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Simultaneous Powering of Forearm Pronation and Key Pinch in Tetraplegia Using a Single Muscle-Tendon Unit

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Summary

The purpose of this study was to provide a clinical evaluation of the concept that both thumb flexion and forearm pronation can be restored by brachioradialis (BR)-to-flexor pollicis longus (FPL) tendon transfer if the BR is passed dorsal to the radius. This may be necessary when a tetraplegic patient requires restoration of key pinch function but has only a single muscle with pronatory effect (BR). Six patients (2 females, 4 males, 32.3 (4.9) (23 – 56) years) underwent tendon transfer of the BR-to-FPL dorsal to the radius and through the interosseus membrane (IOM). The operated upper extremities were categorized according to the International Classification as O1 to OCu3 group. Rehabilitation was divided into two training periods: The first period started on the first postoperative day and focused on early mobilization of the BR-driven forearm pronation/thumb flexion action. The second period included task-oriented training that was introduced 4 weeks after restricted training of motion. Lateral key pinch strength and pronation range of motion (ROM) were measured one year after surgery. A group of 6 patients (2 female, 4 males, 31.2 (5.0) (19 – 52) years) who underwent traditional palmar BR-to-FPL was included for comparison. Active pronation was significantly greater in the dorsal transfer group postoperatively compared to the palmar group (149 (6°) vs. 75 (3°), respectively) when measured from the position of maximal supination to maximal pronation. Increased pronation was accomplished with no loss in pinch strength, as dorsal transfer patients were not significantly weaker compared to those having the traditional tendon transfer (1.28 (0.16) kg vs. 1.20 (0.21) kg, respectively). We conclude that it is both feasible and effective to reconstruct simultaneously, lateral key pinch and forearm pronation using only the brachioradialis (BR) motor in this select subpopulation. To prevent loss in strength and range of motion due to muscle-tendon adhesions to surrounding tissues, the use of early controlled functional training is imperative.

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Keywords

tetraplegia; tendon transfer surgery; thumb flexion; forearm pronation; brachioradialis muscle

Introduction

Tendon transfers are commonly-used to restore lost function after spinal cord injury (Fridén and Lieber, 2002). Choosing donor muscles for tendon transfers requires the surgeon to balance the function gained by the transfer against any morbidity created by harvesting and rerouting a donor muscle. This choice is particularly delicate when only a few potential donors are available. For example, in restoring key pinch for the C5/6 spinal cord-injured patient, the most common donor muscle is the brachioradialis (BR) because of its outstanding excursion (Fridén et al., 2001). Based on a knowledge of the physiological cross-sectional area (PCSA) of the elbow flexors and their moment arms (Murray et al., 2000), it can be calculated that BR harvesting would result in an approximately 20% loss of elbow flexion strength. While this is considered acceptable (Fridén and Lieber, 2002), less attention has been paid to the loss of pronation strength that accompanies the BR-to flexor pollicis longus (FPL) transfer when transferred by the traditional palmar route (Freehafer et al., 1988). This is not a problem in a patient who has sufficient pronator teres (PT) function to pronate the forearm after BR removal but many patients with this level of injury can only pronate using the BR itself. As a result, after BR-to-FPL transfer, they are left in the less desirable condition of requiring gravity-powered pronation or key pinch in a supinated forearm position.

Recently, in an effort to solve the problem of loss of pronation resulting from BR harvest in this subpopulation of patients with no other pronators, we proposed rerouting the BR dorsally around radius and through the interosseus membrane (IOM) to create simultaneous key pinch and forearm pronation (Ward et al., 2006). While this modification was shown in a cadaver model to create a 2-3 mm pronation moment arm and was predicted to create a ~60° increase in pronation range of motion compared to the traditional palmar transfer, it is not clear whether such a rerouting procedure would produce clinically acceptable results. Dorsal routing of the BR could result in functional failure (i.e., loss of pinch strength and pronation) due to (1) restriction of BR amplitude secondary to friction or fibrosis, (2) inability of an individual to activate the BR performing two functions, (3) morbidity resulting from IOM resection, or (4) harming vital structures (e.g., median nerve, interosseus vessels) that could occur during passage through the distal IOM. Therefore, based on the biomechanical promise of this transfer, and addressing its potential limitations, the purpose of this study was to implement the dorsal BR-to-FPL transfer in a cohort of patients in order to increase forearm pronation range of motion without losing key pinch strength.

