Comparison of Wrist and Elbow Stabilization Following Pinch Reconstruction in Tetraplegia

M. Elise Johanson, DPT, Wendy M. Murray, PhD, Vincent R. Hentz, MD

Purpose Individuals with spinal cord injuries resulting in tetraplegia may receive tendon transfer surgery to restore grasp and pinch function. These procedures often involve rerouting the brachioradialis (Br) and the extensor carpi radialis longus tendons volar to the flexion-extension axis of the wrist, leaving the extensor carpi radialis brevis (ECRB) muscle to provide wrist extension strength. The purpose of this study was to determine whether externally stabilizing the wrist after transfer procedures would improve the ability to activate the transferred Br and resulting pinch force, similar to the effect observed when the elbow is externally stabilized.

Methods We used a one-way repeated-measures study design to determine the effect of 3 support conditions on muscle activation and lateral pinch force magnitude in 8 individuals with tetraplegia and previous tendon transfer surgeries. Muscle activation was recorded from Br and ECRB with intramuscular electrodes and from biceps and triceps muscles with surface electrodes. We quantified pinch strength with a 6-axis force sensor and custom grip. We recorded measurements in 3 support conditions: with the arm self-stabilized, with elbow stabilization, and with elbow and wrist stabilization. Pairwise differences were tested using Wilcoxon signed-rank tests.

Results Maximum effort pinch force magnitude and Br activation were significantly increased in both supported conditions compared with the self-supported trials. The addition of wrist stabilization had no significant effect compared with elbow stabilization alone.

Conclusions A strong ECRB has adequate strength to extend the wrist, even after multiple transfers that contribute an additional flexion moment from strong activation of donor muscles. Anatomical and functional differences between the wrist and elbow musculature are important determinants for self-stabilizing joints proximal to the tendon transfer. The ability to increase Br activation and resulting pinch force may be determined, in part, by the individual's ability to develop new coordination strategies. *(J Hand Surg 2011;36A:480–485. Copyright © 2011 by the American Society for Surgery of the Hand. All rights reserved.)*

Type of study/level of evidence Therapeutic IV.

Key words Electromyography, lateral pinch, spinal cord injury, tendon transfer, tetraplegia.

From the VA Palo Alto Health Care System, Rehabilitation Research and Development Center, Palo Alto, CA; the Departments of Biomedical Engineering and Physical Medicine and Rehabilitation, Northwestern University, Evanston; and the Edward Hines Jr. VA Hospital, Hines, IL.

The authors thank Neils Smaby, PhD, for important contributions to the laboratory and data collection; the subjects who contributed their time and interest; as well as the Spinal Cord Injury Services at the VA Palo Alto Health Care System, Palo Alto, CA, and the Santa Clara Valley Medical Center, San Jose, CA.

Received for publication June 30, 2010; accepted in revised form November 3, 2010.

Supported by the Department of Veterans Affairs, Rehabilitation Research and Development Service, Project A3741R.

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

Corresponding author: M. Elise Johanson, DPT, VA Palo Alto Health Care System, Rehabilitation Research and Development Center, 3801 Miranda Ave/153, Palo Alto, CA 94304; e-mail: johanson@va51.stanford.edu.

0363-5023/11/36A03-0017$36.00/0
doi:10.1016/j.jhsa.2010.11.006

CERVICAL SPINAL CORD INJURY (tetraplegia) is a debilitating and costly condition in which quality of life is greatly reduced because of impaired hand function.[1–3] In selected patients, tendon transfer surgeries can restore grasp and pinch strength. Individuals with spinal cord injury at or below the sixth cervical level (C6) often have residual motor strength in several muscles that perform the same function. In this patient group, the brachioradialis (Br; an accessory elbow flexor) may be transferred to the paralyzed flexor pollicis longus (FPL) to restore pinch strength. Similarly, the extensor carpi radialis longus (ECRL; one of the 2 primary wrist extensors) may be transferred to the paralyzed flexor digitorum profundus (FDP) to restore grip strength.[4] However, restored grip[5] and pinch forces are variable,[6,7] even for individuals with similar injury levels; for some, they may not be adequate to perform functional tasks.[8]

