An Elbow Extension Neuroprosthesis for Individuals with Tetraplegia

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***Abstract*—Functional electrical stimulation (FES) of the triceps to restore control of elbow extension was integrated into a portable hand grasp neuroprosthesis for use by people with cervical level spinal cord injury. An accelerometer mounted on the upper arm activated triceps stimulation when the arm was raised above a predetermined threshold angle. Elbow posture was controlled by the subjects voluntarily flexing to counteract the stimulated elbow extension. The elbow moments created by the stimulated triceps were at least 4 N·m, which was sufficient to extend the arm against gravity. Electrical stimulation of the triceps increased the range of locations and orientations in the workspace over which subjects could grasp and move objects. In addition, object acquisition speed was increased. Thus elbow extension enhances a person's ability to grasp and manipulate objects in an unstructured environment.**

I. INTRODUCTION

INDIVIDUALS with spinal cord injury in the cervical region, who are classified as C5 or C6 on the American Spinal Injury Association (ASIA) scale, retain voluntary elbow flexion but lack voluntary extension. This limits the work space over which they can perform functional activities that require overhead reach or pushing objects away from the body. Other activities such as transfers, weight shifts and wheelchair propulsion are also limited. Rehabilitation alternatives for providing powered elbow extension include a voluntary tendon transfer of the posterior deltoid to the triceps [1], [2], a mechanical orthosis that provides passive elbow extension [3], and FES systems that activate the triceps electrically to counteract gravity [4]–[6]. The posterior deltoid transfer has the advantage that it is always available (nothing needs to be donned or doffed), but not all people have sufficient posterior deltoid strength, the strength might depend strongly on shoulder position, and the transfer might interfere with residual shoulder control [7]. The orthotic solution has the disadvantage of poor cosmesis, relative difficulty in donning and doffing, and limited strength. In contrast, the FES system described below can be implemented relatively easily as an incremental augmentation of an implanted hand grasp neuroprosthesis. Implementation requires only one or two additional stimulating electrodes and uses a simple, natural, sensor-driven command/control scheme.

II. METHODS

A. Subjects

A portable hand grasp/elbow extension neuroprosthesis was implemented and evaluated in two persons with C6 level tetraplegia (complete lesions) on at least one side following cervical spinal cord injury. In addition to the selection criteria for the hand grasp neuroprosthesis [8], candidates for stimulated elbow extension must fit the following criteria: 1) intact lower motor neurons innervating elbow extensors (resulting in a stimulatable triceps of at least grade 3 on the ASIA motor grading scale), 2) minimal to no upper extremity contractures, 3) voluntarily controlled elbow flexion (grade 4), and 4) sufficient shoulder function to enable them to use their arm functionally. Following their injuries, both subjects had learned to use many techniques to substitute partially for missing voluntary elbow extension. For example, they could reach overhead by first externally rotating their upper arms to allow gravity to extend their arms at the elbow, then flexing or abducting their shoulders. They also used gravity to assist passive pronation by abducting the shoulder with the elbow flexed.

The first subject that was implemented had an implanted hand grasp neuroprosthesis [9], as well as two percutaneous intramuscular triceps electrodes [10] on his left side which were implanted for this study. He had used a hand grasp neuroprosthesis for over 17 years, including the implanted version for the last ten years. He began using the combined elbow/hand system in May, 1995, and his use of the system was evaluated at four and 16 months. The second subject had a similar implanted hand grasp neuroprosthesis on his right side, although in this case the triceps was implanted with an intramuscular electrode [11] that was connected directly to the implanted stimulator [12]. He also had a surgical transfer of the posterior deltoid to the triceps. He had the implanted neuroprosthesis since July 1996 and his use of the system was evaluated six months after surgery.