Materials and Methods

Patients

Six patients (2 females, 4 males, aged 32.3 (4.9) (23 – 56) years) with tetraplegia were selected for the dorsal BR transfer procedure. All were undergoing surgical reconstruction of

key pinch by tendon transfer of the BR-to-FPL. Patients lacked PT function and were classified as O1 to OCu3 according to the International Classification (1976). The mechanism of spinal cord injury was traumatic and due to motor vehicle accident, sport, and diving into shallow water (Table 1). Time between the onset of paralysis and time of operation was 8.8 (8.3) (2 – 32) years (mean (SD), (range)). A comparison group of 6 patients (2 female, 4 males, 31.2 (5.0) (19 – 52) years) who were operated upon using the traditional palmar BR-to-FPL route (Freehafer, 1991) during the same time period (3 years) was included in order to compare pinch strength and pronation ability using two routes of tendon transfer. 2 out of 6 and 3 out of 6 patients demonstrated preoperatively active pronation powered by BR (MRC 1 - 3) in the dorsal and palmar group, respectively. Pronation strength was assessed at the initiation of pronation from the most supinated position of the forearm to avoid the difficulties with the gradual loss of pronation strength as pronation progresses towards and beyond neutral forearm rotation.

Operative technique

The distal BR tendon was exposed and released via a curved incision over the palmar aspect of the radial styloid. Through a separate incision on the dorsal aspect of the BR myotendinous junction, the muscle was extensively released until a minimum 5 cm amplitude was obtained (Fridén et al., 2001). For the dorsal transfer group, the IOM was exposed 5 cm proximal to the proximal border of the pronator quadratus muscle. An incision was made in the IOM, a 1×1 cm² area removed and the hole widened using blunt dissection. Special care was paid to protect the anterior and posterior interosseous vessels and nerves. Using hemostats, BR was routed dorsally, passed through the IOM (Fig. 1) and secured to the FPL tendon using side-to-side running 2-0 Ti-Cron® sutures (Sherwood, Davis & Geck, St. Louis, MO, USA) back and forth and along both sides of the donor tendon (Fig. 2). In order to insure stability and permit immediate mobilization, which is critical when performing transfers through IOM, the overlap between the donor and recipient tendon was 5 cm (Fig. 2, inset) (Brown et al., 2010). For the traditional group (palmar transfer), all procedures were the same with the exception that BR was passed palmar to the radius and secured to FPL. For both techniques, CMC of thumb was always fused to direct the resulting power of BR-FPL transfer into the radial aspect of the index finger at the level of middle phalanx. MCP of the thumb was left free and IP joint tenodeses (FPL – EPL tenodesis to prevent hyperflexion of IP joint after BR – FPL transfer).

BR passive tension was set identically in both groups so that a substantial touch was achieved between the thumb pulp and the proximal interphalangeal joint of the index finger while the elbow was flexed in 90°, the wrist was maintained in 20° of extension and the forearm was fully pronated. After surgery, the reconstruction was protected in a well-moulded plaster splint until training commenced the following day.

Postoperative rehabilitation and evaluation

Patients undergoing dorsal BR transfer underwent the same postoperative regimen as those undergoing traditional palmar BR transfer. The rehabilitation was divided into two training periods: The first period started on the first postoperative day and focused on early mobilization of the BR-driven forearm pronation/thumb flexion action. Task-oriented

training was introduced after 4 weeks of motion restricted by an orthosis in order to parallel the functional training. All patients were evaluated 4 weeks, 3 months, 6 months and one year after the operation.

Apart from the routine clinical evaluation of patients at each time point, a goniometer was used to measure active supination and pronation. Pronation was measured as the total active pronation range of motion from the maximal supination position (start point) to maximal pronation position (end point). Lateral key pinch was measured as the average of 3 voluntary contractions using a Preston pinch gauge (European Bissel Health Care Ltd., Winchester, England). In 2 selected cases, the amplitude of the BR tendon motion through the IOM was visualized by ultrasound during forearm pronation from a fully supinated to maximally pronated position.

