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Restoration of elbow extension via functional electrical stimulation in individuals with tetraplegia

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Abstract—Functional electrical stimulation of the triceps is a method of restoring elbow extension to individuals with paralyzed triceps. Eleven arms of individuals with cervical-level spinal cord injuries (SCIs) received a triceps electrode as an addition to a hand-grasp neuroprosthesis. Stimulation was controlled either as part of a preprogrammed pattern or via a switch or an accelerometer that was connected to the neuroprosthesis external controller. The outcome measures were (1) elbow extension moments at different elbow positions, (2) performance in controllable workspace experiments, and (3) comparison to an alternative method of providing elbow extension in these individuals—a posterior deltoid (PD) to triceps tendon transfer. Stimulated elbow extension moments in 11 arms ranged from 0.8 to 13.3 N•m. The stimulated elbow extension moments varied with elbow angle in a manner consistent with the length-tension properties of the triceps. Triceps stimulation provided a significantly stronger elbow extension moment than the PD to triceps tendon transfer. The elbow extension moment generated by the tendon transfer and triceps electrode being activated together was always greater than either method used separately. Stimulation of the long head of the triceps should be avoided in persons with weak shoulder abduction, since the long head adducts the shoulder and limits shoulder function in these cases. Statistically, elbow extension neuroprostheses significantly increased the ability to successfully reach and move an object and significantly decreased the time required to acquire an object while reaching.

Key words: elbow extension, electrical stimulation, neuroprosthesis, spinal cord injury, tendon transfers, tetraplegia.

INTRODUCTION

Individuals with tetraplegia at the C5 or C6 level typically have some voluntarily controlled elbow flexor muscles and a paralyzed triceps muscle, preventing voluntary elbow extension against gravity. The lack of voluntary elbow extension limits their ability to reach overhead or push objects away, reducing their functional workspace. Tendon transfers, orthoses, and functional electrical stimulation (FES) are interventions that have been used to

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Abbreviations: ANOVA = analysis of variance, CWRU = Case Western Reserve University, EMG = electromyogram, EMT = elbow moment transducer, FES = functional electrical stimulation, SCI = spinal cord injury, VA = Department of Veterans Affairs.

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address this problem. In the tendon transfers typically used to provide elbow extension, the distal tendons of either the posterior deltoid or biceps muscles are transferred to the triceps muscle [1–6]. While tendon transfers have the advantage of being always available, they require an accessible voluntary muscle that has sufficient strength and they require the recipient to learn a new muscle activation pattern. Mechanical orthoses that provide passive elbow extension typically have poor cosmesis and difficult donning and doffing procedures [7–9].

FES systems activate the triceps with electrical stimuli, either through surface electrodes [10], percutaneous electrodes [11–15], or implanted electrodes [16,17]. Individuals who are candidates for triceps stimulation generally are already receiving a hand-grasp neuroprosthesis [18]. For these people, control of elbow extension can be achieved via a single channel of stimulation. In eight-channel Food and Drug Administration (FDA)-approved Freehand™ neuroprostheses (NeuroControl Corporation, Cleveland, Ohio), the cutaneous channel can be diverted to stimulate the triceps.

The feasibility of an elbow extension neuroprosthesis has been demonstrated previously in two individuals [16]. The data presented in this paper are a continuation of the previous study, with a larger population of individuals (10, including 1 bilateral user) who had elbow extension function restored via FES.

METHODS

Subjects

We evaluated 11 triceps electrodes in 10 upper-limb neuroprosthesis users (including one bilateral user) in this study (see the **Table**). Two additional triceps electrode recipients were unavailable for follow-up. Either epimysial or intramuscular electrodes were implanted on the triceps [19]. Standard stimulation exercise regimens were followed postsurgery [16]. Five of the eleven users received the FreeHand™ neuroprosthesis. The other six users received the neuroprosthesis as part of the Cleveland FES Center research program. The spinal cord injury (SCI) levels ranged from weak C5 (O:0 in the International Classification [20]) to strong C6 (OCu:2). Six of the eleven arms also had a tendon transfer to aid in elbow extension (either the posterior deltoid or biceps muscle tendon was transferred to the triceps). Except where otherwise identified, stimulated triceps strength was measured with the individual at rest so that the strength of the voluntarily controlled tendon transfer did not affect the results.

We also compared elbow extension strength measurements for 16 arms (12 individuals with SCI) that had received a posterior deltoid to triceps tendon transfer (see the **Table**). These 16 arms included 4 arms that also had received a triceps electrode.

