Activation of Brachioradialis Muscles Transferred to Restore Lateral Pinch in Tetraplegia

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Purpose: Surgical transfers of muscles are used to restore lateral pinch in tetraplegia; however, outcomes are variable. The purpose of this study was to compare activation of the brachioradialis (Br) after transfer to the flexor pollicis longus during maximum effort in its primary function (elbow flexion) with maximum effort in its postoperative function (lateral pinch) and to record Br activation during functional tasks.

Methods: Fine-wire electrodes recorded activation of the Br in 11 arms with tetraplegia. Subjects produced maximum lateral pinch force with and without elbow stabilization and were classified according to elbow strength. The elbow was stabilized by supporting the arm and limiting elbow motion. A force sensor mounted on a custom grip recorded the pinch force. Electromyographic (EMG) signals recorded during lateral pinch were expressed as a percentage of the maximum voluntary contraction recorded during maximum-effort elbow flexion.

Results: The EMG activation was significantly lower during lateral pinch compared with resisted elbow flexion. The mean EMG during lateral pinch in the self-supported elbow condition was 34% of the maximum voluntary contraction; with the elbow stabilized the EMG increased to 55% of the maximum voluntary contraction. Postoperative pinch-force magnitude was 14 N with self-support and 20 N with the elbow stabilized. Subjects with weak elbow extension strength produced significantly lower pinch forces compared with subjects with strong elbow extension but had similar ability to activate the Br. The Br activation was higher when the pinch tasks were performed successfully.

Conclusions: These findings suggest a reduced ability to activate the transferred muscle fully in lateral pinch function after surgery, even with the addition of elbow support. The Br activation is linked to successful performance of lateral pinch tasks. The subjects' inability to activate the transferred muscle fully may be affected by postoperative muscle re-education and contribute to postoperative weakness. (J Hand Surg 2006;31A:747–753.

Key words: Electromyography, hand function, pinch force, tendon transfer, tetraplegia.

Surgical transfers of selected muscles are used to restore hand function to individuals with spinal cord injuries that result in tetraplegia. Numerous studies have shown that the brachioradialis (Br) is a suitable muscle to transfer to the tendon of the flexor pollicis longus (FPL) to re-establish lateral pinch strength.[1–6] Before surgery the Br must be able to sustain moderate resistance (muscle grade 4) to expect functional levels of pinch force after surgery.[7] The Br normally does not contract during lateral pinch or closing the hand[8–10] but can be re-educated to become activated during pinch tasks and provide pinch force through the tendon of the FPL.[10]

Despite well-defined patient selection and surgical procedures[11] there is considerable variability in the postoperative outcomes measured by lateral pinch force. Previous studies have reported pinch-force measurements after transfer of the Br to the FPL that range from 4.5–45 N (1 to 10 lb).[1,11,12] One factor that could contribute to differences in lateral pinch strength is the individual's ability to activate the

Table 1. Description of Individual Subject Characteristics

Subject (Arm) ID	Injury Level	Group Classification*	Elbow Extension Strength	Triceps Reconstruction
3	C6-7 complete	5	5	None
8	C4-7 complete	5	5	None
5	C6 complete	Missing	5	None
2	C6-7 incomplete	5	4	None
1	C5-6 incomplete†	Missing	3+	None
9	C5-6 complete	Missing	3+	None
7	C6 incomplete	4	3+	Posterior deltoid to triceps
4	C5-6 incomplete	4	3	None
11/L‡	C6 complete	3	2	Biceps to triceps
10/R‡	C6 complete	2	2	Posterior deltoid to triceps
6	C6 complete	3	1	None (refused)

*The number of muscles below the elbow with Grade 4 strength (see below) that are available for tendon transfer. Missing data are from subjects with surgery dates that predate the classification system, for which muscle testing grades were unavailable. *Extension strength*: elbow extension strength assessed at the time of testing by manual muscle testing criteria (2 = poor, unable to extend against gravity through full range of motion; 3 = fair, able to extend against gravity through full range of motion; 3+ = fair+, able to extend against gravity, full range of motion, minimal resistance; 4 = good, able to extend against gravity, full range of motion, moderate resistance; 5 = normal, able to extend against gravity, full range of motion, maximum resistance). *Triceps reconstruction*: active tendon transfer to restore elbow extension strength.
†Subject had a spinal lesion secondary to tuberculosis and was classified as C5-6 incomplete injury level.
‡Same subject.

transferred Br muscle in its new function. After transfer the Br muscle's function is to produce lateral pinch but it also continues to flex the elbow. Waters et al[1] found a relationship between pinch and triceps strength and reasoned that the Br required an antagonist to enable it to contract maximally without causing excessive elbow or wrist flexion. This result was supported in a separate study[5] that showed that patients with weak elbow extension can improve pinch strength if the elbow is immobilized in an orthosis. Neither of these studies recorded muscle activation of the transferred Br but their findings indicate that the ability to activate the transferred Br is linked to elbow extension strength.[1,5] Because many lateral pinch tasks do not require maximum effort[13] some reduction in the activation level of the Br may not affect function adversely.