Statistical Methods

Pre- and postoperative comparison of range of motion for the dorsal transfer patients was made using the paired Student's t-test. Postoperative comparison of the pinch strength between the two patient populations was made using the unpaired Student's t-test. Significance level (α) was set at 0.05. Statistical power for nonsignificant differences was calculated after the data were acquired using the "G*Power" program (Erdfeider et al., 1996) which is an open access program freely available as described in the reference provided. Data are expressed as mean and standard error of the mean unless otherwise noted.

Results

No significant difference was observed between dorsal transfer patients compared to those having the traditional palmar tendon transfer in terms of pinch strength (Fig. 3). Thus, in spite of the fact that the entire length of the BR was in significant contact with the radius and IOM, the dorsal transfer group pinch strength was only about 10% lower than the traditional transfer group, which was not significant ($p>0.5$).

Active pronation was significantly greater in the dorsal transfer group postoperatively, essentially double compared to the palmar group, from 75° to 149° (Fig. 4; $p<0.0001$). Patients were also able to achieve a more pronated forearm after the dorsal transfer (73 (5°) from neutral forearm rotation) compared to the palmar transfer (-5 (5°); Table 1). Thus, patients who underwent palmar transfer could only complete forearm pronation past neutral by using gravity assistance.

In the dorsal transfer group, the thumb could not be actively flexed without simultaneous pronation of the forearm but the forearm could always be independently pronated providing FPL tendon was slackened i.e., when wrist was passively flexed.

Discussion

This study demonstrated that, in those patients for whom it is indicated, it is both feasible and effective to reconstruct simultaneously, lateral key pinch and forearm pronation using

only the brachioradialis (BR) muscle. Biomechanical measurements previously demonstrated the nearly 60° increase in pronation range of motion using the dorsal transfer route (Ward et al., 2006). However, we were still concerned that, in practice, such a result might not be possible. Potential confounding factors included BR adhesion to the IOM, inability of the patient to retrain the BR for simultaneous pronation and key pinch, or obstruction of this novel transfer route by critical neurovascular structures. However, none of these factors limited application of this biomechanical concept to clinical practice and the dorsally transferred muscle was seen by ultrasound to be mobile in the forearm. This novel transfer now permits surgical reconstruction to be performed on patients who have only a single pronator (BR) without concern for morbidity associated with loss of elbow flexion strength or complications due to BR dysfunction when passed through the IOM.

Review of 318 tetraplegia patients in the Swedish National Registry for Reconstructive Hand Surgery in Tetraplegia revealed that 151 (47%) of the patients belong to the groups OCu 1,2 and 3 without active pronator teres muscle function and, thus, this development appears to affect a relatively large population.

Dorsal BR transfer requires several novel surgical steps compared to traditional palmar routing. First, extensive BR release is particularly important to insure a proper line of action through the IOM (Fig. 1, dotted line). We previously argued that extensive BR release enhances the intrinsic functional properties of this muscle (Fridén et al., 2001). Thus, we view this release step as a positive necessity associated with the surgery. While a separate incision is not necessary to resect a distal portion of the IOM, the proximal skin incision must extend sufficiently ulnar to enable “threading” of the BR through the IOM. Lastly, sufficient resection of the IOM is necessary not only to permit distal BR tendon passage but also to permit the BR muscle belly to extend through the IOM opening that occurs if the elbow or wrist is extended. Thus, we removed a $1 \times 1 \text{ cm}^2$ IOM portion and then extended the opening by blunt dissection to prevent any tethering.

Of course, the primary purpose of this reconstructive procedure is to create lateral key pinch. The idea of using a dorsal BR transfer route, should it compromise key pinch strength, would be unacceptable. Theoretically, such a loss in strength would occur if the muscle-tendon unit was tethered to surrounding tissues, stretched to an unfavorable sarcomere length, or subjected to high frictional force loss. Direct measurement of key pinch strength (Fig. 3) showed no difference in strength between patients who had either the dorsal or traditional palmar transfer. Such a negative result requires power analysis to define the validity of the statement. In designing this experiment, we were willing to accept a loss in strength of about 10% (effect size, δ) believing that the gain in pronation would justify a small strength decrease. This corresponds to a pinch strength difference of 0.13 kg (Fig. 3). Given the experimental variability (σ) of 0.15 kg and our sample size of 12 (Table 1), our experiment has a 81% chance of showing this magnitude of a 10% effect (Erdfelder et al., 1996). In other words, this experiment has a statistical power of 81% to prove that a 0.13 kg pinch strength decrease did not occur. A review of clinical reports in the New England Journal of Medicine considers an 80% statistical power excellent (Freiman et al., 1978).

