Department of Veterans Affairs

JRRD Volume 41, Number 3B Pages 461–472
May/June 2004
Journal of Rehabilitation Research & Development

Simulated neuroprosthesis state activation and hand-position control using myoelectric signals from wrist muscles

Jayme S. Knutson, MS; Harry A. Hoyen, MD; Kevin L. Kilgore, PhD; P. Hunter Peckham, PhD
Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH; Center of Excellence in Functional Electrical Stimulation, Louis Stokes Cleveland Department of Veterans Affairs Medical Center, Cleveland, OH; Department of Orthopaedics, MetroHealth Medical Center, Cleveland, OH

Abstract—This paper reports on the initial phase of feasibility testing of a control strategy that uses myoelectric signals (MES) from wrist flexor and extensor muscles to control a hand-grasp neuroprosthesis for C7 tetraplegia. The control strategy was customized to the MES patterns produced during wrist flexion, extension, and relaxation for five able-bodied subjects and two individuals with C7 spinal cord injury. We evaluated the reliability with which the subjects could deliberately activate target neuroprosthesis states and control the degree of opening and closing of a computer-simulated hand using the myoelectric control strategy. Every subject was able to activate at least 99% of the target states for at least 1 continuous second, enough time to prove the activation was deliberate and to achieve significant hand opening or closing. Additionally, every subject was able to control the opening and closing of the simulated hand with enough proficiency to match greater than 87% of the target hand positions for at least 2 continuous seconds. Most of the inadvertent disturbances in simulated hand position were of a magnitude less than 10% of full range of motion for every subject. Future studies will incorporate the control strategy into an electrical stimulation system that opens and closes the hand of an individual with C7 tetraplegia.

Key words: control algorithm, functional electrical stimulation, myoelectric control, neuroprosthesis, spinal cord injury, tetraplegia.

INTRODUCTION

Functional electrical stimulation (FES) has been used to restore hand grasp to individuals with tetraplegia caused by spinal cord injuries (SCIs) at the C5 and C6 neurological levels [1–7]. The implantable neuroprosthetic hand-grasp system developed at the Cleveland Department of Veterans Affairs (VA) Medical Center and Case Western Reserve University [2,3] provides palmar and lateral pinch, enabling users to grasp, hold, and release objects. The system has been demonstrated to improve grasp strength, enable manipulation of objects of various sizes and weights, and increase independence in performing activities of daily living [8–11]. This research focuses on one aspect of our efforts to improve user performance and

Abbreviations: CGP = Change Grasp Pattern, ECRB = extensor carpi radialis brevis, FCR = flexor carpi radialis, FES = functional electrical stimulation, MES = myoelectric signals, SCI = spinal cord injury, VA = Department of Veterans Affairs.

This material was based on work supported by National Institutes of Health (NIH) contract N01-NS-1-2333, Department of Veterans Affairs Predoctoral Associated Health Rehabilitation Research Fellowship, and a Whitaker Foundation Predoctoral Fellowship.

Address all correspondence to Jayme S. Knutson, Rehabilitation Engineering Center, 2500 MetroHealth Drive, H601, Cleveland, OH 44109; 216-778-8364; fax: 216-778-8409; email: jayme.knutson@cwru.edu.

JRRD, Volume 41, Number 3B, 2004

to expand the clinical indications of the system by developing control methods that are more natural to the user. We are investigating a control strategy that uses myoelectric signals (MES), the electrical manifestation of the neuromuscular activation associated with a contracting muscle [12], from forearm muscles that can be volitionally activated in synergy with hand function.

The use of myoelectric signals to control the neuroprosthesis is appealing for several reasons. First, an internal rather than external sensor [13,14] can be used to detect the volitional activity that controls the neuroprosthesis. The use of an internal sensor (electrode) eliminates the inconvenience of donning a transducer and its associated cables, improves cosmesis, reduces the potential of interfering with retained upper-limb mobility, and reduces variations in controllability that may be caused by variations in transducer placement and settings. Second, if the myoelectric signals are recorded from muscles that act synergistically with those in the hand, then the control method may be more natural to the user. Development of a synergistic control method is especially important for individuals with C7 tetraplegia, since they retain a significant amount of upper-limb mobility that must not be sacrificed in order to control the hand [15]. The availability of volitionally active wrist muscles in individuals with C7 tetraplegia allows us to take advantage of the natural biomechanical synergy between wrist action and hand opening and closing, where the fingers tend to close with wrist extension and open with wrist flexion [16]. Finally, bilateral implementation of the hand-grasp neuroprosthesis may be possible if ipsilateral muscles are used to control the hand [17].

The myoelectric control strategy we evaluated in this study is shown in **Figure 1**. It is conceptually similar to state control strategies that have been used for controlling prosthetic arms and hands by individuals with upper-limb amputations [18]. The graph of MES space is partitioned into four regions that correspond to four different neuroprosthesis states: Open, Close, Hold, and Change Grasp Pattern (CGP). Each state is activated by moving the operating point (which represents the simultaneous MES in both control muscles) into its corresponding region of the graph. The regions are positioned so that MES accompanying wrist extension activates the Close state and MES accompanying wrist flexion activates the Open state. Strong cocontraction of the wrist muscles activates the CGP function, which toggles the stimulation pattern (palmar or lateral) that is sent to the hand muscles. In this

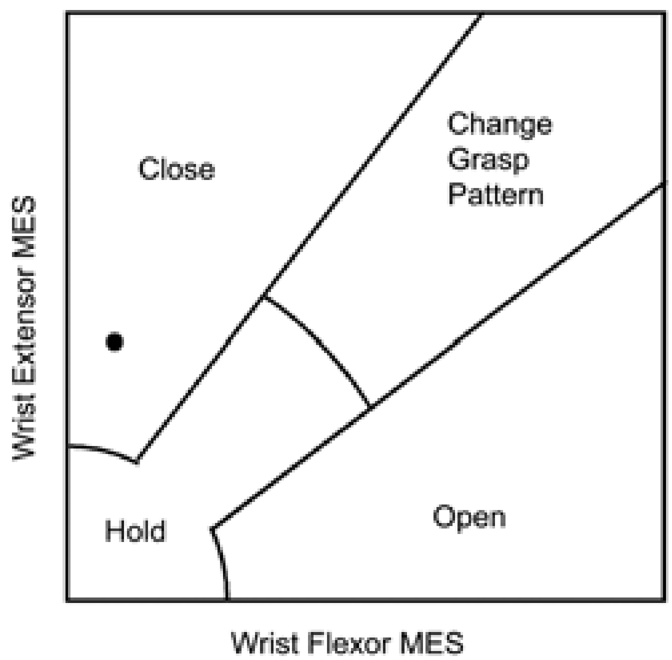

Figure 1.
Myoelectric control strategy for hand-grasp neuroprosthesis. Signal space is partitioned into four regions that correspond to neuroprosthesis states. State is activated by positioning operating point in corresponding region by appropriate contractions of wrist flexor and extensor muscles. Thresholds and boundaries customized for each subject. MES = myoelectric signals.