Control Methods

Elbow extension neuroprostheses have been implemented with three techniques in our laboratory [16,17]. In all cases, control of elbow angle was attained by flexing the biceps against the constantly stimulated triceps, which we refer to as "Voluntary Antagonist Control." One technique uses an augmented external controller (**Figure 1**), which has a switch that allows the user to activate the triceps independently of hand grasp. When the switch is pressed, triceps stimulation ramps up to a preprogrammed level and remains constant until the switch is pressed again, then the triceps stimulation ramps down and turns off.

A second technique uses an accelerometer mounted on the upper arm that senses the orientation of the arm in the gravitational field. This accelerometer connects to the augmented external controller. When the arm is elevated above a threshold angle, the triceps stimulation ramps up to a preprogrammed level and remains constant until the arm elevation decreases below a second threshold angle. The second threshold angle is slightly less than the initial threshold angle to allow for hysteresis that prevents arm oscillations, which could occur if a single threshold angle was used.

With the third technique (which uses an unmodified external controller), the triceps electrode is programmed as part of the hand-grasp stimulation control pattern. The triceps typically remains on at a constant level throughout the grasp pattern. In the FreeHand™ external controller, there are only two grasp patterns (one lateral, one palmar) and triceps is programmed in each one. In the Cleveland FES Center external controller, four grasp patterns were programmed, allowing the user to select a lateral grasp with or without the triceps activated, or the palmar grasp with or without the triceps activated.

Strength Measurements

We measured elbow moments generated by the stimulated triceps or via the transferred posterior deltoid

Table.
Arms with triceps electrodes and/or posterior deltoid to triceps tendon transfer listed from most impaired to least impaired. Last column indicates which tests were performed with each subject.

Subject	Arm	Gender	ASIA	International Classification	Surgery Date	Time Postsurgery When First Tested (mo)	Tests Performed*
Triceps Electrode Only							
A	Left	Male	C5	O:0	10/97	3	A, B
G	Left	Male	C5	O:0	3/98	12	A, B
B (R)	Right	Male	C5	O:1	3/97	4	A, B, C
H	Left	Male	C5	O:1	4/00	3	A, B
E	Right	Male	C5	OCu:1	4/97	6	A, B, C
B (L)	Left	Male	C6	OCu:2	9/97	11	A, B, C
Triceps Electrode and PD Tendon Transfer							
J	Left	Female	C5	O:1	3/01	6	A, B, D
F	Right	Male	C6	O:1	10/98	8	A
I (R)	Right	Male	C6	O:2	5/96 (PD) 8/00 (FES)	60 (PD) 1 (FES)	A, B, D
C	Right	Male	C6	OCu:2	7/96	4 (FES) 24 (PD)	A, B, C, D
D	Right	Male	C6	OCu:2	9/93 (PD) 9/97 (FES)	86 (PD) 6 (FES)	A, B, C, D
PD Tendon Transfer Only							
L (L)	Left	Female	C5	O:1	3/94	80	B
L (R)	Right	Female	C5	O:1	3/94	81	B
R	Left	Male	C5	O:1	3/95	73	B
P	Right	Male	C5	O:1	9/00	4	B
K (L)	Left	Male	C5	OCu:1	1/96	58	B
Q	Left	Male	C6	O:2	12/98	27	B
K (R)	Right	Male	C6	OCu:2	1/96	58	B
I (L)	Left	Male	C6	O:3	5/96	60	B
M	Left	Male	C6	OCu:3	7/99	17	B
N	Right	Female	C6	OCu:3	6/00	6	B
O (L)	Left	Female	C6	OCu:3	5/00	7	B
O (R)	Right	Female	C6	OCu:3	5/00	7	B

ASIA = American Spinal Injury Association (standards for neurological and functional classification of spinal cord injury)
L = left
R = right
*Tests:
A = moment at 90°
B = moment versus angle
C = workspace
D = posterior deltoid (PD) transfer and triceps stimulation

either with a custom elbow moment transducer (EMT) or a six-axis force/moment transducer [21]. Elbow moment measurements were made at three or four elbow angles (30°, 60°, 90°, and 120° elbow flexion), with at least three trials done at each angle. The shoulder was positioned at 90° abduction and 0° horizontal adduction (so that the upper arm was horizontal and the elbow was in line with both acromions). Only the triceps electrode was activated during the triceps stimulation trials, and the triceps stimulation was set to the stimulus level that was used functionally. For each trial, the stimulation was turned on for 3 s followed by a 30 s rest period. During the posterior deltoid transfer trials, the individual was asked to maximally extend the elbow for 3 s. The triceps