Numerous studies have demonstrated that after Br to FPL transfer,[6,9] postoperative pinch force can be limited if the elbow cannot be stabilized. In a previous study,[10] we reported that subjects who retained some active triceps function (grade 4/5) were able to generate greater pinch force than subjects with weak elbow extension (26 ± 8.6 N vs 7 ± 9.8 N, respectively). When external elbow support was added in our cohort of subjects, pinch force levels could be increased in both groups (those with weak and strong elbow extension strength). An unexpected finding was that the Br activation only increased to 55% (±24%) of the activation level recorded in resisted elbow flexion. Thus, the transferred Br is capable of notably greater postoperative activation, and if achieved, it would be expected to lead to stronger pinch force levels.

Based on our findings of increased Br activation with elbow stabilization, we hypothesized that subjects who had ECRL to FDP, Br to FPL, or both transfers might improve the ability to activate the Br in the presence of added wrist stabilization. Because of their anatomic relationship to the elbow flexion-extension axis and to their postoperative relocation volar to the wrist flexion-extension axis, both the Br and ECRL exert a flexion moment at the wrist as well as the elbow. Thus, during forceful pinch and grip, both transfers are activated, and external stabilization of the wrist may facilitate the patient's ability to increase the activation level of the Br and corresponding pinch strength.

To test this hypothesis, we externally stabilized the wrist in addition to the elbow while subjects produced their maximum effort pinch force. We expected that the addition of wrist and elbow support would result in greater Br activation, and thus greater pinch force, compared with the activation level produced with elbow support alone, or when neither the elbow nor the wrist was supported.

MATERIALS AND METHODS

We quantified muscle activation and lateral pinch force magnitude in 8 individuals with cervical spinal cord injury and previous tendon transfer surgeries. Each subject signed a consent form approved by the local institutional review board that included Health Information Portability and Accountability Act consent. The subjects produced their maximum effort pinch force with the arm self-supported (SS), with external elbow support (ES), and with both the elbow and the wrist supported (E+W). Using fine-wire or surface electrodes, we recorded activation of the transferred Br, nontransferred ECRB, biceps, and triceps muscles simultaneously with pinch force.

Subject characteristics

Subjects included 7 men and one woman with a mean age of 46 years (range, 30–55 y). Their levels of injury included C6-8, (one C4-7 level) with 7 complete and 1 incomplete injury. All subjects had previous tendon transfer surgeries: 8 of 8 had transfer of the Br to FPL and 7 of 8 also had transfer of ECRL to FDP. The mean time since surgery was 7 years (SD, 8 y). As a part of the clinical evaluation at the time of surgery, each subject was classified using the International Classification of Muscle Function in Tetraplegia[11] according to the number of voluntarily controllable muscles below the elbow with at least grade 4 strength (the ability to move through the full range of motion and maintain against resistance from the examiner).[12] A chart review showed that subjects were stratified in groups 2 through 5 at the time of surgery—that is, with 2 to 5 muscles under voluntary control with adequate strength available for transfer. At the time of postoperative testing, we assessed elbow extension strength as grade 4 or 5, except in 2 subjects. One subject with biceps to triceps transfer had residual weakness (grade 3), and another subject who declined reconstruction had absent elbow extension strength. Wrist extension strength was graded 4 or 5 for all subjects.

Equipment

Subjects were seated in wheelchairs with the arm supported in abduction at or below shoulder level (Fig. 1) on a height-adjustable table. The tabletop was designed with stops (padded pegs) that could be positioned to limit elbow motion and maintain selected positions for each subject. A wall-