The purpose of this study was to compare the activation of a surgically transferred Br during maximum effort in elbow flexion with its activation during maximum effort in its posttransfer function (lateral pinch). Because of the previous work that has shown increased pinch force with external elbow support, we evaluated Br activation with and without external elbow stabilization and compared the results among subjects with different levels of elbow extension strength. An additional objective of the study was to ascertain if the postoperative activation level of the transferred Br was related to the ability to perform lateral pinch tasks.

Materials and Methods

Subjects

Muscle activation, lateral pinch force, and the ability to complete a set of functional tasks requiring lateral pinch force were quantified in 10 individuals (11 arms) with cervical-level spinal cord injury and a Br-to-FPL tendon transfer. Each subject signed a consent form approved by the local institutional review board that included Health Information Portability and Accountability Act consent. The average length of time since surgery was 10.1 years (SD, 9 y; range, 1–23 y). The subjects included 8 men and 2 women with a mean age of 52 years (SD, 7 y; range, 42–65 y). Spinal cord injury level ranged between C4 and C7. The subjects were categorized in groups 2 through 5 of the international classification for tetraplegia, indicating that there were between 2 and 5 muscles below the elbow with at least grade 4 strength.[7,14] Three of the subjects' arms did not have preoperative elbow extension strength and a surgical procedure to restore elbow extension strength was performed (Table 1).

The subjects were classified as having weak or strong elbow extension strength using manual muscle testing grades[14] at the time of testing. Muscle testing grades in the fair range (≤3+) were classified as weak because of the inability to maintain elbow extension against moderate resistance. Elbow extension was classified as strong if the muscle test grade was good to normal (≥4) because of the ability to

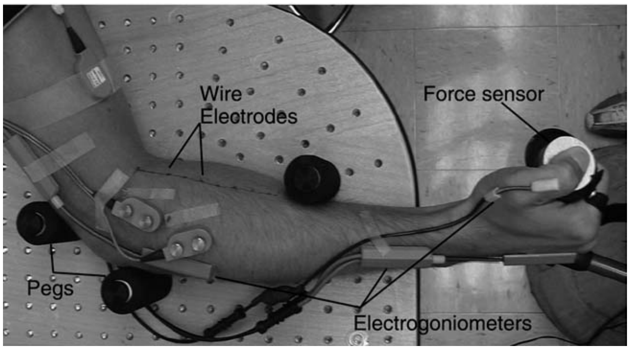

Figure 1. Top view of the experimental setup. The subject's arm is resting at shoulder height on the shelf with adjustable pegs that limit elbow position (showing the externally supported condition). The location of the Br is marked on the subject's forearm and the electrode insertion sites are identified. The force sensor is mounted to a custom grip the subject is holding. Electrogoniometers record the position of the elbow, wrist, and metacarpophalangeal joint of the thumb.

sustain elbow extension against moderate resistance (Table 1). By using this classification system 4 of the arms tested had strong elbow extension (grades 4, 5) and 7 had weak elbow extension (grades 1–3+).

Equipment

The subjects were seated in their wheelchairs with the arm supported in abduction at shoulder height (Fig. 1). To record muscle activation, sterile, paired, fine-wire electrodes were inserted into the Br muscle and their placement was confirmed with mild electrical stimulation through the wires. Surface electrodes (Motion Lab Systems, Baton Rouge, LA) also were placed over the biceps and triceps muscle groups. Electrogoniometers (Biometrics Ltd., Ladysmith, VA) were attached to record elbow, wrist, and thumb positions during the performance of the test activities. The position data were used to evaluate the elbow position in the unsupported conditions and to describe the functional tasks so that the electromyographic (EMG) sample representing the subjects' attempts to perform the task could be identified.