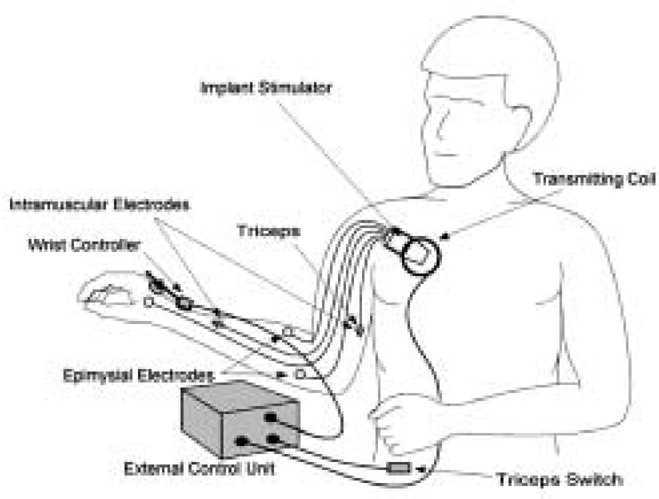

Figure 1.
Augmented hand-grasp neuroprosthesis.

stimulation was off during these trials. In four of the five individuals who had both a triceps electrode and a posterior deltoid tendon transfer, elbow strength was measured during triceps stimulation, during voluntary activation of the transferred muscle, and by both activated together.

A potential drawback of placing an electrode on the long head of the triceps, which crosses the shoulder, is that it can produce a shoulder adduction moment that may limit a subject's ability to reach if he or she had weak shoulder abductor muscles. In the neuroprosthesis users with weak C5 (O:0) tetraplegia (who are more likely to have weak shoulder abductor muscles), the six-axis transducer was used to simultaneously measure elbow and shoulder moments produced by triceps stimulation.

Workspace Assessment

We assessed the effect of triceps stimulation on the controllable workspace by having individuals reach, grasp, and move an instrumented book-like object from a "high" location or orientation to a "low" location or orientation [16,22]. Preliminary experiments in the earlier study indicated that the differences in performance were more prominent at the higher locations [16]. Three near and three far locations were used (**Figure 2**). Each location was approximately 32 cm higher than the subject's acromion. The three far locations (D, E, and F in **Figure 2**) were at a fixed radius from the acromion that was slightly less than arm's length. Location E was aligned with a sagittal plane through the shoulder, while locations D and F were 45° to either side. The three near locations (A, B, and C in **Figure 2**) were aligned with the subject's wheelchair armrests, with A and C placed at the end of the armrests and B centered between the armrests. Trials were done with the instrumented book either horizontal or vertical and with the triceps stimulation on or off. Each location, orientation, and stimulation combination had eight trials. Individuals who had elbow extension tendon transfers were free to use the transferred muscles during all the trials. The hand-grasp stimulation was also on in every trial, so differences in performance can be attributed to the triceps stimulation alone. We compared the success rates and acquisition times with and without triceps stimulation. A trial was considered successful if the book was acquired, moved, and released without being dropped or knocked over. Force and orientation sensors on the instrumented book and contact switches at the targets were used to time events during the trials. The acquisition time was defined as the time from the initial contact of the hand on the book and the point where the book was removed from the platform, sensed by the contact switch.

RESULTS

Of the 11 arms with triceps electrodes that we evaluated, the 5 FreeHand™ system users had only one option for control—the triceps was programmed at a constant level in both grasp patterns. The users who were implanted as part of our research program could choose among the three control signals described earlier (switch with the augmented controller, accelerometer with the

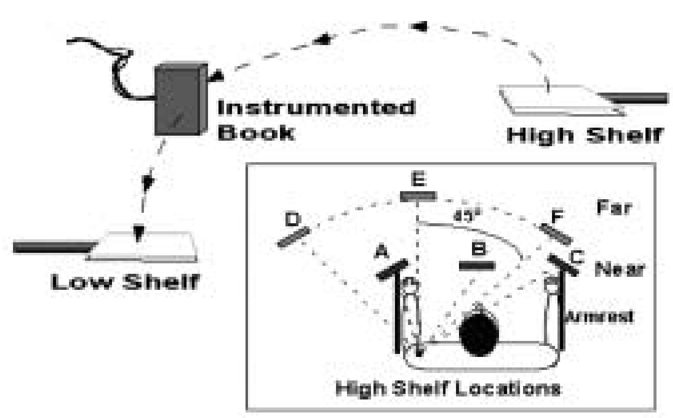

Figure 2.
Object positions for workspace assessments. Six high shelf locations are shown in inset (A to C = near; D to F = far). Low shelf location was always under location B.

augmented controller, or programmed patterns with the standard controller). For five of these six arms, the users chose to activate the triceps by using the programmed patterns method. One user would alternate between the switch method and the programmed patterns method. No one preferred to use the accelerometer because of a reluctance to don an external device and cable on the arm. Also, the augmented external controller was larger and heavier than the standard controller. This had a negative effect on the desirability of both the accelerometer and switch methods.