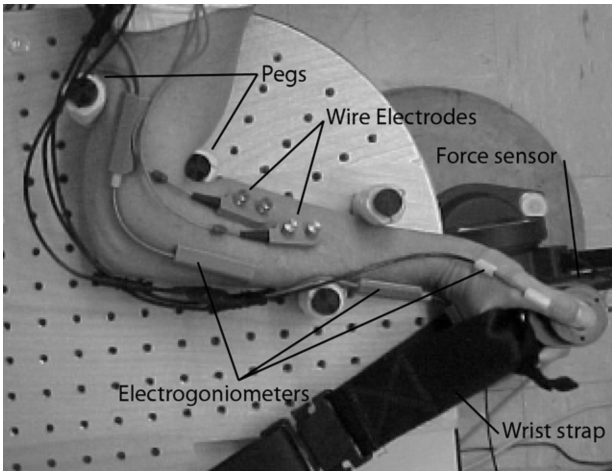

FIGURE 1: Top view of the experimental setup. The subject's arm is resting at shoulder height in the E+W supported condition. The pegs are positioned to limit elbow flexion and a wrist strap limits wrist flexion. The length of the wall-mounted wrist strap can be adjusted to match the wrist position each subject chose in the SS and ES trials. Shortening the strap results in greater wrist extension. The wire electrodes located in the Br and ECRB are instrumented for recording EMG signals (surface electrodes are not pictured). Electrogoniometers record the position of the elbow, wrist, and metacarpophalangeal joint of the thumb.

mounted strap was added to limit wrist flexion for the E+W supported conditions.

To record muscle activation, we inserted sterile, paired fine-wire electrodes into the Br and ECRB muscles and confirmed their placement with mild electrical stimulation through the wires. Surface electrodes were also placed over the biceps and triceps muscle groups of the same arm (Motion Lab Systems, Baton Rouge, LA). We applied electrogoniometers with double-sided tape and calibrated them to record elbow, wrist, and thumb position during performance of the test activities (Biometrics Ltd., Ladysmith, VA). The position data were used to evaluate the elbow position in the unsupported conditions and the wrist position in all trials.

We recorded pinch force with a 6-axis force sensor mounted to a custom grip (ATI Industrial Automation, Apex, NC). The force that was applied perpendicular to the surface of 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 for recording position in space (MicroScribe digitizer; Immersion, San Jose, CA) was attached to the force sensor grip. We corrected the output for forces attributed to changes in orientation of the sensor with respect to gravity. 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; this design has been described previously.[10] We collected electromyographic (EMG), force, and position data using a LabVIEW data acquisition interface (National Instruments, Austin, TX).

Testing protocol

The recording procedures were explained, and the custom grip was adjusted to fit each subject's hand. Before recording the pinch force trials, each subject performed a maximum voluntary contraction (MVC) of resisted elbow flexion. This trial recorded the activation level of the Br during maximum effort in its original function (elbow flexion) as well as for the biceps. Similarly, an MVC trial for the ECRB was recorded by resisting maximum effort wrist extension and for the triceps in resisted elbow extension. We recorded the MVC trials in standard muscle testing positions.[12] We quantified EMG signals for the 0.5-second sample with the greatest activity and used them to normalize muscle activation. In subsequent trials, subjects were instructed to produce the maximum lateral pinch force. The subjects had visual feedback from the force sensor during a 10-second trial. The EMG signal was quantified during the 0.5-second sample that occurred when the maximum pinch force was produced. A 1-minute rest period was maintained between each trial to prevent fatigue.

In the lateral pinch trials, the elbow was maintained in 60° of flexion either by the subject (SS) or by the adjustable stops on the tabletop (ES, E+W). For the ES trials, the arm and forearm were supported on the table and the stops were adjusted to limit elbow movement (Fig. 1). This permitted maximum activation of the transferred Br that was not influenced by the subject's need to control the elbow position. For the E+W trials, a strap was added to limit wrist flexion during pinch. The wall-mounted strap fit in the palm of the hand, and the length of the strap was adjusted to allow the subject to assume the self-selected wrist posture during pinch force production. The self-selected wrist position was important to maintain a consistent posture for comparison with the self-supported and elbow-supported conditions; in our experience, it is critical in this patient population for maximum performance. In the SS condition, the subject was expected to maintain an elbow position of 60° while producing the maximum pinch force possible. During these trials, each subject lifted the arm from the shelf and the pegs were removed. The order of support conditions was randomized. Each subject performed 2 to 3 trials in the 3 support conditions,

TABLE 1. Pinch Force Compared Across Support Conditions

Condition	Self-Supported (N)	Elbow Supported (N)	Elbow Plus Wrist Supported (N)
All subjects (N = 8)	27.1 (29.2)	34.8 (29.3)	38.9 (32.2)
Weak elbow extension strength (n = 2)	2.4 (1.0)	14.4 (7.9)	21.9 (20.3)
Strong elbow extension strength (n = 6)	35.3 (29.5)	41.6 (31.1)	44.1 (35.1)

Pinch force in Newtons was compared across support conditions for all subjects. Differences between individuals with weak and strong elbow extension strength are described but not tested for significance owing to sample size. Standard deviations are in parentheses.

and the trial with the highest pinch force was used for analysis.