control strategy, activating the desired neuroprosthesis state is the means by which the user modulates a command signal that is sent to the neuroprosthesis controller. Command signal modulation directly corresponds to modulating the stimulation sent to the muscles; therefore, the movement and force of the hand grasp are graded by modulating the command signal [19]. The command signal decreases when the Open state is activated, increases when the Close state is activated, and remains constant at its most recent value when the Hold or CGP state is activated. The speed of command signal modulation, and corresponding hand motion, is proportional to the magnitude of the myoelectric signal. In summary, this control strategy makes provision for the user to (1) grade opening, closing, and force of grasp; (2) maintain a desired hand position or grasp force; and (3) select different stimulation patterns.

This paper reports on the first phase of feasibility testing of the described myoelectric control strategy. The scope of this phase of feasibility testing included characterizing MES from the wrist muscles and evaluating subjects' ability to use the control strategy to perform control tasks that would be required in an actual neuroprosthesis. The specific objectives of this study were to (1) derive subject-specific thresholds and state boundaries for the control strategy and (2) test the subjects' ability to perform simulated neuroprosthesis state activation and command signal modulation. No electrical stimulation was used in this study. Future experiments that involve implantation of stimulation electrodes for hand grasp will be conducted based on the results of this study.

METHODS

Subjects and Experimental Setup

Five able-bodied subjects and two subjects with C7 SCI participated in the study (**Table**). Our institutional review board approved the study protocol, and informed consent was obtained from each subject. Both subjects with SCI had adequate strength in the wrist flexors and extensors to provide full range of motion against gravity and some resistance (grade 4). Neither of the subjects with SCI were candidates for the FES system because their finger muscles were not excitable with electrical stimulation due to denervation. However, this did not preclude them from being candidates for the study, since no muscle stimulation was required.

MES from the wrist muscles were recorded using fine-wire intramuscular electrodes (Nicolet Biomedical Inc., Madison, WI). Surface electrodes were used for subject 6 due to time and scheduling constraints. The intramuscular electrodes were fabricated from pairs of insulated nickel-alloy wires (45 µm) with 2 mm of wire exposed at each tip. The bent tips of the wires were staggered at 2 and 5 mm to help maintain separation between the exposed ends. The intramuscular electrodes were inserted into the flexor carpi radialis (FCR) and extensor carpi radialis brevis (ECRB) via 25-gauge hypodermic needles. A bandage with a connector block affixed to it was placed near the electrode exit site, creating an interface that made connecting the electrodes to the MES recording equipment easy. The electrodes remained in the muscles for 3 to 5 days (**Table**), the duration of the study. With subject 6, pregelled surface electrodes with a 2 cm × 2 cm contact area (Kendall-LTP, The Ludlow Company LP, Chicopee, MA) were placed over the ECRB and FCR parallel to the muscle fibers with a center-to-center spacing of approximately 3 cm. With all the subjects, a single-surface electrode was placed on the lateral epicondyle of the humerus for use as a reference electrode.

A block diagram of the stages of data acquisition and signal processing is shown in **Figure 2**. The MES were amplified with the use of preamplifiers (Motion Control, Inc., Salt Lake City, UT) and a differential amplifier (Cambridge Electronic Design, Ltd, Cambridge, UK), together having an effective passband of 10 to 1,000 Hz. The signals were sampled at 5 kHz with 16-bit analog-to-digital conversion, debiased, rectified, and smoothed with a running time window averager with a window length of 240 ms that updated every 80 ms. The processed signals were normalized by the amplitudes of the maximum voluntary contractions and were displayed on a computer screen with the use of LabVIEW™ software (National Instruments Corporation, Austin, TX).

Control Strategy Customization: Partitioning Signal Space

The first set of experiments determined how to partition the signal space into regions that correspond to the Open, Close, and Hold states (**Figure 1**).

Table.
Subject demographics.

Subject	Years Postinjury	Age	Gender	Days Implanted
1	N/A	41	Male	5
2	N/A	26	Male	4
3	N/A	49	Male	3
4	N/A	20	Male	4
5	N/A	23	Female	4
6	5.5	50	Male	N/A
7	9.5	36	Male	4

Note: Subjects 6 and 7 had traumatic spinal cord injury resulting in tetraplegia at the American Spinal Injury Association (ASIA) C7 functional motor level. Subject 6 was classified as group 5, and subject 7 was classified as group 6, according to the International Classification for Surgery of the Hand in Tetraplegia. Surface electrodes were used to record myoelectric signals in subject 6; therefore, no explant of electrodes was necessary.

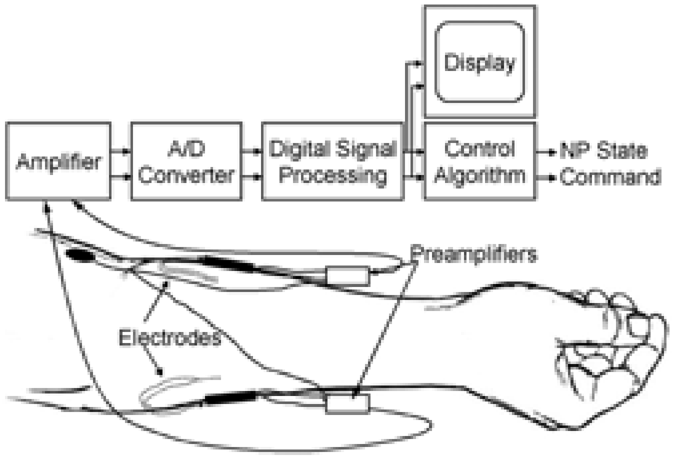

Figure 2.
Block diagram of experimental setup.