B. Neuroprosthesis System

The combined hand grasp/elbow extension neuroprosthesis was implemented by augmenting the external controller of the

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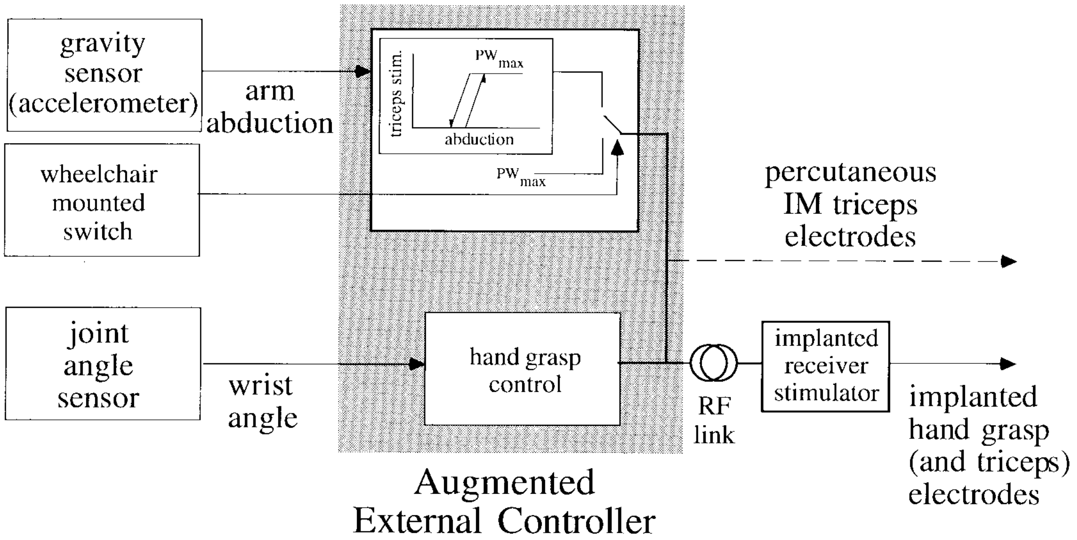

Fig. 1. Block diagram of the neuroprosthesis for restoring both hand grasp and elbow extension. An implanted receiver-stimulator (IRS) with epimysial and/or intramuscular electrodes stimulates the hand grasp muscles. An external controller activates the IRS via a radio frequency link. An external joint angle sensor on the ipsilateral wrist controls hand grasp. The hand grasp controller is augmented with stimulation channels to excite the triceps via either percutaneous intramuscular (IM) electrodes (subject 1) or an additional implanted intramuscular electrode controlled through the radio frequency link (subject 2). The augmented external controller processes signals from an accelerometer sensing arm abduction and a switch mounted on the side of the wheelchair contralateral to the arm with the neuroprosthesis. The triceps is stimulated at a fixed level when either the switch is on or the arm is abducted above a threshold level.

hand grasp neuroprosthesis (Fig. 1), with an accelerometer to sense the orientation of the arm in the gravitational field and a microprocessor to implement the elbow control algorithm. In the first subject, eight stimulus channels for percutaneous electrodes were also added to the external controller (only two were used). In both cases, the external hardware was slightly larger than the standard hand grasp system, but was still fully portable and was donned daily by the subjects with the assistance of their personal attendant or caregiver.

The site for implanting the percutaneous electrodes in the first subject was determined by surface stimulation. Two separate motor points were identified, likely corresponding to two of the three heads of the triceps. Two electrodes were implanted near each motor point using hypodermic needles [10]. The insertion site was covered with a bandage and the electrodes were not stimulated for a two week period, allowing the positions of the electrodes to stabilize. After this period, the triceps was exercised by electrical stimulation in a preprogrammed sequence to strengthen the muscle and increase endurance [8]. The exercise regimen consisted of five hours of stimulation every other day, which was reduced to two hours every other day after the muscle became conditioned. The stimulus waveform was a balanced biphasic, cathodic-first, capacitively coupled, constant current pulse, with a fixed stimulus amplitude of 20 mA, a variable pulse-width from 0 to 200 μs, and a frequency of 16 Hz.

