension to stabilize the elbow during hand function, and the cross-sectional area and the length of the transferred brachioradialis are the same as those of the unimpaired, non-transferred muscle. These assumptions should be considered when evaluating the potential clinical impact of this study as discussed below.

Little is known about how effectively transferred muscles are voluntarily controlled, and this remains an important topic for further study. A recent study[2] of eleven subjects treated with a brachioradialis-to-flexor pollicis longus tendon transfer demonstrated that muscle activation was submaximal during lateral pinch, even when subjects were encouraged to produce the maximal pinch force possible. Submaximal activation during lateral pinch was observed both in subjects with weak elbow extensors and in those with strong elbow extensors. On the basis of these new data, we tested the sensitivity of our computer simulations to lower muscle activation. The main finding derived from the original simulations—namely, that a brachioradialis transfer with a longer attachment length produced its peak active force in an elbow position that was more flexed than the position in which the same transfer with a shorter attachment length produced its peak active force—was not sensitive to substantially lower, uniform muscle activation.

The muscle parameters (i.e., optimal fiber length and physiological cross-sectional area) that were used in our model to predict muscle force are generally only available from unimpaired muscles that have not been surgically altered. It is possible that adaptations in muscle structure and force-generating capability may occur with spinal cord injury or secondary to tendon transfer[36]. Rather than predict a specific value for maximum active force, we used the biomechanical simulations to evaluate how the active force produced by the transferred brachioradialis changes in different elbow and wrist postures. As a result, the conclusions of this study are not sensitive to differences in the cross-sectional areas of brachioradialis muscles that may exist between individuals without impairment and patients with spinal cord injuries and tendon transfers. However, if muscle adaptations following a transfer led to substantial change in brachioradialis fiber lengths, the changes in active force with elbow and wrist positions predicted by the model would be affected. Additional study of structural adaptations in muscle following spinal cord injury and tendon transfer is warranted.

Because lateral pinch force (a clinical outcome measure) provides a measure of brachioradialis muscle force following transfer of the brachioradialis to the flexor pollicis longus[37], this study yielded several clinically testable hypotheses. The effect of surgical attachment length on hand function can be fully demonstrated when the intraoperative data described here are paired with postoperative assessments of lateral pinch force in the same patients. Future work in this direction has the potential to form the basis for educating surgeons on the consequences of different surgical techniques and ultimately may improve patient care. ■

NOTE: The authors thank Thor Besier, PhD, for helpful discussions as well as for contributing simulation code that we implemented to calculate muscle force during submaximal activation.

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In support of their research for or preparation of this manuscript, one or more of the authors received grants or outside funding from the Rehabilitation Research and Development Service of the Department of Veterans Affairs (Palo Alto B2785R and San Diego A2626R) and the National Institutes of Health (RO1 HD046774 and RO1 HD048501). None of the authors received payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, educational institution, or other charitable or nonprofit organization with which the authors are affiliated or associated.

doi:10.2106/JBJS.E.00973

References

1. McDowell CL, Moberg EA, House JH. The second international conference on surgical rehabilitation of the upper limb in tetraplegia (quadriplegia). J Hand Surg [Am]. 1986;11:604-8.

2. Johanson ME, Hentz VR, Smaby N, Murray WM. Activation of brachioradialis muscles transferred to restore lateral pinch in tetraplegia. J Hand Surg [Am]. 2006;31:747-53.

3. Lo IK, Turner R, Connolly S, Delaney G, Roth JH. The outcome of tendon transfers for C6-spared quadriplegics. J Hand Surg [Br]. 1998;23:156-61.

4. Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR. Upper-limb surgery for tetraplegia. J Bone Joint Surg Br. 1992;74:873-9.

5. Paul SD, Gellman H, Waters R, Willstein G, Tognella M. Single-stage reconstruction of key pinch and extension of the elbow in tetraplegic patients. J Bone Joint Surg Am. 1994;76:1451-6.

6. Waters R, Moore KR, Graboff SR, Paris K. Brachioradialis to flexor pollicis longus tendon transfer for active lateral pinch in the tetraplegic. J Hand Surg [Am]. 1985;10:385-91.

7. Brys D, Waters RL. Effect of triceps function on the brachioradialis transfer in quadriplegia. J Hand Surg [Am]. 1987;12:237-9.

8. Johanson ME, Valero-Cuevas FJ, Hentz VR. Activation patterns of the thumb muscles during stable and unstable pinch tasks. J Hand Surg [Am]. 2001; 26:698-705.

9. House JH, Comadoll J, Dahl AL. One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. J Hand Surg [Am]. 1992;17:530-8.

10. Gordon AM, Huxley AF, Julian FJ. The variation in isometric tension with sarcomere length in vertebrate muscle fibres. J Physiol. 1966;184:170-92.

11. Herrmann AM, Delp SL. Moment arm and force-generating capacity of extensor carpi ulnaris after transfer to the extensor carpi radialis brevis. J Hand Surg [Am]. 1999;24:1083-90.