The ECRB and FCR MES were recorded during wrist flexion, extension, and rest. The subjects attempted to match five progressively increasing target contraction strengths by flexing and extending the wrist with nonisometric muscle contractions. The increase in the peak-to-peak fluctuation in the MES that occurs as the strength of contraction increases [20] was approximated with a linear fit, as described by Vodovnik and Rebersek [21]. From this relationship, estimates of the distinct levels of sustained contraction expected from both muscles were calculated. MES were then recorded during trials in which the subject attempted to match the calculated target levels. The muscle contractions recorded were 4 s in duration, followed by 2 s of rest. Visual and audible cues prompted the subjects when to contract and relax and whether to flex or extend the wrist.

These trials were repeated with the arm in four functional postures, with and without a weight (1 or 2 lb) fastened to the hand. This was done to help ensure that the control strategy would accommodate changes in MES characteristics that may accompany variations in arm posture or load in the hand. The four postures were the four combinations created when the arm was either reaching up to the side or held in front of the body and when the forearm was either neutral or prone. These four postures, with and without the load on the hand, made up eight arm-forearm-load combinations at which MES data during wrist flexion and extension were recorded.

Data points from the final 2 s of the 4 s sustained wrist flexion and extension contractions from all trials were displayed on a graph of signal space (ECRB vs. FCR), and were color-coded so that wrist flexion and extension data could be distinguished. The positions of the side boundaries, which define the width of the Open and Close regions, were determined by inspection of the data and were placed so that they enclosed at least 95 percent of the data points recorded during sustained wrist flexion and extension. Baseline thresholds, the boundaries that separate the Hold from the Open and Close regions, were similarly determined by examination of the data collected during the rest periods between flexion and extension contractions and during additional trials in which subjects were asked to move the arm in space while keeping the wrist relaxed. The boundary that separates the CGP state from the Hold state was placed at a radius of 0.4 or 0.5 units based on pilot data, which indicated that the vector magnitude of MES that subjects could produce during cocontraction was usually 0.4 to 0.6 units. The Open and Close regions were partitioned into subregions based on the calculations of achievable distinct MES levels. Each subregion corresponded to a distinct speed of command modulation; the slowest speed was set at 25 percent per second and the fastest was 50 percent per second.

Control Strategy Evaluation

The second set of experiments evaluated the suitability of the customized control strategy. The customized control algorithm, which calculated the instantaneous neuroprosthesis state and command level given a single sample of MES from both muscles, was incorporated into the test setup. We tested each subject's ability to (1) activate each neuroprosthesis state by moving the operating point into each region when prompted and (2) open, close, and maintain target positions of a computer-simulated hand. These experiments were patterned after those of Daly et. al., who described a similar paradigm for evaluating control strategies for multifunction prosthetic arms [18].

State Activation Test

This test determined the reliability with which a subject could deliberately activate the Open, Close, and Hold neuroprosthesis states. The graph of signal space, including its customized boundaries, was displayed on a computer screen (**Figure 3(a)**). The setup allowed the subject to move a cursor (representing the amplitude of myoelectric activity in both wrist muscles) on the graph by contracting and relaxing the wrist muscles. The test required

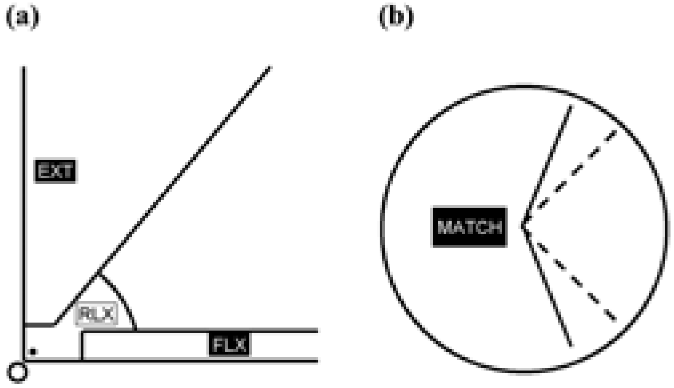

Figure 3.
Real-time displays of subject performance during control strategy evaluation: **(a)** State Activation Test display. Cursor near origin of plot marks instantaneous simultaneous amplitude of MES recorded in wrist flexor (FLX) and extensor (EXT) muscles. Rectangular indicators light up in turn, cuing subject to move cursor into its respective region. When cursor is in target region, round indicator in lower left corner lights up. **(b)** Position Matching Test display. Dotted lines mark target position, and position of solid lines is controlled by subject's myoelectric activity. MATCH indicator lights up when subject-controlled position is moved within ±5% of target lines. RLX = relaxation.

the subject to move the cursor into the target region of the graph, indicated by a light that turned on in that region, and to maintain the cursor in the target region as long as the light remained on. The target region changed every 4 s from Hold to Close to Hold to Open ten times. The test was repeated at the eight arm-forearm-load conditions previously described. Prior to testing, the subject was allowed to practice moving the cursor into the different regions of the graph until he or she understood what wrist actions were required to do the test.

The following data were recorded for each target presented: (1) the maximum number of continuous seconds the target state was activated, (2) the number of nontarget states activated while attempting to activate and maintain the target state (errors), and (3) the duration of time during which errant states were activated. For each target state, error detection started when any region other than the previous target region was reached; but if the state being activated at the beginning of the new target was not the previous target, then an error was counted and error detection began as soon as the target was presented. From these data, the rate of state activation, the incidence of error, and the average time duration of an error were calculated. The rate of state activation was the percentage of target presentations during which the subject positioned the cursor in the target region for at least a specified number of continuous seconds. The rate of state activation was calculated for several fractions of target duration. The incidence of error was the percentage of target presentations during which one or more errors were registered. For each subject, the results of all eight repetitions of the test were pooled.

Change Grasp Pattern Test

This test evaluated the subjects' ability to activate the CGP state. As in the State Activation Test, the graph of state space, with boundaries customized to the subject, was displayed. The task was to move the cursor into the CGP region from the relaxed state when cued by a light 10 times. The subject was not required to maintain the cursor in the CGP region, only to position it in the region transiently. The light remained on until the subject successfully moved the cursor into the region. Each cue to enter the CGP region was presented 2 s after the previous cue light was extinguished. The test was repeated at the eight arm-forearm-load conditions. A period of practice prior to testing allowed the subject to learn how the test worked and to develop a cocontraction strategy.

The following data were recorded for each target presented: (1) the time required to activate the CGP state and (2) the number of cocontraction attempts that failed to move the cursor into the CGP region. From these data, the average time to activate the CGP state and the average number of failed attempts per target presentation were calculated. For each subject, the results of all eight repetitions of the test were pooled.