Data analysis

We sampled the EMG, force, and electrogoniometer data at 2,000 Hz and reviewed raw data for signal quality. Custom software calculated the root-mean-square value of the EMG signals for quantification. The quantified EMG signal recorded during maximum lateral pinch effort was expressed as a percentage of the MVC trials for each muscle and used for statistical analysis.

We used Friedman's 2-way analysis of variance by ranks (χ_r^2) to determine significant differences across support conditions for pinch force and muscle activation ($p \leq .05$). This test is designated as a 2-way analysis based on the interpretation that subjects are an independent variable in this repeated-measures design; it is an alternative to the parametric one-way repeated-measures analysis of variance (F).[13] For significant tests, 3 pairwise comparisons were done using Wilcoxon signed-rank tests and the alpha level was adjusted ($p \leq .02$) to reduce the possibility of a type I error.

RESULTS

Pinch force magnitude during maximum effort pinch was significantly increased in both supported conditions, compared with the self-supported condition ($p \leq .02$). When pinch force with elbow support was compared with pinch force with elbow and wrist support, the mean difference in pinch strength was not significant (Table 1). The subjects with weak (n = 2) versus strong (n = 6) elbow extension strength had lower pinch force outcomes and a greater response to elbow stabilization.

As expected, the normalized Br activation was significantly higher ($p \leq .02$) with the elbow externally stabilized compared with the self-supported condition (Fig. 2). However, the added wrist support did not result in a significant increase in Br activation during pinch effort. None of the subjects were able to activate the Br during pinch to the same level recorded during resisted elbow flexion, even with both the wrist and elbow stabilized. Only 4 trials in supported conditions had Br activation between 70% and 80% MVC.

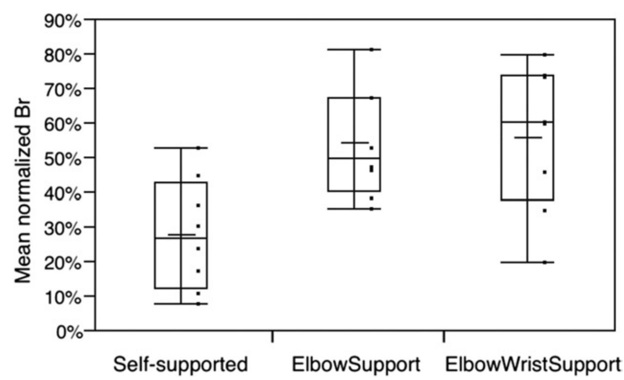

FIGURE 2: The boxplots show the 3 distributions of Br activation for each support condition during pinch effort. The Br activation is expressed as % of MVC. The upper and lower margins of the box indicate the interquartile range, demarcating the 25th and 75th percentiles. The centerline of the box is the median score, and the centerline of the distribution is the mean score for the group. The outer bars (whiskers) indicate the ranges of Br activation at each end of the distribution.

The activation levels of the other muscles studied (the nontransferred biceps, triceps, and ECRB) were not significantly different across support conditions, but exhibited a coordinated pattern of activation (Fig. 3). On average, the ECRB and the triceps (antagonists to the transferred Br and ECRL during pinch) had activity ranging from 38% to 61% of their MVC levels. The biceps EMG was relatively lower, ranging from 26% to 27% of MVC level. Only the transferred Br exhibited significantly greater activity (independent of the biceps synergist) in the supported conditions compared with self-supported trials.