The pinch force was recorded with a 6-axis force sensor mounted to a custom grip (ATI Industrial Automation, Apex, NC). The force perpendicular to the force sensor (z direction) was used to quantify the magnitude of the pinch force. The force sensor was positioned between the subject's thumb and index finger and the fingers were flexed around the grip. A flexible mechanical linkage (MicroScribe digitizer; Immersion, San Jose, CA) for recording position in space was attached to the force sensor grip and corrected the output for forces attributed to changes in orientation of the sensor with respect to gravity. The force sensor consists of a tool plate and a mounting plate fixed to each other through a strain gage instrumented structure. If the sensor orientation changes, the force of gravity on the mass of the tool plate changes the force readings on the sensor on the order of 0.1–0.3 N. The design of the grip enabled subjects to hold the sensor in the most natural wrist and forearm posture without affecting the pinch-force magnitude. The EMG, force, and position data were collected using a data acquisition interface (LabVIEW; National Instruments, Austin, TX).

Testing Protocol

Each subject performed a maximum voluntary contraction (MVC) of resisted elbow flexion in a functional elbow position (≈60° of elbow flexion). This trial recorded the activation level of the Br during maximum effort in its original function (elbow flexion). The EMG data were quantified for the 0.5-second sample with the greatest activity. In subsequent trials the subjects were instructed to produce their maximum lateral pinch force during the middle 5 seconds of a 10-second trial by using visual feedback from the force sensor. The EMG signal was quantified during the .5-second sample that occurred when the maximum pinch force was produced. A 1-minute rest period was maintained between each trial to minimize fatigue.

In the lateral pinch trials the elbow position was maintained in 60° of elbow flexion. These trials were repeated with and without external elbow support. For the externally stabilized trials the arm and forearm were supported using a shelf with adjustable pegs to limit elbow movement (Fig. 1). The shelf was positioned at shoulder height and limited flexion or extension of the elbow beyond 60° of flexion. This permitted maximum activation of the transferred Br that was not limited by the need to control the elbow position. With the elbow self-supported subjects were expected to maintain an elbow position of 60° while producing the maximum pinch force possible. During these trials the subjects lifted the arm from the shelf and the pegs were removed (Fig. 1). Each subject performed 2 to 3 trials in both elbow conditions and the trial with the highest pinch force was used for analysis.

Each subject was presented with 12 functional tasks that required a range of lateral pinch strength. The tasks included using a key, an automated teller machine card, electrical plug, fork, and remote-con-

Table 2. Description of Functional Tasks

Task	Description	Thickness (mm)*	Force Required (Newtons)†
Fork in	Four-tine fork, into Air Putty (North Coast Medical, Inc., Morgan Hill, CA), medium, soft	2.0	10.4
Key in/out	Standard key in and out of an entrance lock	2.4	6.2 in/5.0 out
Plug in/out	Three-prong plug, into wall outlet	22.9	31.4 in/23.6 out
Open/close vertical zipper	5-mm closure width, 2 cm zipper tab	1.6	3.5 open/6.9 close
Open/close horizontal zipper	8-mm closure width, 1.5 cm zipper tab	1.8	9.3 open/18.4 close
ATM in/out	Standard card into (actual) ATM mechanical device	0.7	8.9 in/6.8 out
Remote button pressed	Doorbell remote, button diameter 13.6 mm	22.0	1.4

ATM, automated teller machine.
*Thickness refers to the thickness of the object used in the task.
†The force requirements for each task were measured in a previous study.[13]

trol button and opening and closing zippers. The forces required to perform each task were quantified in a previous study[13] and ranged from 1.4 to 31 N. The tasks and device specifications are described in Table 2. The position data identified each subject's attempt to perform each task and the EMG data that were recorded during the attempt were quantified. Data from 1 subject were not included because the tasks were not performed correctly; 1 subject attempted only 5 tasks and another subject attempted 11 tasks. The subjects (11 arms) attempted a total of 112 tasks (5 + 11 + 96 = 112 tasks).

Data Analysis

The EMG, force, and electrogoniometer data were sampled at 2,000 Hz and raw data were reviewed for signal quality. Custom software calculated the root-mean-square value of the EMG signal for quantification. The quantified EMG signal recorded during maximum lateral pinch effort and during the performance of the pinch tasks was expressed as a percentage of the MVC during resisted elbow flexion and was used for statistical analysis (described later).

