A Neuroprosthesis for Restoring Arm and Hand Function via Functional Electrical Stimulation Following High Cervical Spinal Cord Injury

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Abstract

This paper describes the development and implementation of an implanted neuroprosthesis for restoring hand and arm function to an individual with high level tetraplegia resulting from a C1 “Brown Sequard” spinal cord injury. This individual has complete motor paralysis of one arm below the level of the neck and is thus highly disabled. The neuroprosthesis that has been surgically implanted was designed to restore basic upper extremity movements needed for simple yet important daily activities such as eating and grooming. The neuroprosthesis utilizes 24 channels of stimulation, muscle-based electrodes for stimulation of hand muscles, and nerve cuff electrodes for stimulation of shoulder and elbow muscles. The two implanted stimulators also include a total of four implanted bipolar EMG recording channels that sample activity in neck and facial muscles. These signals, along with measurements of head orientation, provide the user command interface for this system.

1 Introduction

This paper describes a significant ongoing effort by our research group to provide useful arm and hand movement control to individuals with high cervical (C1-C4) spinal cord injury, a condition referred to as high tetraplegia. These injuries are at the highest level of the spinal cord and leave those afflicted with extensive paralysis below the neck – typically such individuals are left with volitional control of just the head, neck, and in some cases shoulder shrug. Individuals with high tetraplegia are usually totally dependent on others for all aspects of care, and traditional rehabilitation procedures offer very limited options and result in limited functional improvement [1].

Neuroprostheses are systems that apply controlled electrical stimulation to paralyzed nerves and muscles to restore function. These systems can be used to restore different functions to individuals with a variety of different neurological disorders, although many applications to date have been for individuals with spinal cord injuries.

We have recently developed and then surgically deployed an implantable neuroprosthesis for individuals with high cervical spinal cord injury. This system, illustrated schematically in Figure 1, uses several existing components: an implantable 12-channel stimulator with two EMG recording channels, muscle electrodes for hand muscles, nerve cuff electrodes for stimulation of elbow and shoulder muscles, and an external controller unit for implementing control algorithms and powering the stimulators via an inductive link. Two stimulators rather than one were used to activate 24 muscles, and the stimulators have been modified for use with nerve cuff electrodes. The following sections will summarize progress to date on each of these components and describe how they were integrated together to form the neuroprosthesis.

2 Methods

2.1 Musculoskeletal Model-Based Muscle Selection

Musculoskeletal modeling is the process by which the mechanical properties of a limb are described mathematically. This description includes the mass and inertial properties of the limb segments, the geometry of the limb, and the properties of the muscles that power the
Simulations performed with a musculoskeletal model are particularly useful for neuroprosthesis development because they allow many different situations to be examined before a neuroprosthesis is implemented. Simulations with our musculoskeletal model were used to determine the optimal set of shoulder and elbow muscles required to perform a set of tasks important for providing some independence to individuals with high tetraplegia, specifically for providing tabletop to mouth motions needed for eating and grooming, and reaching in the coronal and scapular planes from the laptop to shoulder level needed for many tasks.

We performed simulations using the Delft shoulder and elbow model [2] that was systematically modified to vary the number of muscles and the specific muscles used, mimicking FES systems using different muscle combinations. We also examined the effects on function of simultaneously activating several muscles via their common peripheral nerve (e.g., via a nerve cuff electrode).

2.2 Stimulation Hardware

The stimulation channels needed for proximal control (described above) and for hand and wrist function were providing through the use of an existing stimulator-telemeter device (Figure 3) that provides 12 stimulation channels and two bipolar EMG channels. Two of these units were used to implement this neuroprosthesis, bringing the total capability to 24 stimulation channels and 4 EMG recording channels. This device has been modified to allow safe stimulation through nerve cuff electrodes (for proximal muscles) while also maintaining the capability for stimulation through muscle-based electrodes (lower right of Figure 3) for hand and wrist muscles. EMG signals can be obtained during inter-stimulus periods through bipolar electrodes (lower left in Figure 3) surgically placed on muscles above the level of the spinal cord injury.