In the second subject, the triceps electrode was implanted as part of the surgical implantation of the neuroprosthesis. The epimysial electrode was positioned over the medial surface of the long head of the triceps via a posterior incision. The incisions were allowed to heal for a three week period, after which the electrical exercise regimen was started.

The command signal that modulated the triceps stimulation was derived from the output of a single-axis ±2 g silicon micromachined accelerometer (IC Sensors, Milipitas, CA, model 3145-002). This sensor was 2.3 cm by 2.3 cm and 1.1 cm thick, and contained signal conditioning circuitry, eliminating the need for external signal conditioning and minimizing electrical noise problems. Its sensitive axis was perpendicular to the face of the sensor. The accelerometer sensed the tilt of the upper arm relative to the gravitational field. In the first subject, the sensor was placed on the lateral aspect of the upper arm, approximately 5 cm distal to the shoulder, with the sensitive axis normal to the arm surface. In the second subject the accelerometer was mounted in a similar location, but with the sensitive axis parallel to the long axis of the humerus, a more ideal situation since the sensor was therefore less sensitive to humeral rotation. However, this increased the profile of the sensor on the arm, a situation acceptable to the second subject. The first subject elected to keep the lower profile, more placement-sensitive configuration. In this subject, placing the sensor close to the shoulder minimized the sensitivity to humeral rotation while maximizing the sensitivity to shoulder abduction.

As each subject elevated his upper arm to reach for an object, the triceps was stimulated and the elbow extended. Elbow posture was controlled by the subject voluntarily flexing to counteract the elbow extension. The control of arm posture by cocontraction of a voluntarily controlled agonist and a stimulated antagonist is a simple, natural, and effective method, that eliminates the need for additional unrelated command control sources such as voluntary movement at other joints [13].

The accelerometer signal was digitized and compared to a programmable threshold elevation angle. When the signal increased past the threshold, the stimulus to the triceps was turned on, increasing in proportion to the accelerometer signal until the maximum stimulus level was reached. Hysteresis was programmed into the system, so that the stimulus would start to decrease at a lower threshold than the threshold required to turn on the stimulus. This technique prevented triceps stimulation from going into oscillation at the threshold angle.

The exact placement of the accelerometer and the values of the thresholds were determined by the activities for which the subjects principally desired elbow extension. The lower limit for the threshold for the first subject (with the low-profile sensor configuration) was determined by his desire to extend his elbow to assist in pushing a disk into a computer, which indicated that the stimulus should come on at a shoulder flexion or abduction angle slightly below horizontal. At the same time, the subject did not want elbow extension to interfere with eating. The threshold to begin stimulation to the triceps was 0.86 g (59° sensor tilt from horizontal), and the threshold to turn off the stimulation was 0.77 g (51° sensor tilt). The lower threshold limit for the second subject (with the sensitive axis of the sensor parallel to the long axis of the humerus) was determined by his desire to extend his elbow when his shoulder flexion or elevation angle was slightly above horizontal. The threshold to begin stimulation to the triceps was set to 0.43 g (25° sensor tilt from horizontal), and the threshold to turn off the stimulation was 0.26 g (15° sensor tilt). A separate switch was recently mounted on the wheelchair of both subjects to allow the elbow stimulation to be turned on independently of the gravity sensor. Each individual used this switch to activate the triceps when he wanted to push with his arm at angles which were below the threshold value.

C. *Quantitative Assessment*

After the subjects electrically exercised the triceps for at least four weeks, elbow moment measurements were made at different elbow and shoulder angles to examine the dependence of elbow extension moment on arm posture. The subject's upper arm was supported so that it was in a horizontal plane. The wrist was placed in a splint that was attached to a six degree-of-freedom force sensor. For the subject who had had the posterior deltoid-to-triceps transfer, we measured voluntary elbow extension strength, stimulated elbow extension strength, and the combination of both. In the subject with percutaneous electrodes, we measured elbow moment with different combinations of two of the four electrodes, with stimulus pulse widths in the range from 0 to 200 μs. The pair of electrodes that produced the highest moments were selected to be used functionally.