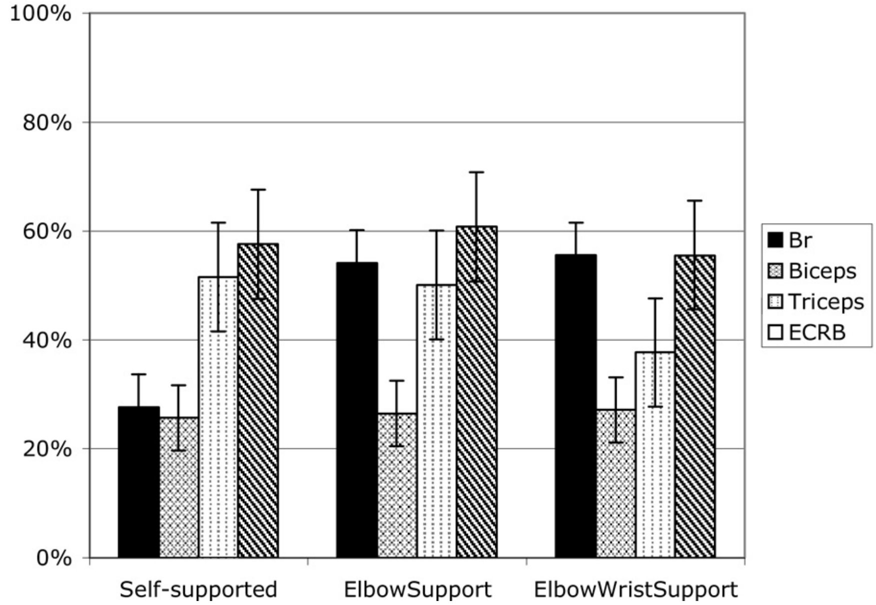

FIGURE 3: Comparison of muscle coordination patterns across conditions. The mean (normalized) activation is shown for all 4 muscles during maximum pinch force production in each support condition.

TABLE 2. Mean Degree of Wrist Extension in Each Support Condition

Condition	Self-Supported	Elbow Support	Wrist Plus Elbow Support
Wrist extension	33° (21°)	42° (20°)	47° (18°)

One subject maintained a wrist position close to neutral when the wrist was free (wrist posture flexed 7° with elbow support and extended 6° in self-supported conditions). Standard deviations are in parentheses.

In all of the SS and ES trials, subjects actively extended the wrist during pinch. Only 1 subject maintained a wrist position close to neutral when the wrist was unconstrained. The degree of wrist extension chosen by each subject in the self-supported condition was matched as well as possible for the E+W trials by adjusting the length of the strap supporting the wrist in extension (Table 2).

DISCUSSION

Supporting the wrist during maximum pinch effort did not significantly improve subjects' ability to increase the activation level of the transferred brachioradialis muscle or to produce greater pinch strength. This indicates that in these subjects, the nontransferred ECRB has adequate strength to stabilize the wrist even after multiple tendon transfers to restore grasp (ECRL transfer to FDP) and pinch (Br transfer to FPL). Both of these procedures transfer the tendon of the muscle volar to the flexion-extension axis of the wrist and contribute an additional wrist flexion moment when the donor muscles are activated. Thus, on clinical assessment, a grade 4 ECRB seems to provide sufficient antagonist power to keep the wrist from falling into flexion during strong pinch and grasp.

We anticipated that by providing additional wrist stabilization, there would be a significant gain in pinch force and activation of the Br, similar to what has been reported after stabilizing the elbow. In this and previous studies, even subjects with strong elbow extension strength were able to improve their pinch force production when they were not required to self-stabilize the elbow. Because most lateral pinch tasks require less than 31 N of pinch force,[8] those individuals with weak elbow extension strength are most likely to experience noteworthy functional gains if wrist and elbow stabilization can be achieved by surgical intervention or targeted rehabilitation. Outcome measures that identify patients' self-perceived performance and satisfaction with grasp and pinch function would be useful in future studies to assess the benefits of smaller gains in the ability to produce pinch force.

Anatomical and functional differences between the wrist and elbow likely contribute to the different outcomes in response to stabilization of joints proximal to the tendon transfer. When either of the 2 transferred muscles is activated to produce force during lateral pinch or grip, they simultaneously generate both an elbow flexion torque and a wrist flexion torque. The elbow flexion moment arm of the Br (~5.5 cm at 60° elbow flexion[14]) is over 3 times larger than the moment arm of the FPL about the wrist (~1.5 cm between 30° and 50° wrist extension)[15]). Similarly, the elbow flexion moment arm of ECRL (~2.0 cm at 60° elbow flexion)[14] is on the order of 2 times larger than the moment arm of the FDP about the wrist (~0.9 cm between 30° and 50° wrist extension).[15] Thus, the moment arms of these muscles suggest that the actions of the transferred muscles at the elbow are substantially larger than at the wrist.