2.3 Peripheral Nerve Cuff Electrodes

A substantial effort has been invested in bringing nerve cuff electrodes into use in this neuroprosthesis for several reasons. Such electrodes guarantee complete activation of potentially weak, partially denervated muscles and have the potential to allow selective activation of several muscles from a single cuff. Nerve cuff electrodes are particularly appropriate for the proximal joints of the upper extremity because most of the nerves serve a single muscle or just a few synergistic muscles, because these muscles have highly branched intramuscular innervation patterns that are not well suited for muscle-based electrodes, and because these muscles have large motions that tend to wrap along bony surfaces.

We have set up a manufacturing capability that allows the fabrication of spiral nerve cuff electrodes [3] of specific sizes and electrode configuration (i.e., single or multiple contacts). We have also developed a surgical tool that greatly simplifies surgical installation and minimizes trauma to the nerve. We have performed a large series of cadaver dissections that demonstrated that all of the nerves of interest are large enough in diameter and have sufficient branch-free lengths to accept the cuffs. We have obtained an IDE from the FDA that allows these cuffs to be permanently installed in the upper extremities of human subjects.

2.4 User Command Interface

One of the more difficult challenges for restoring arm and hand function in individuals with high tetraplegia is providing an effective, reasonably natural interface for the user to specify desired actions. This is a challenge
because many different degrees of freedom are paralyzed and must be commanded, while the number of voluntary functions that could be used to command these functions is quite limited. All of the available voluntary functions are located in the region of the neck and head, and thus none of them normally participate in arm control in the intact system.

We are currently evaluating three different user interfaces for controlling the 3D endpoint of the arm based on signals that can be readily recorded from these individuals: 3D head orientation, neck muscle EMG signals, and facial EMG signals. The one subject with an implanted neuroprosthesis received recording electrodes on the right platysma, left platysma, left trapezius, and right auricularis. Head orientation signals are obtained using a commercial sensor (Microstrain 3DM) and facial EMG signals have been obtained thus far using surface EMG recordings. All signals serve as inputs to a “gated-ramp” algorithm whereby a constant velocity motion in the commanded degree of freedom is initiated when the signal exceeds a specified threshold and continues until the signal decreases below a second threshold.

3 Results

3.1 Musculoskeletal Model-Based Muscle Selection

The results of these simulations are presented in Table 1. We found a number of muscles were required in order to perform the selected set of functional movements, including the triceps, biceps, deltoid, serratus anterior, infraspinatus, supraspinatus, latissimus dorsi, pectoralis major, pronator quadratus, and supinator. The simulations also indicated that the long head of the triceps should NOT be activated, that biceps and brachialis should be independently activated, that deltoid and teres minor (which share the axillary nerve) should be independently activated, that only the lower part of the serratus anterior should be activated, and that the infraspinatus and supraspinatus could be activated together without functional loss. These simulation results were combined with surgical considerations to determine the final muscle set and the location of nerve cuff electrodes on several peripheral nerves.

3.2 Surgical Installation

The system illustrated in Figure 1 was implanted in one individual with a C1 Brown-Sequard spinal cord injury. Nine of the 24 stimulation channels in an implanted neuroprosthesis are contacts located on six separate nerve cuff electrodes. These cuff electrodes have exhibited excellent and stable performance for more than one year.

4 Discussion and Conclusions

This paper has described our work that shows that an arm and hand neuroprosthesis for high cervical SCI is feasible (via musculoskeletal model simulations), that an existing implantable stimulation and EMG recording device can be used to physically implement such a system, that nerve cuff electrodes are feasible and highly desirable for activating larger proximal muscles of the upper extremity, and that relatively simple interfaces can provide the user with the ability to command her or his own arm. Deployment of such a neuroprosthesis in a human subject has been successfully performed and extensive functional assessment of this system is underway.

References


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