The average stimulated elbow extension moment for the 11 arms (with the elbow at 90° flexion) ranged from 0.8 to 13.3 N•m (**Figure 3**), with a median value of 4.2 N•m. The variation in elbow moment across subjects was significantly greater than the variation within subjects (analysis of variance [ANOVA], $p < 0.001$). The elbow extension strength produced by triceps stimulation did not correlate with impairment level. Of the 11 arms, 8 could extend against gravity with triceps stimulation. Only 1 of the 11 arms could extend against gravity without triceps stimulation, including the 6 arms that had tendon transfers. The individual who could extend against gravity without triceps stimulation was able to do so by self-triggering a spasm that resulted in triceps activation.

We tested the elbow moment generated by triceps stimulation at different elbow angles in 10 of the 11 arms. Overall, the elbow moment was usually weakest with the elbow in the more extended position (30° flexion) and peaked with the elbow flexed at 90° (**Figure 4**). This difference in stimulated elbow moment at different elbow angles was statistically significant (ANOVA, $p < 0.001$).

The elbow extension moment produced by subjects with a posterior deltoid tendon transfer ranged from 0 to 11.2 N•m. The variation in average elbow moment at different elbow angles is shown in **Figure 4**. This variation was not statistically significant. The elbow moment generated by triceps stimulation at 90° and 120° elbow flexion was significantly greater than the elbow moment produced by the posterior deltoid tendon transfer (ANOVA, $p < 0.05$). There was no statistically significant difference in elbow moment between the two elbow extension methods at 30° elbow flexion.

The average elbow extension moments at different elbow angles for the four subjects who had both a triceps electrode and a posterior deltoid tendon transfer are shown in **Figure 5**. In all cases, activating the triceps stimulation and the posterior deltoid together provided a greater elbow moment than either of the methods alone. This difference was significant at each of the elbow positions (ANOVA, $p < 0.05$), except for at 90°, where no significant difference was found between the combined elbow moment and the elbow moment because of triceps stimulation alone. In several trials in which both methods were used simultaneously, the resulting elbow moment was greater than the additive sum of the moment from triceps stimulation and the tendon transfer activated separately.

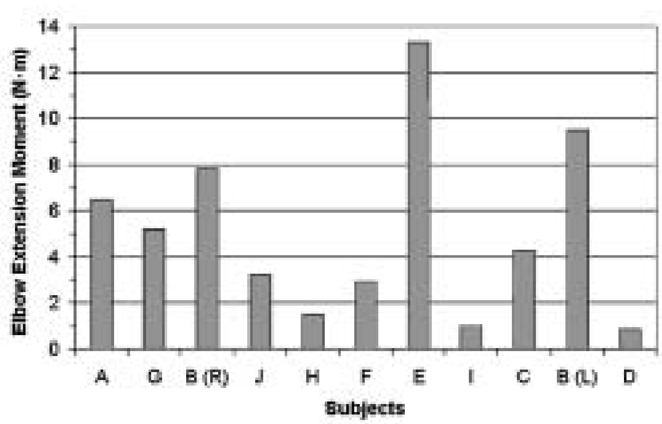

Figure 3.
Average stimulated elbow extension moment at 90° elbow flexion listed from most impaired subjects to least impaired subjects (see **Table**). Measurements were made with shoulder at 90° abduction and 0° horizontal adduction.

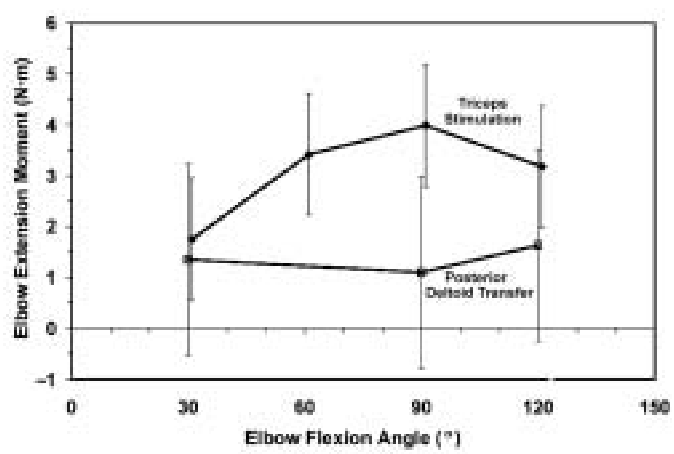

Figure 4.
Average elbow extension moment at different elbow flexion angles produced by triceps stimulation and by posterior deltoid to triceps tendon transfer. Error bars are 95% confidence limits. Triceps stimulation data are horizontally shifted by one unit to allow error bars to be seen more clearly.