Nonparametric Wilcoxon signed-rank tests were used to determine if there were significant differences ($p \leq .05$) in Br activation during maximum elbow flexion compared with maximum pinch. For this pairwise test the Br activation level during resisted elbow flexion was assigned a value of 1.0 (ie, representing 100% activation) and then compared with the activation level recorded during pinch, expressed as a percentage of 1.0 (ie, % MVC). The Wilcoxon signed-rank test also was used to test for differences in Br activation and pinch force between the 2 elbow conditions (self-supported vs externally supported). Mann-Whitney *U* tests (for unequal samples) were used to determine if triceps strength had an effect on the Br activation or the pinch-force magnitude in each elbow condition. The activation level of the transferred Br during the performance of the lateral pinch tasks was evaluated with descriptive statistics (mean and standard error). The EMG signals were plotted for all of the tasks completed successfully against all of the tasks that the subjects attempted but failed to perform.

Results

The activation level of the transferred Br was significantly lower ($p \leq .05$) during maximum-effort lateral pinch compared with maximum-effort elbow flexion. This was true regardless of elbow support for all subjects. Overall, without considering the effects of elbow support or elbow extension strength the Br activation during pinch was 45% (SD, 25%) of that recorded during elbow flexion.

Externally supporting the elbow significantly ($p \leq .05$) increased the Br activation compared with the self-supported elbow condition (Fig. 2A). The mean difference in Br EMG level between the 2 elbow conditions (externally supported − self supported) was 21%, ranging from -6% to 55%. Two of the arms tested

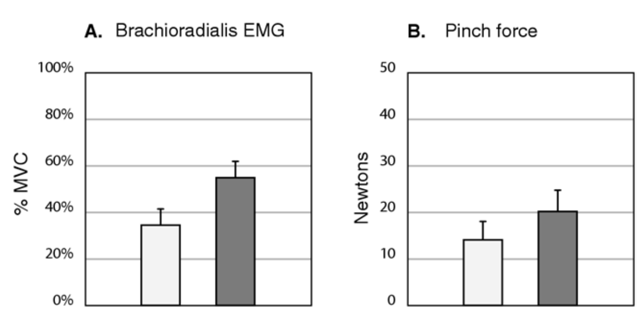

Figure 2. (A) Mean Br EMG and (B) pinch force recorded during maximum pinch effort in the self-supported (□) and externally supported (■) elbow conditions.

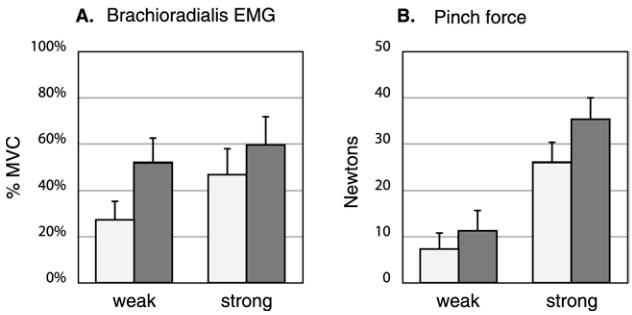

Figure 3. (A) Mean Br EMG and (B) pinch-force magnitude for subjects with weak and strong elbow extension strength. ☐, self-supported elbow condition; ■, with external elbow support recorded during maximum-effort pinch.

did not have an increase in Br EMG with external support; both of these subjects were in the weak elbow extension strength group. There was also a significant ($p \leq .05$) increase in lateral pinch force in the supported elbow condition across all subjects (Fig. 2B). The mean difference in pinch force (externally supported − self-supported) was 6 N and ranged from 0.2 N to 14 N.

When the subjects were classified according to elbow extension strength subjects with both weak and strong elbow extension strength increased lateral pinch force and Br activation with the addition of external elbow support (Fig. 3). It is notable that even the subjects with strong triceps strength increased Br activation and pinch force with the elbow externally supported. There were significant differences, however, between the weak and the strong groups. The subjects with strong triceps ($n = 4$) had significantly higher pinch-force magnitude compared with the subjects with weak triceps ($n = 7$), independent of elbow support ($p \leq 05$); however, the normalized Br activation level was not significantly higher for the subjects with strong elbow extension. Thus the higher pinch force observed in the subjects with strong elbow extension was not associated with a higher Br activation level.

On average the Br had a higher activation level when the functional tasks were performed successfully (Fig. 4). Of the 112 tasks attempted 73 were performed successfully. Performance of the pinch tasks required a range of pinch force and this was reflected in the range of EMG values (% MVC) observed across the tasks. Fifty-six of the tasks that were performed successfully were completed with less than 34% of maximum Br activation. The subjects responsible for the failed tasks all were in the group with weak triceps (except for 1 subject in the strong triceps group who was unable to insert or remove the plug).