Position Matching Test

This test determined the reliability with which a subject could control the degree of opening and closing of an on-screen representation of a hand, a task that directly corresponded to modulating the command signal. The simulated hand appeared as a round dial with two indicator needles (**Figure 3(b)**) that were programmed to open and close in response to the state activated by MES recorded from the wrist muscles. The command signal was linearly mapped to the position of the indicator needles so that 0 percent command corresponded to the fully opened position and 100 percent command corresponded to the fully closed position. A target position (indicated by the dashed lines in **Figure 3(b)**) was superimposed on the simulated hand. The subject's task was to move the position of the indicator needles (by activating the appropriate state via myoelectric control) so that it matched the target position within ±5 percent and to maintain the target position until it changed. A light indicated when the position of the indicator needles was within ±5 percent of the target position. The subject was instructed to correct overshoots and undershoots of the target until the position of the indicator needles was within ±5 percent of the target. Every 8 s the target position changed to one of three positions, 25 percent, 50 percent, and 75 percent of full closure, which were each presented 10 times in that order. The test was repeated at the eight arm-forearm-load conditions. Prior to testing, the subject practiced opening and closing the indicator needles until he or she understood what wrist actions were required to do the test.

The following data were recorded for each target presented: (1) the maximum number of continuous seconds the target position was matched, (2) the number of times the indicator needles moved away from the target position instead of toward it (errors), and (3) the magnitude of inadvertent command change made each time the indicator needles moved away from instead of toward the target. From these data, the rate of position matching, the incidence of error, and the distribution of the errors by magnitude of inadvertent command change were calculated. The rate of position matching was the percentage of target presentations during which the subject matched the target position for at least a specified number of continuous seconds. This rate of position matching was calculated for several fractions of target duration. The incidence of error was the percentage of target presentations during which one or more errors were registered. For each subject, the results of all eight repetitions of the test were pooled.

RESULTS

Control Strategy Customization

For each subject, it was possible to define distinct regions of signal space that encompassed at least 95 percent of the data points collected during sustained wrist extension and flexion at the eight arm-forearm-load combinations (**Figure 4**). Each subject was able to maintain two to four distinct amplitudes of ECRB and FCR MES. The baseline thresholds used in the control algorithms ranged from 0.10 to 0.20 across the seven subjects.

State Activation Test

Every subject was able to activate at least 99 percent of the target states for more than 1 continuous second, and at least 90 percent of the target states for more than 2 continuous seconds (**Figure 5(a)**). The incidence of error (percentage of target presentations during which nontarget states were activated) ranged from 2 percent to 52 percent across subjects (**Figure 5(b)**). The total number of errant state activations ranged from 8 to 282 (not shown), giving a mean number of errant state activations per target presentation that ranged from 0.03 to 0.88. These results compare favorably to the control strategy evaluations for prosthetic arms, where the mean number of errant state selections per trial ranged from 0.07 to 1.30 [18]. The average duration of all errant state activations ranged from 135 to 330 ms (**Figure 5(c)**).

Subjects 1 and 5 consistently exhibited a reflex burst of myoelectric activity from the FCR during the initiation of wrist extension. This bursting activity of the flexor muscle resulted in transient inadvertent activation of the Open state when the Close state was the target. The frequent occurrence of this error accounts for the relatively large number of errors made by subjects 1 and 5. Neither subject could prevent the reflex bursting, but the amplitude of the burst could be somewhat diminished if wrist extension was performed slowly.

Change Grasp Pattern Test

The average time to activate the CGP state was less than 1 s for all subjects except subject 6 (**Figure 6(a)**). The average number of failed attempts to activate the CGP state per target presentation ranged from 0.01 to 0.60 across subjects (**Figure 6(b)**). Subject 6 required a significantly greater amount of time to activate the CGP state as compared to the other subjects because of his higher frequency of failed attempts.

Position Matching Test

Every subject could match at least 87 percent of the target positions for more than 2 continuous seconds, and at least 70 percent of the target positions for more than 4 continuous seconds (**Figure 7(a)**). The incidence of error (percentage of target presentations during which the subject-controlled indicator needles moved away from the target position) ranged from 18 to 53 percent across subjects (**Figure 7(b)**). The total number of errors (inadvertent opening or closing of the indicator needles) ranged from 57 to 234 (not shown). Most of these errors