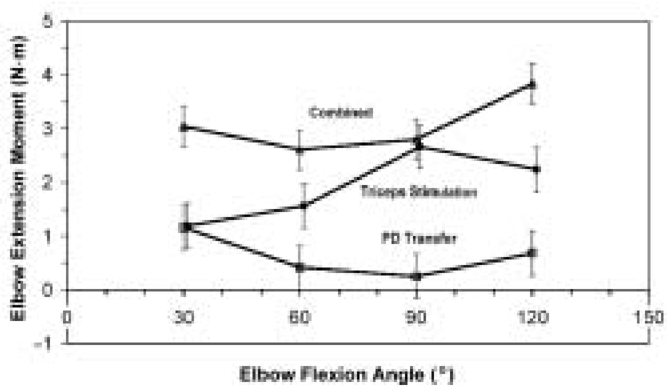

Figure 5.
Average elbow extension moments for four persons who had both a triceps electrode and a posterior deltoid to triceps tendon transfer. Measurements were made of elbow moments produced by triceps stimulation and tendon transfer activated separately and together, at different elbow flexion angles. Error bars are 95% confidence limits. Triceps stimulation data are horizontally shifted by one unit to allow error bars to be seen more clearly.

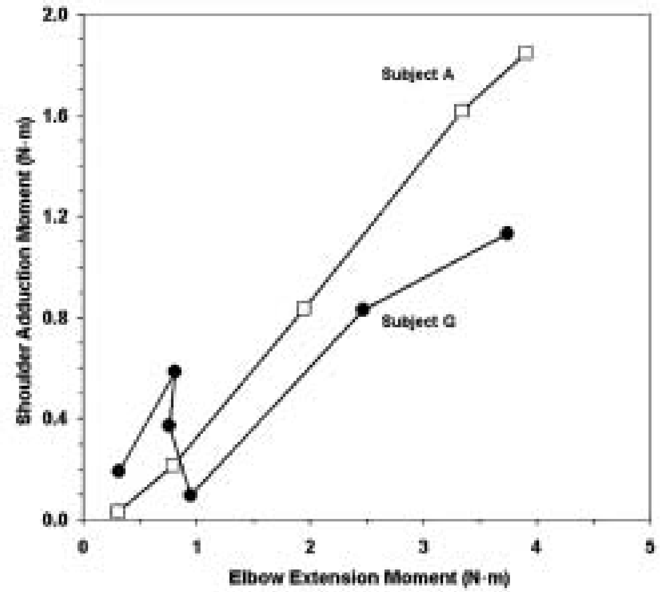

Figure 6.
Coupling of elbow extension and shoulder adduction moments for two subjects with weak C5 (O:0) injuries.

Measurements of shoulder adduction moments and elbow extension moments generated during triceps stimulation were made for two of the more impaired subjects (subjects A and G, **Table**). Shoulder adduction was coupled to elbow extension in both subjects (**Figure 6**), although it only affected subject A functionally. Subject A's partially denervated deltoid muscle would fatigue quickly, making it difficult to oppose the shoulder adduction moment produced by stimulation of the long head of the triceps. Subject G also had partial denervation of the deltoid but was able to consistently abduct his arm during triceps stimulation.

The quantitative workspace assessment was performed on five arms (**Figure 7**). In all five arms, trials were more successful with the triceps stimulation than without the triceps stimulation (**Figure 7(a)**). The improvement in success rates varied from 15 percent (63% success with stimulation versus 48% success without stimulation) to 61 percent (97% success with stimulation versus 36% success without stimulation). This increase in success rate was significant statistically for each subject (chi-square test, $p < 0.05$). Success rates were improved for all subjects at both the far and near locations. Success rates were also improved for all subjects when the book was oriented vertically. When the book was oriented horizontally, success rates improved for three of the subjects. One subject had a slightly higher success rate without stimulation when the book was horizontal (79% to 75%). One subject was unable to perform the task when the book was horizontal (with or without triceps stimulation) because of limitations in his hand grasp.

Average acquisition times with the triceps stimulation were less than without the triceps stimulation for four of the five arms (**Figure 7(b)**). The improvement in average acquisition time ranged from 3.2 s to 6.4 s in the four subjects showing improvement. This decrease in acquisition time was significant in three of the arms (unpaired t-test, $p < 0.01$) and was not significant for one arm (subject B (R), $p = 0.076$). Average acquisition time increased for one subject (D) by 2.9 s. This increase in acquisition time was significant ($p < 0.05$). The changes in acquisition time were consistent for both the far and near locations and for both the horizontal and vertical book orientations.