Discussion

The postoperative activation of the Br was reduced in its role of providing active lateral pinch force compared with its primary function of flexing the elbow. The marked reduction in postoperative activation of the Br in the presence of external elbow support was

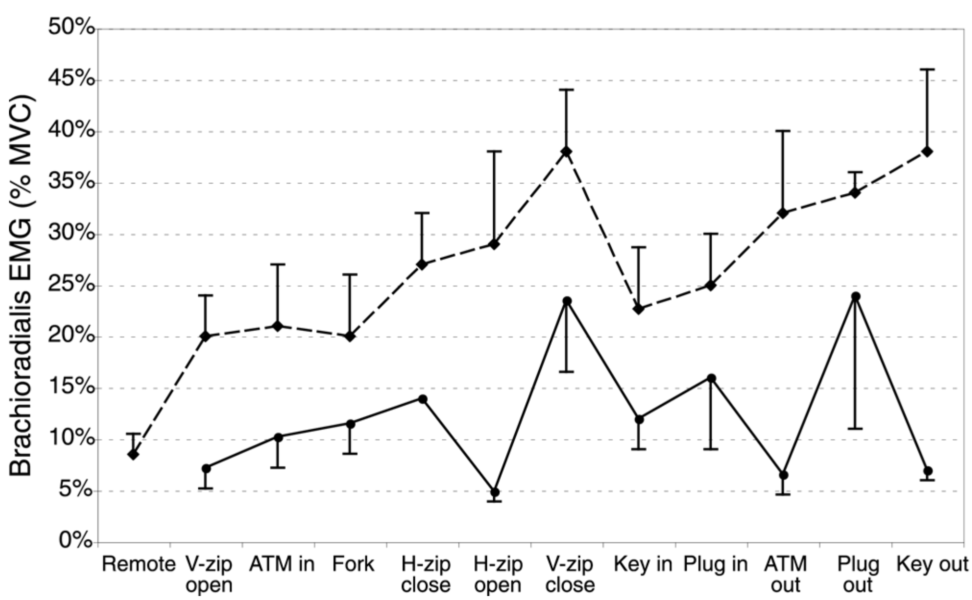

Figure 4. The EMG recorded during the performance of functional tasks described in Table 2. For each task the mean Br EMG (% MVC) is plotted for the subjects who were able to perform the task successfully (----) and for those who could not perform the task (—). Pushing the remote button was performed successfully by all of the subjects. The error bars extend in 1 direction only to make the plot easier to read. v-zip, vertical zipper task; h-zip, horizontal zipper task.

unexpected. We anticipated that the addition of external elbow support would reveal each subject's ability to activate the Br fully, independent of differences in elbow extension strength. Although the Br activation during pinch effort improved significantly with external bracing of the elbow, on average it did not exceed 55% of that recorded during elbow flexion (Fig 2A). Previous studies[1,5] that reported that bracing the elbow improved pinch-force measurements in patients with weak elbow extension strength did not record the postoperative activation level of the Br. The data presented here indicate that after surgery the Br should be capable of increasing its activation level during lateral pinch to at least the same level recorded during elbow flexion.

In the present study the subjects with a weak triceps also had a weak Br, as evidenced by low pinch forces. Specifically, when external support was added to the elbow the activation of the Br increased but the pinch-force magnitude did not reach a level comparable with that of the subjects with strong triceps. All subjects with weak elbow extension strength also had weak pinch forces, and the elbow position was the same for all testing conditions. Therefore it is not likely that the weak pinch forces were a result of variability in the force-length properties of the transferred Br imposed by either surgical tensioning or testing at different muscle lengths. Similar activation levels but reduced force instead may be a result of changes in the force-generating capacity of motor units, which still are under voluntary control in spinal cord injury, as shown by Thomas et al.[15] They found that some motor units had a normal EMG potential but did not contribute to twitch force under certain conditions. This is consistent with disuse atrophy, in which the muscle still is under voluntary control but the muscle fibers decrease in size and force production diminishes. The Br may have become weak after the transfer in the presence of a weak triceps because functional use of the arm was limited. In that case the Br may not be used in its role as a thumb flexor, resulting in progressive weakness.