Functional tasks were also assessed quantitatively to evaluate the ability of the elbow extension system to increase the controllable workspace of the arm, rather than just the reachable workspace. The reachable workspace was defined as the range of locations where the person could position his arm, even if only transiently. For a location to be in the controllable workspace, the person had to be able to perform a specified task at that location. Thus, the controllable space is a subset of the reachable space. The portion of the reachable space that is outside of the controllable space is potentially useful if control could be improved. Since individuals with C5 and C6 cervical level spinal cord injuries have restricted control at all joints of the upper extremity, object orientation was also considered to be a primary determinant of the controllable workspace and was a controlled variable.

Workspace assessment was based on the technique of specific task analysis [14]. The subject performed a specific task analogous to a realistic functional activity, in this case picking up and moving a book-like object from one location/orientation, and placing it in another location/orientation. The task was instrumented to provide quantitative mechanical information. The book-like object (301 g) was instrumented with strain gauges and accelerometers to measure grasp force and object orientation [15]; the starting and ending locations were moveable stands instrumented with contact switches to detect object liftoff and placement.

A set of preliminary experiments was performed with each subject to identify the stand locations that warranted further study. The starting and ending locations for the stands were chosen to cover a coarse grid of far and close positions within the subject's reachable workspace. Far locations were at a fixed radius from the acromion that was slightly less than arm's length (57 cm for subject #1, 67 cm for subject #2); close locations were in a para-coronal plane 25 cm in front of the subject, at the end of the wheelchair armrests. A 3 × 3 grid of locations was chosen at each distance. Each grid contained a low row (at armrest height), a high row (at a standard bookshelf height), and a middle row in between. The center column of the far grid was aligned with the sagittal plane through the shoulder, while the lateral and medial columns were 45° to either side. The lateral and medial columns of the close grid were aligned with the chair armrests, while the center column was centered between them.

Subsequently, assessment experiments focused on the high row locations, since our preliminary experiments revealed prominent performance differences at these locations. For the first subject, the high row was 137 cm. The second subject had a taller wheelchair and longer arm length, so the highest row for him was set to 155 cm.

A single trial consisted of reaching for the book at the starting location/orientation, grasping it, moving it to the ending location/orientation, and releasing it. Starting locations for the trials were defined by placing a stand at different high row locations specified by the grids. For each starting location, movements were made in two book orientations (horizontal and vertical), and with two elbow neuroprosthesis states (on and off). Thus there were four movement conditions for each location. For each subject, each movement condition was performed eight times over two days, with the order of conditions changed, giving 96 trials per day, and a total of 192 trials for all conditions.

A trial was recorded as successful if the subject completed the task within 90 s without losing control of the book or knocking it over. An additional assessment goal was to characterize movement quality to assess difficulty and cosmetic aspects of movement control. Thus, in addition to recording successes and failures, the successful trials were also analyzed to quantify the time required to perform individual elements of the task (the task phases). The *Reach* phase was defined as the time from the start of the trial until the first detectable contact force (0.2 N) was registered on the book. The *Acquisition*

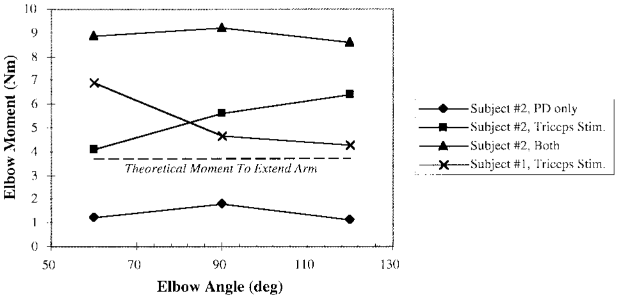

Fig. 2. Elbow moments for different elbow angles for each subject. Each point is an average of the maximum moment generated at three different shoulder positions (0, 45, and 65° horizontal flexion for subject #1; 0, 45, and 90° horizontal flexion for subject #2). Subject #2's elbow moments generated by his posterior deltoid to triceps transfer (PD), stimulated triceps, and a combination of both are shown. Subject #1 did not have the PD transfer, so only the stimulated triceps data are shown. Each subject generated more than enough moment from his stimulated triceps to exceed that which was needed to extend his arm against gravity (shown as dashed line).