DISCUSSION

The placement of an electrode on the triceps has become a common option for upper-limb neuroprostheses. Of the 148 upper-limb neuroprostheses (based on the Case Western Reserve University [CWRU]/Department of Veterans Affairs [VA] design) implanted in the United States

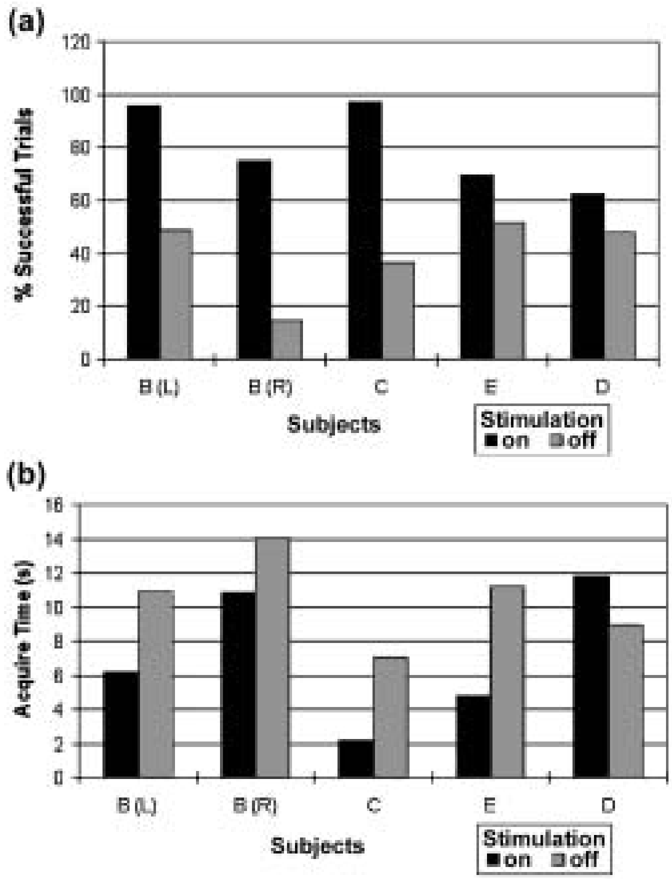

Figure 7.
(a) Successful completions and **(b)** acquisition times for quantitative workspace assessments on five arms.

as of April 2001 [23], 39 have included an electrode on the triceps [24].

The choice of a control signal source for triceps activation was influenced by practical issues such as the weight and size of the augmented external controller and the addition of more external cables. The participants who had a choice of control sources usually opted to forego the flexibility in triceps activation provided by the switch and accelerometer control signals in favor of the reduced weight, size, and number of cables of the standard external controller. The preferred control signal may change with the development of new external controllers that are significantly smaller and lighter. External cables may continue to be an issue, though.

Voluntary Antagonist Control involves a fixed level of triceps stimulation and control of joint angle by varying the level of voluntary elbow flexion. This has been widely accepted by the neuroprosthesis users, and the same principle has been applied to pronation and supination control [25]. It is a simple and natural control method that does not require additional proportional command signals and is easily learned and controlled. Other techniques are also being developed that can avoid the potential fatigue caused by constant stimulation, and the reduction in maximal flexion strength caused by constant activation of the extensor. In particular, reducing triceps stimulation in proportion to the biceps voluntary electromyogram (EMG) is a feasible method of producing a natural reciprocal activation pattern [26].

Although we expected individuals with higher impairment levels to have lower motor neuron damage more frequently to the radial nerve (and thus a reduced stimulated elbow extension strength), no correlation between impairment level and stimulated elbow extension strength was found (**Figure 3**). Possible explanations are differences in denervation patterns, electrode locations, and frequency of exercise. Of the three subjects with the least moment generated, one (subject H) had significant triceps denervation and two subjects (D and I) had limited stimulation to avoid recruiting nearby elbow flexors or shoulder muscles. The subject (E) with the highest moment generated placed weights on his wrist during his electrical exercise regimen. His results suggest that perhaps adding resistance to the exercise routine can increase strength.

The variation in elbow extension moment with elbow angle (**Figure 4**) is most likely due to the normal length-tension properties of the triceps and to the variation in moment arm as the elbow angle changes, since the shape of the curve is similar to that of able-bodied subjects [3,27]. It is also possible that the distance between the electrode and nerve could vary as the triceps is stretched, which would affect the excitation of the nerve.