It is clear from this and other studies that the ability to self-stabilize the elbow enhances the outcome of a Br-to-FPL transfer. At the time of testing only 4 of the 11 arms in this study had grade 4 strength or better. A previous study[16] showed that only 26% of individuals with spinal cord injuries at or above C7 had adequate voluntary strength to work against gravity. For this reason we recommend to our patients that they have surgery to improve elbow extension either before or in conjunction with a Br-to-FPL transfer. We believe that the optimal sequence is triceps reconstruction, either by deltoid-to-triceps or biceps-to-triceps transfer, followed sometime later by a Br-to-FPL transfer, and we advise our patients that combining these procedures may downgrade the outcome of both somewhat. We often combine these procedures at a patient's request, however, because we understand that the markedly greater emotional impact of 2 surgical procedures and the associated periods of increased dependence are a great obstacle for these patients.

Brachioradialis activation was related to successful performance of pinch tasks in this study. Under normal circumstances activities of daily living do not require maximum pinch effort. The tasks chosen for this study required less than 31 N of force to perform successfully and 8 tasks required less than 10 N of force. The subjects who were able to perform the tasks successfully did not require maximum-level activation of the Br to produce the pinch force required for the task. For those subjects who failed to perform the task one contributing factor was the inability to activate the Br to the same level as those subjects who successfully performed the task (Fig 4). Lower activation during a functional task may be caused by the increased demand of coordinating a variety of proximal joint positions and securing a small narrow object (such as the zipper tab, key, or fork) compared with the force sensor and grip used to record maximum pinch. Because most of the failed tasks (37 of 39) were attempted by subjects in the weak triceps group, it is important to consider weak pinch force as another factor that contributed to failed task performance. The relationship between activation and pinch-force magnitude requires further investigation.

Lower activation and postoperative weakness of the Br contributed to the differences in lateral pinch performance observed in this study. The difficulty in predicting postoperative pinch-force strength may be improved if it is possible to differentiate muscle strength from muscle activation deficits. All of the subjects had the potential to activate the Br to a higher level (indicated by the activation observed during elbow flexion) but were unable to do so in lateral pinch. A greater understanding of the factors that affect the ability to activate the transferred Br will help identify rehabilitation goals to improve functional pinch strength and reduce variability in surgical outcome.

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References

1. 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 1985;10A:385–391.
2. House JH. Reconstruction of the thumb in tetraplegia following spinal cord injury. Clin Orthop 1985;195:117–128.
3. House JH, Gwathmey FW, Lundsgaard DK. Restoration of strong grasp and lateral pinch in tetraplegia due to cervical spinal cord injury. J Hand Surg 1976;1:152–159.
4. Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR. Upper-limb surgery for tetraplegia. J Bone Joint Surg 1992;74B:873–879.
5. Brys D, Waters RL. Effect of triceps function on the brachioradialis transfer in quadriplegia. J Hand Surg 1987;12A: 237–239.
6. 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 1994;76A: 1451–1456.
7. Keith MW, Lacey SH. Surgical rehabilitation of the tetraplegic upper extremity. J Neurol Rehab 1991;5:75–87.
8. Freehafer AA, Peckham PH, Keith MW, Mendelson LS. The brachioradialis: anatomy, properties, and value for tendon transfer in the tetraplegic. J Hand Surg 1988;13A: 99–104.
9. Johanson ME, Skinner SR, Lamoreux LW. Phasic relationships of the intrinsic and extrinsic thumb musculature. Clin Orthop 1996;322:120–130.
10. 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 1990;15A:335–339.
11. Hentz VR. Surgical strategy: matching the patient with the procedure. Hand Clin 2002;18:503–518.
12. House JH, Comadoll J, Dahl AL. One-stage key pinch and release with thumb carpal-metacarpal fusion in tetraplegia. J Hand Surg 1992;17A:530–538.
13. Smaby N, Johanson ME, Baker B, Kenny DE, Murray WM, Hentz VR. Identification of key pinch forces required to complete functional tasks. J Rehabil Res Dev 2004;41:215–224.
14. Kendall HO, Kendall FP, Wadsworth GE.Muscles testing and function.Baltimore, MD: Williams and Wilkins, 1971: 66–73.
15. Thomas CK, Broton JG, Calancie B. Motor unit forces and recruitment patterns after cervical spinal cord injury. Muscle Nerve 1997;20:212–220.
16. Thomas CK, Zaidner EY, Calancie B, Broton JG, Bigland-Ritchie BR. Muscle weakness, paralysis, and atrophy after human cervical spinal cord injury. Exp Neurol 1997;148: 414–423.