phase was defined as the time from the end of reach until the last time the book lost contact with the first stand. The *Move* phase was defined as the time from the end of *Acquisition* to the first time the book made contact with the second stand. The *Release* phase was defined as the time from the end of *Move* to the time the grasp force on the book was finally removed and the arm started to move to its resting position on the armrest.

Both persons' performances were analyzed with and without the triceps extension neuroprosthesis, but the hand grasp neuroprosthesis was always activated and under the subject's control. Thus, the differences in performance described below are attributed to the addition of stimulated elbow extension, and are not due to the hand grasp neuroprosthesis.

III. RESULTS

Elbow extension strength for each subject was measured isometrically at three different shoulder and elbow angles (Fig. 2). For subject #1, the stimulated elbow moment decreased with increasing elbow angle (flexion), with an overall average of 5.4 N·m. For subject #2, the stimulated elbow moment (overall average 5.3 N·m) increased with increasing elbow angle, and was greater than the voluntary elbow moment resulting from the posterior deltoid transfer (overall average 1.4 N·m). When the subject voluntarily extended at the same time that the triceps was stimulated, the resultant elbow moment was greater than the sum of the separate measurements (overall average 8.9 N·m). These differences were statistically significant (paired t-test, $p < 0.0001$). Based on published anthropometric data [16], the maximum extension moment required for elbow extension was estimated to be approximately 3.7 N·m (with the arm in an orientation where gravity would produce the maximum elbow flexion moment). This increases to approximately 5.5 N·m with a 0.5-kg object in the hand. The functional requirements are less, since an individual is typically operating at a much lower angle of arm elevation. Thus, the moments generated by the triceps electrodes in our subjects are adequate for many activities.

The first aspect of the task-based quantitative assessment focused on changes in the controllable workspace that were provided by active elbow extension. The criterion for this part of the assessment was success or failure in performing the functional task at different points in the workspace. It was hypothesized that an individual would be able to perform the task over a greater range of locations/orientations with active elbow extension than he could without it.

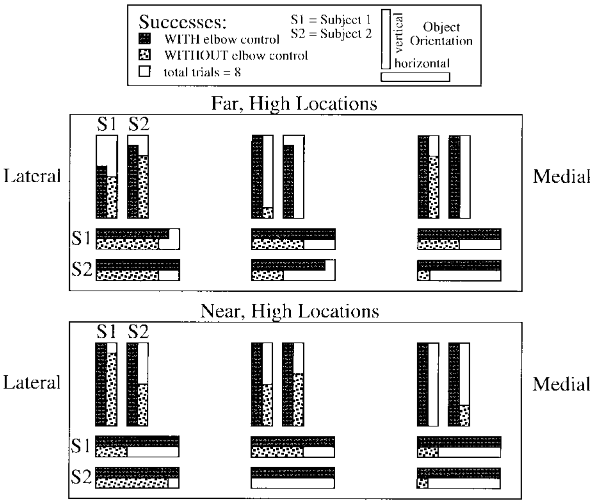

Fig. 3. Effect of elbow extension on success in completing the task of picking up an object at different locations in the workspace with the object in either a horizontal or vertical orientation. Successes are shown as different length vertical or horizontal bars, corresponding to the number of successes in the vertical or horizontal orientations respectively. Eight trials (open bars) were performed with the system on (solid bars) or off (stippled bars) at each of the six high locations for both subjects.