The average elbow moments produced by persons who have had a posterior deltoid to triceps tendon transfer (**Figure 4**) are lower than those reported by others [2,3]. This may be due partially to injury level. Both of the other studies involved only C6-level injuries, while the present study includes a number of C5-level injuries. These individuals have other shoulder muscle deficits, which may compromise the function of the tendon transfer and make training more difficult. The shoulder position used during the measurements (90° abduction, 0° horizontal adduction) is a weaker position biomechanically, but is a useful functional position [28]. Elbow moment measurements were also made with the shoulder positioned at 45° and

90° horizontal adduction for the people with posterior deltoid tendon transfers. Although stronger moments were recorded at these positions (data not presented here), they were still less than the moments generated by triceps stimulation. For the statistical analysis, we only presented the data for the two elbow extension methods made at the same shoulder positions.

Although triceps stimulation provided a significantly greater elbow extension moment than did the posterior deltoid tendon transfer in this group of subjects, we are not advocating that triceps stimulation should be used instead of a tendon transfer. Rather, triceps stimulation should be used in conjunction with tendon transfer for individuals who are candidates for both procedures. As shown in the four subjects who had both procedures (**Figure 5**), the greatest elbow moment is generated when both methods are used simultaneously. Why this simultaneous activation often produced a moment that was greater than the sum of the two moments measured separately is not clear. Possibly, the combined approach provided an increased stability at the shoulder, thus allowing a greater moment at the elbow. However, we did not evaluate shoulder stability in this study. Also possible is that the stimulation reflexively increased voluntary moment, but this was not examined either. Another significant advantage to having both procedures is that the individual has some elbow extension strength even when the neuroprosthesis is not turned on. This advantage must be balanced with the disadvantage of the relatively long recovery time following tendon-transfer surgery.

Triceps stimulation produced shoulder adduction moments in both individuals who had similar impairments and higher injury levels (**Figure 6**). The subject with the higher shoulder adduction moment (subject A) was unable to oppose the adduction moment and perform functional reaching activities. The other subject (G) was able to perform functional reaching activities, but it is unclear whether that was because the shoulder adduction moment was less or because his voluntary shoulder abductor muscles were stronger than those of subject A. Selectively stimulating the lateral or medial head of the triceps and avoiding the long head should prevent shoulder adduction in future implementations in the weak C5 tetraplegic population [16].

Triceps stimulation significantly increased the task success rate in the workspace assessment tests in individuals with either C5 or C6 level SCIs. The improvements in success rate and acquisition time that were seen were due to more than just an increase in the reachable workspace. With triceps stimulation, the participants could maintain their hands in an appropriate position to acquire the object. Thus, it is the controllable workspace that determines functional performance, not just the reachable workspace.

The performance on the workspace assessment was strongly influenced by the quality of the individual's hand grasp. Subjects B (R) and D both have weak hand grasps. Because of this, both subjects were slower than the other subjects at acquiring the book with triceps stimulation. In addition, the weak hand grasps made acquiring the book more difficult when it was in the horizontal orientation. Subject B (R) had relatively strong stimulated elbow strength. This finding could explain why he had a high success rate with triceps stimulation, even though he had a weak grasp (he was able to maintain his arm in a stable position for the time it took him to maneuver his hand around the book). Subject D's stimulated elbow strength was also weak, which might explain why the difference in success rate with the triceps stimulation on and off was not as great as the other subjects.

CONCLUSIONS

Elbow extension neuroprostheses have been successful in providing elbow extension in individuals with a paralyzed triceps, and the triceps is now a commonly used electrode site for the commercially available Free-Hand™ system. A stimulated triceps increases the functional workspace and decreases object acquisition time. This finding agrees with other assessments of functional task performance with triceps stimulation [17].

For subjects with weak shoulder abductors, shoulder adduction associated with stimulating the long head should be avoided so that selective stimulation of the lateral and medial heads of the triceps muscle can be provided.

In addition to the functional workspace improvements described in this paper, triceps stimulation may be useful in assisting individuals with tetraplegia in performing weight shifts and sliding transfers. Most likely, these functions will require a greater elbow extension moment than that which has been described here. Methods of providing increased stimulated elbow extension moment are currently being investigated.