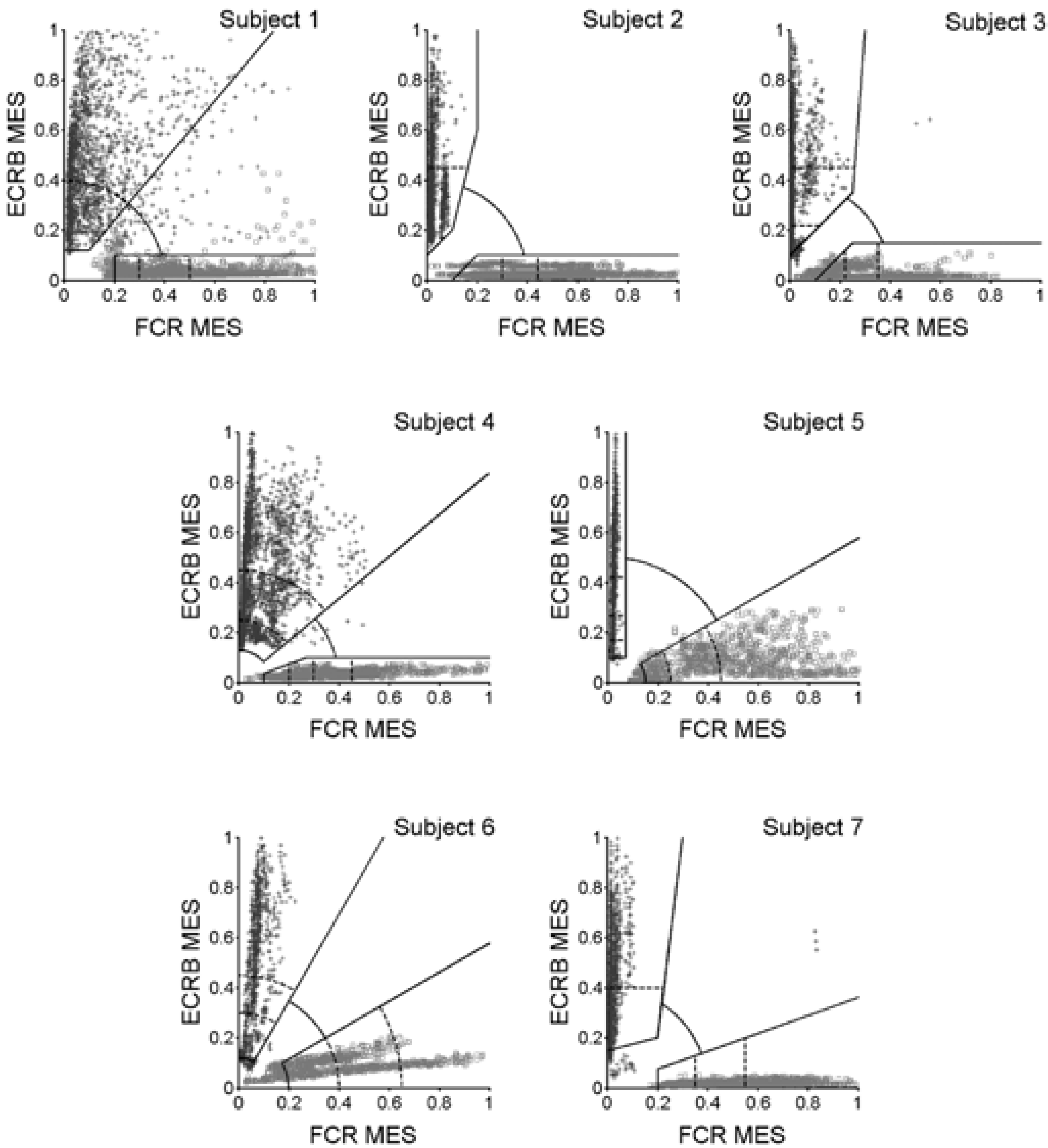

Figure 4.
Graph of signal space for each subject. Each data point is sample of processed MES recorded simultaneously from ECRB and FCR during wrist extension (+) or flexion (□) contractions sustained at various strengths under eight different arm-forearm-load conditions. Solid lines indicate baseline thresholds and boundaries that partitioned signal space into regions corresponding to neuroprossis states. Dashed lines subdivided Open and Close regions into subregions corresponding to different speeds of command modulation.

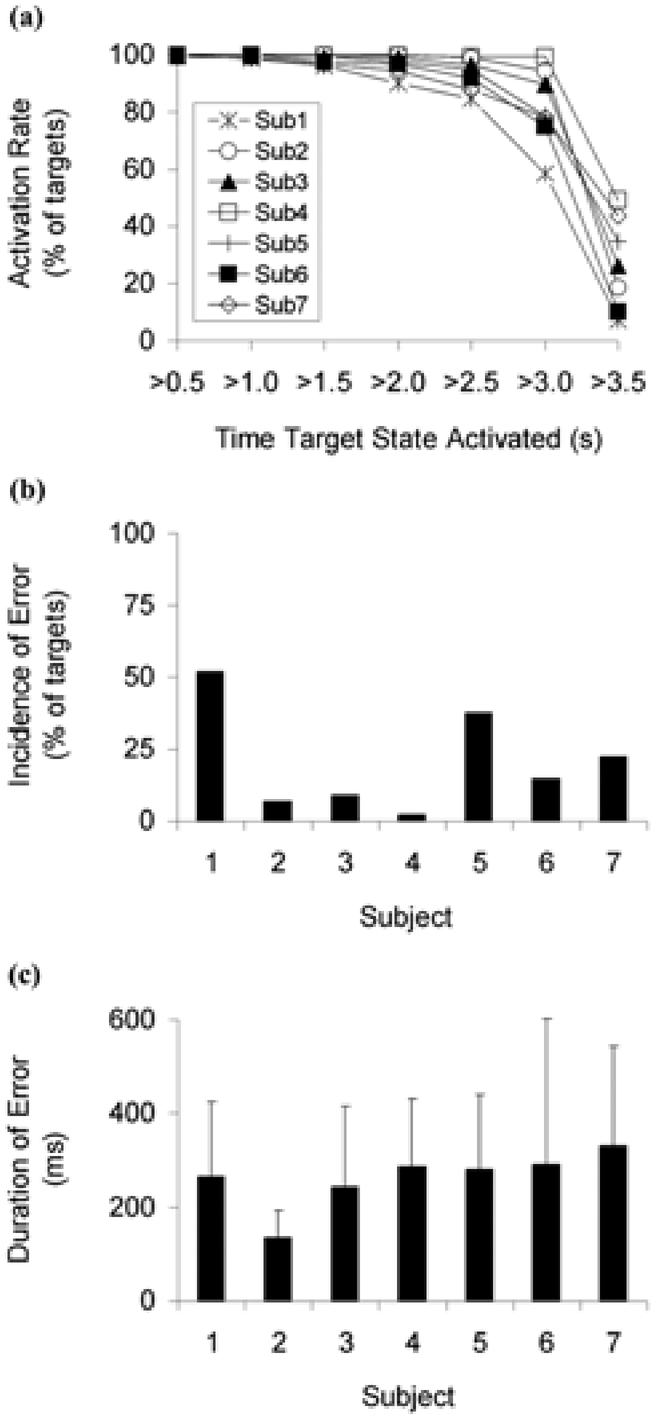

Figure 5.
Summary of State Activation Test results. For each subject, results from all eight test repetitions were pooled. **(a)** Activation Rate, percentage of 320 targets presented that were activated for specified fractions of total target duration (4 s). **(b)** Incidence of Error, percentage of 320 targets presented during which one or more nontarget states was activated. **(c)** Duration of an Error, average and standard deviation of durations of errant state activation.