12. Lieber RL, Fridén J. Intraoperative measurement and biomechanical modeling of the flexor carpi ulnaris-to-extensor carpi radialis longus tendon transfer. J Biomech Eng. 1997;119:386-91.

13. Murray WM, Bryden AM, Kilgore KL, Keith MW. The influence of elbow position on the range of motion of the wrist following transfer of the brachioradialis to the extensor carpi radialis brevis tendon. J Bone Joint Surg Am. 2002;84:2203-10.

14. Fridén J, Lieber RL. Evidence for muscle attachment at relatively long lengths in tendon transfer surgery. J Hand Surg [Am]. 1998;23:105-10.

15. Fridén J, Ejeskär A, Dahlgren A, Lieber RL. Protection of the deltoid to triceps tendon transfer repair sites. J Hand Surg [Am]. 2000;25:144-9.

16. Lieber RL, Murray WM, Clark DL, Hentz VR, Fridén J. Biomechanical properties of the brachioradialis muscle: Implications for surgical tendon transfer. J Hand Surg [Am]. 2005;30:273-82.

17. Lieber RL, Loren GJ, Fridén J. In vivo measurement of human wrist extensor muscle sarcomere length changes. J Neurophysiol. 1994;71:874-81.

18. Holzbaur KR, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann Biomed Eng. 2005;33:829-40.

19. Smaby N, Johanson ME, Baker B, Kenney DE, Murray WM, Hentz VR. Identification of key pinch forces required to complete functional tasks. J Rehabil Res Dev. 2004;41:215-24.

20. Johanson ME, Murray WM. The unoperated hand: the role of passive forces in hand function after tetraplegia. Hand Clin. 2002;18:391-8.

21. Saul KR, Murray WM, Hentz VR, Delp SL. Biomechanics of the Steindler flexorplasty surgery: a computer simulation study. J Hand Surg [Am]. 2003;28:979-86.

22. Murray WM, Buchanan TS, Delp SL. The isometric functional capacity of muscles that cross the elbow. J Biomech. 2000;33:943-52.

23. Powell PL, Roy RR, Kanim P, Bello MA, Edgerton VR. Predictability of skeletal muscle tension from architectural determinations in guinea pig hindlimbs. J Appl Physiol. 1984;57:1715-21.

24. Fridén J, Albrecht D, Lieber RL. Biomechanical analysis of the brachioradialis as a donor in tendon transfer. Clin Orthop Relat Res. 2001;383:152-61.

25. Zajac FE. Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. Crit Rev Biomed Eng. 1989;17:359-411.

26. Murray WM, Buchanan TS, Delp SL. Scaling of peak moment arms of elbow muscles with upper extremity bone dimensions. J Biomech. 2002;35:19-26.

27. Lateva ZC, McGill KC, Johanson ME. Electrophysiological evidence of adult human skeletal muscle fibres with multiple endplates and polyneuronal innervation. J Physiol. 2002;544:549-65.

28. Gutowski KA, Orenstein HH. Restoration of elbow flexion after brachial plexus injury: the role of nerve and muscle transfers. Plast Reconstr Surg. 2000;106:1348-59.

29. Green DP. Radial nerve palsy. In: Green DP, Hotchkiss RN, Pederson WC, editors. Green's operative hand surgery. 4th ed. New York: Churchill Livingstone; 1999. p 1481-96.

30. Jones NF, Khiabani KT. Tendon transfers in the upper limb. In: Mathes SJ, Hentz VR, editors. Plastic surgery. 2nd ed. Philadelphia: WB Saunders; 2006.

31. Reid RL. Radial nerve palsy. Hand Clin. 1988;4:179-85.

32. Low CK, Pereira BP, Chao VT. Optimum tensioning position for extensor indicis to extensor pollicis longus transfer. Clin Orthop Relat Res. 2001;388:225-32.

33. Littler J. Restoration of power and stability in the partially paralyzed hand. In: Converse JM, editor. Reconstructive plastic surgery: principles and procedures in correction, reconstruction, and transplantation. 2nd ed. Philadelphia: WB Saunders; 1977. p 3266-306.

34. Freehafer AA, Peckham PH, Keith MW. Determination of muscle-tendon unit properties during tendon transfer. J Hand Surg [Am]. 1979;4:331-9.

35. Mendelson LS, Peckham PH, Freehafer AA, Keith MW. Intraoperative assessment of wrist extensor muscle force. J Hand Surg [Am]. 1988;13:832-6.

36. Fridén J, Pontén E, Lieber RL. Effect of muscle tension during tendon transfer on sarcomerogenesis in a rabbit model. J Hand Surg [Am]. 2000;25:138-43.

37. Waters RL, Stark LZ, Gubernick I, Bellman H, Barnes G. Electromyographic analysis of brachioradialis to flexor pollicis longus tendon transfer in quadriplegia. J Hand Surg [Am]. 1990;15:335-9.