The elbow extension neuroprosthesis increased the controllable space in a graded rather than absolute sense. The preliminary experiments showed several things that helped to focus the assessment experiments. First, all task failures occurred in acquisition. Second, there were no failures at the low locations, and only a few at the middle height locations, either with or without elbow extension. Third, there were clear differences at the high locations.

The overall success rate at the far and near high locations/orientations (Fig. 3) was very large (96% for subject #1, 97% for subject #2) with stimulated elbow extension, especially in comparison to the success rate without stimulated elbow extension (49% for subject #1, 6% for subject #2). This difference was significant statistically for each subject (chi-square test, $p < 0.0001$). With the triceps stimulation on, there were only a few failures (7/192, 3.6%), and 4/7 (57%) of these occurred at the ipsilateral, far, high location with a vertical object orientation. All of these failures occurred at far rather than at near locations, and more (5/7) occurred with vertical than horizontal orientations.

Without the elbow system, each subject could still perform the task at many of the locations/orientations at least occasionally. However, the success rate was very low at some locations. The number of failures at the far locations was approximately the same as at the near locations. The number of failures at the horizontal orientations was approximately the same as at the vertical orientations. In summary, the success rate was higher with the elbow control system than without it at all locations.

The second aspect of the task-based quantitative assessment focused on changes in movement quality. The preliminary

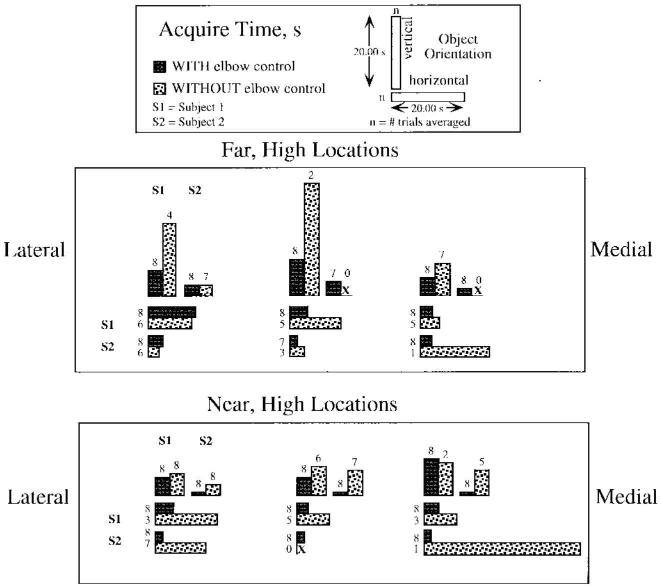

Fig. 4. Effect of elbow extension on the time required to acquire the object in the hand grasp. The mean times are shown for all successful trials, with the same plotting conventions as in Fig. 3. The number of successful trials used to compute the average ranged from zero to eight, and is shown above or to the left of each bar. An "X" is placed where there were no successful trials, indicating that no timing value is available.

assessment in the first subject suggested that object acquisition time was shorter with the elbow system than without it. Thus, the durations of the acquire phases were analyzed for those trials that were completed successfully in the subsequent assessments (Fig. 4 shows the average acquire times).

Active elbow extension improved performance quality by decreasing the acquire time substantially (Fig. 4). When averaged across all high locations and both orientations, the time decreased from 10.9 s to 6.2 s for subject #1, and from 7.1 s to 2.2 s for subject #2, which was significant statistically for both subjects ($p < .001$, unpaired t-test). Acquire times from those trials that were not successfully completed obviously could not be included in this analysis. Stimulated elbow extension decreased the acquire time in all locations and orientations except for one in the first subject; far, high, and lateral, with a horizontal orientation, where the average times were almost equal. With stimulated elbow extension, the average time was slightly higher in the far than in the near locations (7 s vs. 5.4 s for subject #1, 2.8 s vs. 1.7 s for subject #2), but this difference was not significant statistically ($p > .05$, unpaired t-test). There was also no significant difference between the average times for the vertical and horizontal orientations with stimulated elbow extension ($p > .2$, unpaired t-test). Providing active elbow extension improved at least one aspect of movement quality (task performance speed) even in those locations/orientations where each subject could still perform the task successfully without active elbow extension.