Surgeons must be aware that rehabilitation after this surgery requires the active participation of the patient and the knowledgeable guidance of a skilled hand therapist. In our unit, the patient, surgeon, and therapist discuss the necessity of early mobilization of the transferred tendon not only to prevent adhesions but to facilitate the motor control patterns necessary for simultaneous key pinch and forearm pronation. Of course early mobilization requires meticulous attention to the tenorrhaphy between the BR and FPL tendons. We require 5 cm of overlap between donor and recipient tendon in conjunction with running sutures back and forth along both sides of the tenorrhaphy (Brown et al., 2010).

An interesting implication of this study is that it challenges current dogma in tendon transfer, namely, the “one muscle-one function” assertion (Brand and Hollister, 1993). In the procedure described here, the BR acts as both a thumb flexor and forearm rotator. The biomechanical reason that a single motor can simultaneously accomplish these two functions is that they are kinematically independent. Specifically, forearm rotation is completely independent of key pinch since the length change associated with forearm rotation (moment arm = 1-3 mm) is almost a negligible fraction of the long fibers of the BR (121 mm) (Fridén et al., 2001). Such mismatches of fiber length and moment arm are rare in the upper extremity, but the fact that even one example can be envisioned should give surgeons caution in making broad general statements about the functionality of muscles in tendon transfer. We encourage the application of muscle architectural and joint kinematic data to creating other novel tendon transfers.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

Intraoperative view of reflected brachioradialis prior to entry into the tunnel formed by resection of a portion of the interosseus membrane. Hemostats are shown traversing the tunnel from distal to proximal, ready to accept the brachioradialis tendon. Black line and gray dotted line shown anticipated path of transferred brachioradialis.

Figure 2.

Intraoperative view of brachioradialis tendon after traversing the tunnel and prior to tenorrhaphy to the flexor pollicis longus tendon. The proximal belly of the brachioradialis can be seen in the upper portion of the picture. Inset shows the brachioradialis tendon secured to the flexor pollicis longus tendon using side-to-side running sutures back and forth and along both of its sides. This method of tendon fixation insures stability and permits early rehabilitation. FCR, flexor carpi radialis tendon.

Figure 3.

Pinch strength measured in patients who received either traditional palmar transfer or the dorsal transfer of the brachioradialis. In spite of the more circuitous route of the palmarly transferred muscle, there was no significant difference in pinch strength between the two groups. Data expressed as mean + SEM.

Figure 4.

Active pronation range of motion (ROM) measured in patients receiving either traditional palmar tendon transfer or the dorsal transfer of the brachioradialis.. There was a significant doubling of active pronation ROM due to the dorsal transfer ($p < 0.0001$). Data expressed as mean + SE.

Table 1

Patient characteristics.

Pat #	Sex	Age at injury	Age at surgery	Level of injury	Cause of injury	Int Class	BR-FPL transfer route	Follow up (yrs)	Forearm pronation MRC Preop	Forearm pronation MRC Postop	Pinch Strength (kg) Postop
1	M	18	30	C5-C6	Dive	OCu3	Dorsal	2.5	2	2	2.0
2	M	20	25	C6	Sports	OCu2	Dorsal	1.0	0	1	1.2
3	M	22	32	C5-C6	Car	OCu3	Dorsal	1.5	2	2	0.8
4	F	15	23	C5-C6	Dive	OCu3	Dorsal	1.5	0	2	1.5
5	M	26	28	C5-C6	Dive	OCu3	Dorsal	1.0	0	2	1.2
6	F	53	56	C5-C6	Car	O1	Dorsal	1.0	0	1	0.5
7	F	30	37	C5-C6	Sports	OCu2	Palmar	1.0	1	1	1.1
8	M	17	20	C5-C6	Sports	O1	Palmar	1.0	0	0	1.0
9	F	20	52	C5-C6	Fall	O2	Palmar	1.0	0	0	1.0
10	M	17	19	C5-C6	Fall	O1	Palmar	1.0	0	0	1.4
11	M	15	29	C5-C6	Motorcycle	OCu2	Palmar	1.5	2	1	2.0
12	M	23	30	C6	Gunshot	OCu3	Palmar	1.0	3	2	1.2