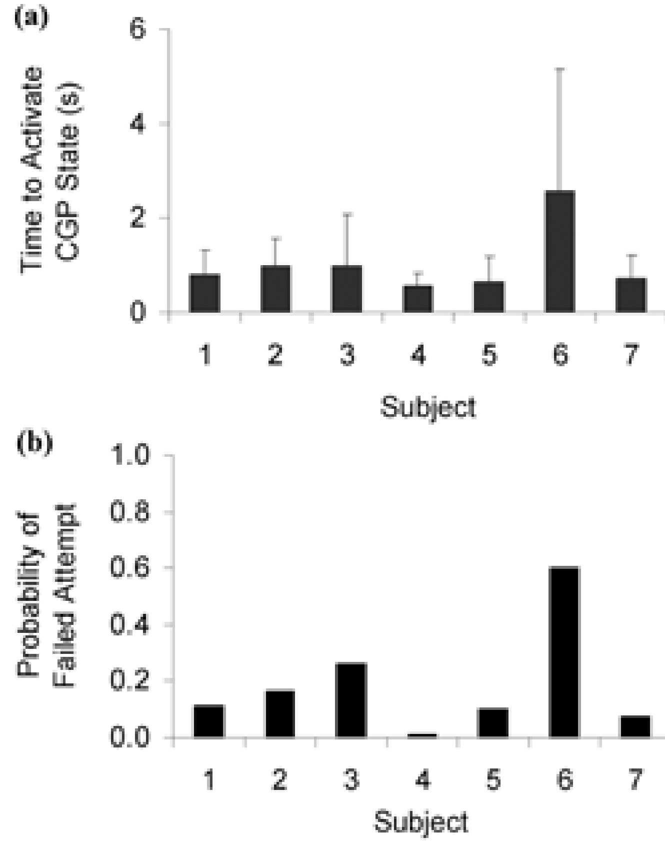

Figure 6.
Summary of Change Grasp Pattern Test results. For each subject, results from all eight test repetitions were pooled. **(a)** Time to Activate CGP State, average and standard deviation of time elapsed before CGP was activated. **(b)** Probability of a Failed Attempt, average number of cocontraction attempts that failed to activate CGP state per target presentation.

occurred because the subjects either forgot whether they should flex or extend the wrist, or overshot the target position because of failure to relax the muscles at the right time or inadvertent state activation upon muscle relaxation. The frequency of these mistakes was highly variable across subjects, accounting for the high variability in overall error rate across subjects. Most of the errors resulted in small inadvertent changes in command. Across all subjects, 34 percent to 63 percent of the errors were of a magnitude less than 5 percent of the command range, and 85 percent to 96 percent of the errors were of a magnitude less than 15 percent of the command range (**Figure 7(c)**).

Effects of Posture, Load, and Target

The variance of the incidence of error in the State Activation Test and Position Matching Test was analyzed

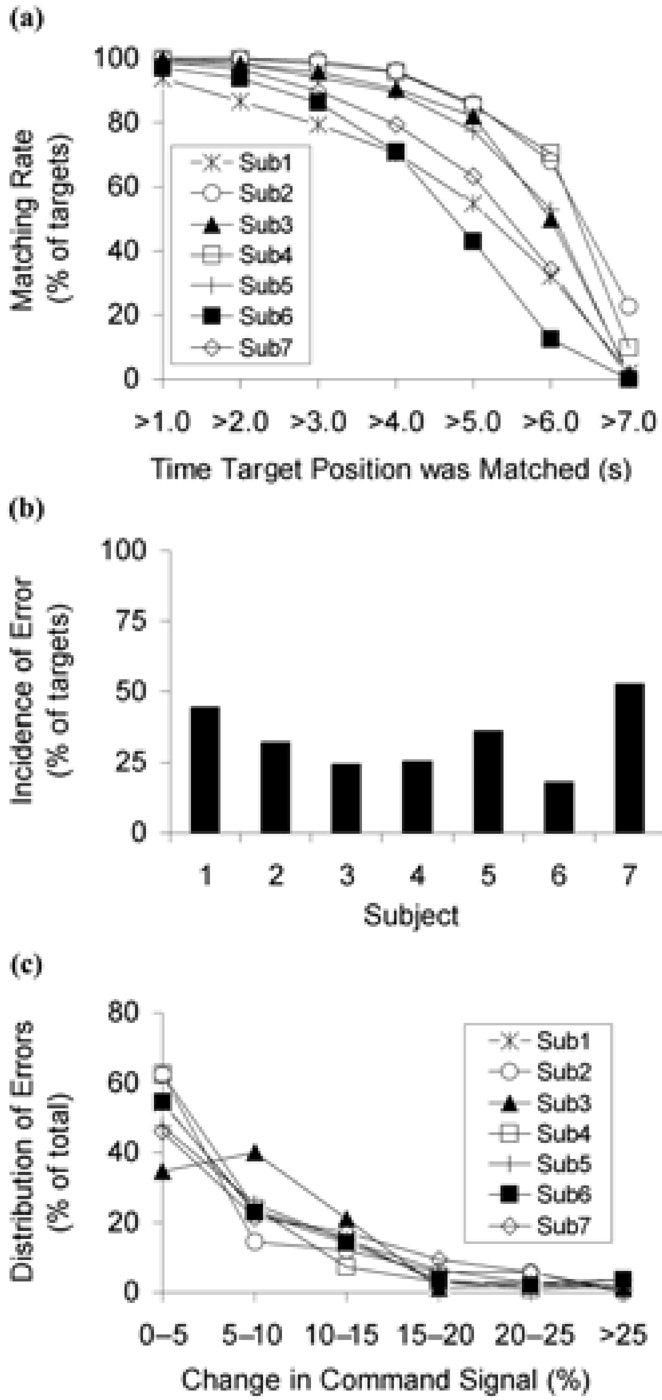

Figure 7.
Summary of Position Matching Test results. For each subject, results from all eight test repetitions were pooled. **(a)** Matching Rate, percentage of 240 targets presented that were matched for specified fractions of total target duration (8 s). **(b)** Incidence of Error, percentage of 240 targets presented during which subject-controlled indicator needles moved away from target position at least once. **(c)** Distribution of Errors, percentage of total number of errors for specified magnitudes of inadvertent command change they caused.

with the use of logistic regression (S-PLUS 2000, MathSoft, Inc., Seattle, WA) with respect to four factors: arm position, forearm rotation, load condition, and target state or position. Different main effects and interactions between factors were found to be significant for different subjects. No consistent pattern emerged from one subject to another in the way the factors affected the incidence of error. Three-way interactions among the factors were found to be significant in all the subjects, which complicated the interpretation of the effect of the factors. With the data from all the subjects pooled, the three-way interaction among the arm position, forearm rotation, and load condition significantly affected the incidence of error in both the State Activation and Position Matching Tests. With interactions eliminated from the logistic regression model, the significant main effects were the target state and load condition in the State Activation Test and the target position, forearm rotation, and load condition in the Position Matching Test.

