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 of an implanted neuroprosthesis for restoring hand and arm function to individuals with high level tetraplegia resulting from C1-C4 spinal cord injury. These individuals have complete paralysis below the level of the neck and are thus highly disabled. The neuroprosthesis under development will restore basic upper extremity movements needed for simple yet important daily activities such as eating and grooming. Simulations performed with a musculoskeletal model of the shoulder and elbow indicate that existing stimulation technology using a realistic number of stimulation channels should be sufficient for providing these functions. The neuroprosthesis will utilize 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, will 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.

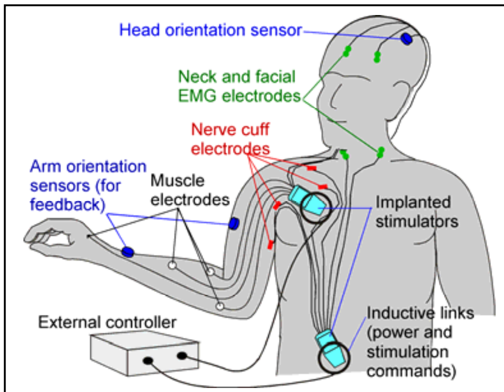

Figure 1: High tetraplegia neuroprosthesis

The implantable neuroprosthesis under development in this study is illustrated schematically in Figure 1. This system uses several existing components: an implantable 12-channel stimulator with two EMG recording channels, muscle electrodes for hand muscles, and an external controller unit for implementing control algorithms and powering the stimulators via an inductive link. Several new components have been added, including nerve cuff electrodes for stimulation of elbow and shoulder muscles, orientation sensors for control of arm position, and an additional sensor for measurement of head orientation as a command interface through which the user specifies desired arm motions. Two stimulators rather than one will be used to activate up to 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.

2. METHODS and RESULTS

2.1. Feasibility: Musculoskeletal modeling

Musculoskeletal modeling is the process by which the mechanical properties of a limb or limbs 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 limb. Simulations performed with a musculoskeletal model are useful for neuroprosthesis development because many different situations can be examined before a neuroprosthesis is actually implemented. That is, the model replaces an actual human subject for a significant portion of the development cycle, allowing the use of powerful mathematical tools to optimize performance and reducing the burden on human subjects.

We are making extensive use of simulations with a musculoskeletal model to develop this neuroprosthesis for high tetraplegia. Specifically, we have evaluated the feasibility of restoring elbow and shoulder function by determining the minimum number of shoulder and elbow muscles (and the forces of each muscle) required to perform a set of tasks important for providing some independence to individuals with high tetraplegia: 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. The results from the model simulations show that it should be feasible to restore these functions with the minimum set of only seven muscles: scapular head of trapezius, serratus anterior, clavicular head of deltoid, infraspinatus, subscapularis, brachialis and supinator. Of these seven muscles, six are typically paralyzed following high level SCI, while trapezius remains under voluntary control, indicating that only six channels of stimulation would be required. The magnitude of the muscle forces required from each of these muscles were typically in the 20-40% range relative to able-bodied, with a maximum of 68% for infraspinatus.

2.2. Stimulation hardware

The musculoskeletal model simulations described above indicated that six stimulation channels was the minimum for providing a small set of simple motions to the arm. Providing redundancy to account for weak muscles (e.g., biceps as well as brachialis, all heads of deltoid, etc.), to compensate for fatigue, and to provide additional arm functions will likely double this channel count. Activation of hand and wrist muscles further increases the number of needed stimulation channels.

We will meet these stimulation needs through the use of an existing stimulator-telemeter device that provides 12 stimulation channels and two bipolar EMG channels. Two of these units will be 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 for hand and wrist muscles. EMG signals can be obtained during inter-stimulus periods through bipolar electrodes surgically placed on muscles above the level of the spinal cord injury.

2.3. Muscle activation: nerve cuff electrodes

A substantial effort has been invested in bringing nerve cuff electrodes into use in this neuroprosthesis for several reasons. Such electrodes basically guarantee complete activation of potentially weak, partially denervated muscles and have the long range 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. We have performed a set of intraoperative tests (as illustrated in Figure 2) during nerve repair surgeries to demonstrate the ability to install the cuff electrodes on nerves of interest and the ability to selectively activate a single muscle from a multi-fascicle nerve trunk.

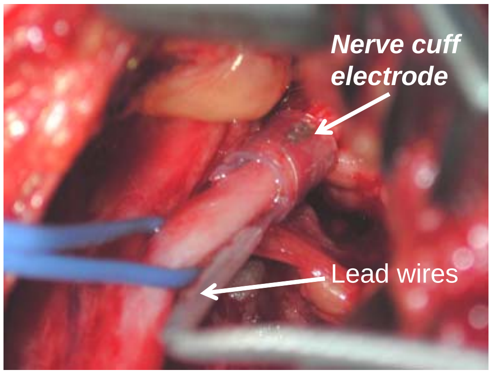

Figure 2. Spiral nerve cuff electrode installed on

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.

Figure 3. Facial EMG and head orientation sensor evaluation setup.

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 (see Figure 3): 3D head orientation, neck muscle EMG signals, and facial EMG signals. The EMG signal recordings will be obtained in the final system using the 4 EMG channels in the two implanted stimulator-telemeter devices, and the head orientation signal can be obtained using a commercial sensor (Microstrain 3DM). 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.

2. DISCUSSION

Restoration of arm and hand function following high cervical spinal cord injury via a neuroprosthesis requires the simultaneous development and integration of several different system components. This paper has described our work that shows such an approach is feasible in general (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 and testing of such a neuroprosthesis in a human subject is planned for the near future.

3. REFERENCES

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