In addition, the balance of agonist and antagonist strength is different for the wrist and elbow in this patient population (spinal cord injury injury level C-5). The elbow flexors, synergistic to the transferred Br, retain function and can generate a substantial elbow flexion torque if activated during hand function. Elbow extension strength needed to balance the flexion torque at the elbow must be supplied by the triceps muscle group, which is often weak[16] or has been surgically restored in this patient population and may not have normal strength. Variability in elbow extension strength will compromise the ability to fully activate the transferred muscles in strong pinch or grasp. In contrast, the wrist and finger flexor muscles are most often paralyzed or functionally weak. Consequently, the wrist flexion torque produced by the weakened wrist flexors is minimal and can be easily balanced by a strong ECRB. Thus, its torque-generating characteristics[17] and preoperative function continue to make ECRB the surgical choice[18] for stabilizing the wrist, even after multiple tendon transfers.

One important determinant of postoperative pinch force is how effectively the patient can activate the transferred Br during pinch effort in a variety of functional postures. The supported trials in the present study create an artificial situation in which the subject can increase Br activation by flexing the elbow against the stops on the table, thus improving the resulting pinch force. This ability to change the level of activity demonstrates the potential for increased activation of the transferred Br postoperatively. In this study, the Br activation was highest when the elbow was supported, thus emphasizing the need for proximal joint stability and elbow extension strength. However, even subjects with strong elbow extension strength experienced a reduction in Br activation and pinch strength in the self-supported condition. One reason for this may be the postoperative muscle coordination between flexor and extensor muscle groups or between the Br and other elbow flexor synergists is inadequate to facilitate maximum Br activation in self-supported postures. Additional studies are needed to determine whether muscle re-education or biomechanical constraints are limiting factors to an individual's ability to improve grasp and pinch strength after tendon transfer.

REFERENCES

1. Connolly SJ, Aubut JL, Teasell R, Jarus T, Team SR. Enhancing upper extremity function with reconstructive surgery in persons with tetraplegia: a review of the literature. Top Spinal Cord Inj Rehabil 2007;13:58–80.
2. Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. J Neurotrauma 2004;21:1371–1383.
3. Snoek GJ, IJzerman MJ, Hermens HJ, Maxwell D, Biering-Sorensen F. Survey of the needs of patients with spinal cord injury: impact and priority for improvement in hand function in tetraplegics. Spinal Cord 2004;42:526–532.
4. Hentz VR. Surgical strategy: matching the patient with the procedure. Hand Clin 2002;18:503–518.
5. Lo IK, Turner R, Connolly S, Delaney G, Roth JH. The outcome of tendon transfers for C6-spared quadriplegics. J Hand Surg 1998;23B: 156–161.
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 1985;10A:385–391.
7. 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.
8. 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;41:215–224.
9. Brys D, Waters RL. Effect of triceps function on the brachioradialis transfer in quadriplegia. J Hand Surg 1987;12A:237–239.
10. Johanson ME, Hentz VR, Smaby N, Murray WM. Activation of brachioradialis muscles transferred to restore lateral pinch in tetraplegia. J Hand Surg 2006;31A:747–753.
11. McDowell CL, Moberg EA, Smith AG. International conference on surgical rehabilitation of the upper limb in tetraplegia. J Hand Surg 1979;4:387–390.
12. Kendall HO, Kendall FP, Wadsworth GE. Muscles testing and function. Baltimore: Williams and Wilkins, 1971:66–73.
13. Portney LG, Watkins MP. Foundations of clinical research. Applications to practice. 3rd ed. Upper Saddle River, NJ: Prentice Hall, 2009:517–519
14. 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.
15. Holzbaur KR, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann Biomed Eng 2005;33:829–840.
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.
17. Lieber RL, Ljung BO, Friden J. Intraoperative sarcomere length measurements reveal differential design of human wrist extensor muscles. J Exp Biol 1997;200:19–25.
18. Hentz VR, Leclercq C. Surgical rehabilitation of the upper limb in tetraplegia. London: WB Saunders, 2002:93–94.