IV. DISCUSSION

Stimulation of the triceps in two persons with C6 tetraplegia produced sufficient elbow extension moment to extend the arm against gravity. The addition of elbow extension to a hand grasp neuroprosthesis produced a significant increase in the performance of an object manipulation task by increasing the success rate and decreasing the time taken to secure an object in grasp.

Restoring elbow extension required only an incremental change in the neuroprosthesis. One to two stimulus channels were added to excite the triceps, and an accelerometer was added to provide on/off control of the stimulation. The stimulated elbow moment was sufficient to fully extend the elbow against gravity. Graded control of elbow posture was achieved by taking advantage of residual voluntary elbow flexion. Increasing voluntary flexion overcame the extension bias produced by the stimulated triceps, making it possible to modulate the equilibrium joint angle over the full range.

Combining the accelerometer with voluntary elbow flexion eliminated the need for a separate gradable command/control source, and integrated stimulated muscle function with voluntary control in a natural way. The accelerometer turned off stimulation when the individual's arm was below the threshold angle, but turned the stimulation on when the arm was lifted above the threshold angle. This differs from the command/control scheme developed earlier by Peckham in which the triceps stimulation was modulated in proportion to the forearm orientation in the gravitational field, estimated by either a combination of shoulder and elbow joint angle sensors [4], or by an accelerometer mounted on the forearm [17]. The proximal sensor placement used in the present study was easier to implement since it eliminated the need for wires crossing the elbow joint and made it easier to conceal the sensor beneath clothing. However, the proximal placement has the potential disadvantage of using more triceps stimulation than was necessary to balance the gravitational flexion moment, with an increased likelihood of fatiguing both the triceps and the elbow flexors more rapidly than with the forearm placement. This was not a problem for the persons studied here, but might be a problem in an individual with weaker elbow musculature.

The specific task analysis revealed clear differences in both increased success rate and in decreased object acquisition time. It was expected that there would be locations and orientations where the task could not be performed at all without stimulated elbow extension, but this was not observed as frequently as expected. Subject #1 was quite skilled in using his residual motor function to perform tasks, taking advantage of inertia, gravity, and environmental supports, even resting his hand on the object stand prior to acquisition. Thus, although the functional enhancement is clear, it is not absolute.

Increased performance was not due simply to an expansion of the reachable space, i.e., an expansion of the space where the hand could be placed. Rather, the increased performance was due to the tasks that could be performed at that location. It is likely that the increased performance was due to increased arm stability, allowing the subjects to maintain a suitable posture while acquiring the object. Although this explanation can not be verified on the basis of the data collected in these functional tests, it is important to analyze the mechanism of the performance improvement. It may be possible to improve performance without large increases in elbow extension strength if stability rather than strength is a major determinant of performance. In addition, simple tests of *reachable* space will not provide adequate measures of changes in function. Quantitative assessments of *controllable* space will require definition of requirements for tasks that are to be performed at each location.

The task analyzed in this study is representative of many functional activities, such as removing a book or videotape from a shelf, using a wall mounted phone, using an automatic teller machine, or grasping a shirt on a hangar. Thus, the increased performance documented in our tests provides a quantitative indication of increased performance in the tasks reported anecdotally. Other tasks that would benefit from elbow extension are pushing objects at low heights, weight shifts, transfers, and wheelchair propulsion. These require different methods of command/control, since the accelerometer is not activated appropriately for these tasks. The wheelchair mounted switch provided a method for these individuals to bypass the accelerometer and push objects at low heights, but not to perform the other activities such as transfers and weight shifts that will require bilateral systems and, in many cases, improved shoulder function.

The improved performance and the simple requirements for implementation demonstrated in this study indicate that elbow extension by triceps stimulation should be tested on a wider range of persons with tetraplegia.

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