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REFERENCES

1. Moberg EA. Surgical treatment for absent single-hand grip and elbow extension in quadriplegia. J Bone Joint Surg Am 1975;57-A:196–206.
2. Lacey SH, Wilber RG, Peckham PH, Freehafer AA. The posterior deltoid to triceps transfer: A clinical and biomechanical assessment. J Hand Surg [Am] 1986;11A:542–47.
3. Rabischong E, Benoit P, Benichou M, Allieu Y. Length-tension relationship of the posterior deltoid to triceps transfer in C6 tetraplegic patients. Paraplegia 1993;31:33–39.
4. Castro-Sierra A, Lopez-Pita A. A new surgical technique to correct triceps paralysis. Hand 1983;15(1):42–46.
5. Kuz JE, Van Heest AE, House JH. Biceps-to-triceps transfer in tetraplegic patients: report of the medial routing technique and follow-up of three cases. J Hand Surg [Am] 1999;24:161–72.
6. Revol M, Briand E, Servant JM. Biceps-to-triceps transfer in tetraplegia. The medial route. J Hand Surg [Br] 1999;24:235–37.
7. Wierzbicka MM, Wiegner AW. Orthosis for improvement of arm function in C5/C6 tetraplegia. J Prosthet Orthot 1996;8:86–92.
8. Wiegner AW, Wierzbicka MM. Mechanical compensation for weak triceps in C5/C6 tetraplegia. IEEE Trans Rehabil Eng 1993;1:72–78.
9. Itzkovich M, Catz A, Ona I. A new double-purpose device for elbow extension in tetraplegia with paralysis below C5. Paraplegia 1993;31:116–18.
10. Nathan RH. An FNS-based system for generating upper limb function in the C4 quadriplegic. Med Biol Eng Compu 1989;27:549–56.
11. Hoshimiya N, Naito A, Yajima M, Handa Y. A multichannel FES system for the restoration of motor functions in high spinal cord injury patients: A respiration-controlled system for multijoint upper extremity. IEEE Trans Biomed Eng 1989;36:754–60.
12. Naito A, Handa Y, Handa T, Ichie M, Hoshimiya N, Shimizu Y. Study on the elbow movement produced by functional electrical stimulation (FES), Tohoku J Exp Med 1994;174:343–49.
13. Smith BT, Mulcahey MJ, Betz RR. Development of an upper extremity FES system for individuals with C4 tetraplegia. IEEE Trans Rehabil Eng 1996;4:264–70.
14. Miller LJ, Peckham PH, Keith MW. Elbow extension in the C5 quadriplegic using functional neuromuscular stimulation. IEEE Trans Biomed Eng 1989;36:771–80.
15. Grill JH, Peckham PH. Functional neuromuscular stimulation for combined control of elbow extension and hand grasp in C5 and C6 quadriplegics. IEEE Trans Rehabil Eng 1998;6:190–99.
16. Crago PE, Memberg WD, Usey MK, Keith MW, Kirsch RF, Chapman G, Katorgi MA, Perreault EJ. An elbow extension neuroprosthesis for individuals with tetraplegia. IEEE Trans Rehabil Eng 1998;6:1–6.
17. Bryden AM, Memberg WD, Crago PE. Electrically stimulated elbow extension in persons with C5/C6 tetraplegia: a functional and physiological evaluation. Arch Phys Med Rehabil 2000;81:80–88.
18. Kilgore KL, Peckham PH, Keith MW, Thrope GB, Wuolle KS, Bryden AM, Hart RL. An implanted upper-extremity neuroprosthesis: follow-up of five patients. J Bone Joint Surg Am 1997;79-A:533–41.
19. Akers JM, Peckham PH, Keith MW, Merritt K. Tissue response to chronically stimulated implanted epimysial and intramuscular electrodes. IEEE Trans Rehabil Eng 1997;5:207–20.
20. 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;11A:604–8.
21. Memberg WD, Murray WM, Ringleb SI, Kilgore KL, Snyder SA. A transducer to measure isometric elbow moments. Clin Biomech (Bristol, Avon) 2001;16:918–20.
22. Memberg WD, Crago PE. Instrumented objects for quantitative evaluation of hand grasp. J Rehabil Res Dev 1997;34:82–90.
23. Bhadra N, Kilgore KL, Peckham PH. Implanted stimulators for restoration of function in spinal cord injury. Med Eng Phys 2001;23:19–28.
24. Rettman T, Memberg W, Bryden A, Thrope G. Obtaining elbow extension by electrically stimulating the triceps muscle with the freehand system. International FES Society. Bologna, Italy; 2001.
25. Lemay MA, Crago PE, Keith MW. Restoration of pronosupination control by FNS in tetraplegia—experimental and

biomechanical evaluation of feasibility. J Biomech 1996; 29:435–42.

26. Giuffrida JP, Crago PE. Reciprocal EMG control of elbow extension by FES. IEEE Trans Neural Syst Rehabil Eng 2001;9:338–45.
27. Buchanan TS. Evidence that maximum muscle stress is not a constant: differences in specific tension in elbow flexors and extensors. Med Eng Phys 1995;17:529–36.
28. Kirsch RF, Acosta AM, Perreault EJ, Keith MW. Measurement of isometric elbow and shoulder moments: position-dependent strength of posterior deltoid-to-triceps muscle tendon transfer in tetraplegia. IEEE Trans Rehabil Eng 1996;4:403–9.

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