DISCUSSION

The control strategy represented in **Figure 1** requires an individual to reliably produce four unique muscle contraction patterns. With the wrist flexor and extensor as control muscles, we hypothesized that most individuals could produce four unique contraction patterns by extending the wrist, flexing the wrist, relaxing both wrist muscles, and cocontracting the wrist muscles briefly. The data in **Figure 4** support this hypothesis, showing that for each subject the MES patterns produced during sustained wrist flexion and extension could be distinguished with at least 95 percent reliability, although we observed considerable variation from subject to subject. Subject 1, in particular, had more cocontraction during wrist extension than the other subjects. Some possible causes of the different degrees of cocontraction across subjects include variation in the placement of the recording electrode relative to the motor point [22,23], variation in the spacing of the two contacts of a single electrode [24,25], or actual differences in neuromuscular control properties, which may be influenced by damage to the spinal cord (e.g., loss of reciprocal inhibition), training, or the nature of regular use of the wrist muscles.

The control strategy being investigated does not require long durations of state activation to achieve good control. Activation of control states for as little as 0.5 s is adequate to modulate the command signal over a significant proportion of the total command range, depending on the speed setting of command modulation. Every subject was able to reliably and deliberately activate the Open, Close, and Hold neuroprosthesis states for adequate time durations, as shown in **Figure 5(a)**. Additionally, it should be understood that **Figure 5(a)** and **Figure 7(a)** do not indicate that the subjects were unable to maintain a state for greater than 4 s or maintain a command level for greater than 8 s. The rates drop to 0 as the fraction of target duration approaches 1 because, even if no errors are made, some time will always be taken up by signal processing delay (~240 ms), reaction time, and, in the case of position matching, the command excursion required to match the target position and the speed of command modulation. The target durations of 4 s and 8 s were chosen so that ample time would be available to reveal errors the subjects may make in activating or maintaining a state.

Although the rates of target state activation were generally high, some subjects also unintentionally activated nontarget states at a high rate (as high as 52%). High error rates in the State Selection and Position Matching Tests, however, do not disqualify the control strategy if the errors have only minimal consequences. The severity of an error is reflected in the magnitude of inadvertent change in command signal that the error caused (**Figure 7(c)**), which is also directly related to the duration of the error (**Figure 5(c)**). The magnitude of most of the inadvertent command signal changes for every subject was less than 10 percent. The magnitude of inadvertent command change that is acceptable depends on the magnitude of inadvertent position change or force change in the grasp. In an actual neuroprosthesis, the relationship of the command signals to the hand position and grasp force is not linear, varies from subject to subject, and depends on the recruitment characteristics of the stimulation electrodes [19]. Based on our experience with neuroprostheses for hand grasp, small inadvertent changes in command signal are not expected to significantly alter hand function.

Requiring cocontraction of antagonist wrist muscles to change the grasp pattern may be acceptable for some subjects, but not for all. High rates of inadvertent CGP activation or a high probability of failing to activate CGP when intended (**Figure 6(b)**) may indicate that the CGP region needs to be modified or that an alternative means of activating CGP needs to be made available. For example, subject 1 had a high incidence of inadvertent CGP activation, 23 percent, during the State Activation Test, which would likely be decreased if the CGP threshold were raised. Subject 6 had an especially high probability of a failed attempt to change the grasp pattern. Posttest analysis suggests that subject 6 would have performed significantly better in the CGP test if the CGP threshold had been set lower. This, however, may have made inadvertent CGP activations more frequent. Alternatively, a different region of signal space could be reserved for the CGP state, such as a subregion of the Close state that would require a transient high-amplitude ECRB contraction.

Because errors in state activation were typically the result of the cursor in signal space crossing quickly through nontarget regions, it may be possible to reduce the occurrence of these errors by adding rules to the control algorithm that require the MES amplitudes (the position of the cursor) to reach a defined degree of stability before a state is activated. We recalculated the number of errors that were made by subject 5 (a subject with FCR bursts during initiation of wrist extension) in the State Activation Test after adding the following rules to the control algorithm: (1) the cursor must be in the same region of signal space for two consecutive samples, (2) the angular difference between two consecutive cursor positions must be less than 3°, and (3) the distance between two consecutive cursor positions must be less than 0.05 normalized MES units before a new state is calculated. With these rules added to the control algorithm, the number of errors was reduced by 71 percent, from 211 to 61. The disadvantage to adding these types of rules to the control algorithm is that the response of the system would be delayed by at least one iteration (80 ms) of data processing.

The control strategy customization procedure was designed to minimize the effects of arm and forearm position and hand loading on controllability by basing the boundary positions on data that were collected at different static arm-forearm-load conditions. Nevertheless, the incidence of error in state selection and position matching did change with arm-forearm-load condition in some subjects. For example, subject 5 generally made more state activation errors while reaching and made fewer errors when she held her arm in front of the body. Arm position had the opposite effect in subject 1. The practical ramifications of this postural and/or load dependence depend on the nature of the errors made, which were shown in this study to be brief, usually resulting in small command signal changes that are expected to be inconsequential.

The frequency with which recalibration of the MES will be necessary in a fully implanted system depends on the repeatability of the MES recordings over time. This, in turn, is affected by neurophysiological changes in the control muscles and changes in the recording properties of the electrodes. If changes in the control muscles do occur, such as increases in strength due to greater use, they are expected to eventually plateau. The recording properties of the electrode are not expected to change if the electrode position within the muscle and contact spacing is stable. The type of electrode to be used in the fully implanted system will be sutured in place. Conversely, the fine-wire electrodes that were used in these experiments may be displaced within the muscle when it contracts, and the separation between the recording contacts may also change [26]. Changes in amplifier gain or in normalization values had to be made from day to day in three of the six subjects that had the fine-wire electrodes because the MES amplitudes had changed. However, the customized thresholds and boundaries were not changed for any of the subjects even though the data that were used to customize the control strategy were collected on a previous day. Once the gain and/or normalization values were set or reset appropriately, the control strategy boundaries did not need to be changed. Therefore, in the final system configuration with implanted MES electrodes having a fixed spacing, recalibration of the MES and of the control strategy boundaries may be needed only infrequently.

This study was an initial evaluation of the suitability of a particular myoelectric control strategy to allow individuals to reliably activate states and modulate a command signal, minimum requirements for controlling a neuroprosthesis. While testing an individual's ability to control the movement of objects on a computer screen may not yield accurate predictions of the ability to control a neuroprosthesis, it does allow us to screen potential control strategies before implementing them with an FES system.

Control difficulties may arise when electrical stimulation is being delivered to muscles that actuate the hand. In future studies, stimulus artifacts in the MES will be suppressed with circuitry that disconnects the MES inputs from the amplifier during delivery of the stimulation pulses. Control difficulties related to limb dynamics and interaction of the hand with objects may emerge when the individual attempts to use his or her hand to perform a task. The effect of these factors on controllability will be investigated in a future study that will incorporate the myoelectric control strategy into an FES system, enabling subjects with low-level tetraplegia to control their own hand with MES from the wrist muscles.

CONCLUSIONS

This study demonstrated that individuals can produce, at static arm postures, contraction patterns from the wrist flexor and extensor muscles that are adequately distinct for using the neuroprosthesis control strategy. The high state-activation and position-matching rates and the small inadvertent changes in command signal provide justification for integrating the control strategy into an FES hand-grasp neuroprosthesis for a final stage of feasibility testing in subjects with low cervical tetraplegia. This will allow us to more fully explore how the controllability is affected by the application of electrical stimulation, limb dynamics, and interaction of the hand with the environment during actual hand-grasp tasks.

ACKNOWLEDGMENT

We wish to thank Anne Bryden, OTR/L, for assisting in subject recruitment and evaluation for this study.

REFERENCES

1. Peckham PH, Marsolais EB, Mortimer JT. Restoration of key grip and release in the C6 tetraplegic patient through functional electrical stimulation. J Hand Surg. 1980;5A: 462–69.
2. Keith MW, Peckham PH, Thrope GB, Stroh KC, Smith B, Buckett JR, et al. Implantable functional neuromuscular stimulation in the tetraplegic hand. J Hand Surg. 1989;14A: 524–30.
3. Kilgore KL, Peckham PH, Keith MW, Thrope GB, Wuolle KS, Bryden AM. An implanted upper-extremity neuroprosthesis: follow-up of five patients. J Bone Joint Surg. 1997; 79A:533–41.
4. Mulcahey MJ, Betz RR, Smith BT, Weiss AA, Davis SE. Implanted functional electrical stimulation hand system in adolescents with spinal injuries: an evaluation. Arch Phys Med Rehabil. 1997;78:597–607.
5. Carroll S, Cooper C, Brown D, Sormann G, Flood S, Denison M. Australian experience with the Freehand System for restoring grasp in quadriplegia. Aust N Z J Surg. 2000;70: 563–68.

6. Hobby J, Taylor PN, Esnouf J. Restoration of tetraplegic hand function by use of the neurocontrol freehand system. J Hand Surg. 2001;26B:459–64.
7. Peckham PH, Kilgore KL, Keith MW, Bryden AM, Bhadra N, Montague FW. An advanced neuroprosthesis for restoration of hand and upper arm control using an implantable controller. J Hand Surg. 2002;27A:265–76.
8. Wijman CA, Stroh KC, VanDoren CL, Thrope GB, Peckham PH, Keith MW. Functional evaluation of quadriplegic patients using a hand neuroprosthesis. Arch Phys Med Rehabil. 1990;71:1053–57.
9. Wuolle KS, VanDoren CL, Bryden AM, Peckham PH, Keith MW, Kilgore KL, et al. Satisfaction with and usage of a hand neuroprosthesis. Arch Phys Med Rehabil. 1999; 80:206–13.
10. Peckham PH, Keith MW, Kilgore KL, Grill JH, Wuolle KS, Thrope GB, et al. Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study. Arch Phys Med Rehabil. 2001;82:1380–88.
11. Taylor P, Esnouf J, Hobby J. The functional impact of the Freehand System on tetraplegic hand function. Clinical results. Spinal Cord. 2002;40:560–66.
12. DeLuca C. Physiology and mathematics of myoelectric signals. IEEE Trans Biomed Eng. 1979;26:313–25.
13. Johnson MW, Peckham PH. Evaluation of shoulder movement as a command control source. IEEE Trans Biomed Eng. 1990;37:876–85.
14. Hart RL, Kilgore KL, Peckham PH. A comparison between control methods for implanted FES hand-grasp systems. IEEE Trans Rehabil Eng. 1998;6:208–18.
15. Smith BT, Mulcahey MJ, Triolo RJ, Betz RR. The application of a modified neuroprosthetic hand system in a child with a C7 spinal cord injury—case report. Paraplegia. 1992; 30:598–606.
16. Johnstone BR, Jordan CJ, Buntine JA. A review of surgical rehabilitation of the upper limb in quadriplegia. Paraplegia. 1988;26:317–39.
17. Scott TR, Peckham PH, Kilgore KL. Tri-state myoelectric control of bilateral upper extremity neuroprostheses for tetraplegic individuals. IEEE Trans Rehabil Eng. 1996;4:251–63.
18. Daly TL, Scott RN, Parker PA, Lovely DF. Operator performance in myoelectric control of a multifunction prosthesis simulator. J Rehabil Res Dev. 1990;27:9–20.
19. Kilgore KL, Peckham PH, Thrope GB, Keith MW, Gallaher-Stone KA. Synthesis of hand grasp using functional neuromuscular stimulation. IEEE Trans Biomed Eng. 1989; 36:761–70.
20. Kreifeldt JG. Signal versus noise characteristics of filtered EMG used as a control source. IEEE Trans Biomed Eng. 1971;18:16–22.
21. Vodovnik L, Rebersek S. Information content of myo-control signals for orthotic and prosthetic systems. Arch Phys Med Rehabil. 1974;55:52–56.
22. Loeb GE, Gans C. Structural and functional factors influencing the EMG signal. In: Loeb GH, Gans C, eds. Electromyography for experimentalists. Chicago: The University of Chicago Press; 1986. p. 50–59.
23. Kamen G, Caldwell GE. Physiology and interpretation of the electromyogram. J Clin Neurophys. 1996;13:366–84.
24. Loeb GE, Gans C. The electrode as an antenna. In: Loeb GH, Gans C, eds. Electromyography for experimentalists. Chicago: The University of Chicago Press; 1986. p. 60–70.
25. Dimitrova NA, Dimitrov GV, Chihman VN. Effect of electrode dimensions on motor unit potentials. Med Eng Phys. 1999;21:479–85.
26. Jonsson B, Bagge UE. Displacement, deformation, and fracture of wire electrodes for electromyography. Electromyography. 1968;8:329–47.

Submitted for publication April 11, 2003. Accepted in revised form September 7, 2003.