Towards a Neuroprosthetic Arm*

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Abstract – **Evidence indicates that user acceptance of modern artificial limbs by amputees would be significantly enhanced by a system that provides appropriate, graded, distally referred sensations of touch and joint movement, and that the functionality of limb prostheses would be improved by a more natural control mechanism. We have recently demonstrated that it is possible to implant electrodes within individual fascicles of peripheral nerve stumps in amputees, that stimulation through these electrodes can produce graded, discrete sensations of touch or movement referred to the amputee's phantom hand, and that recordings of motor neuron activity associated with attempted movements of the phantom limb through these electrodes can be used as graded control signals. We report here that this approach allows amputees to both judge and set grip force and joint position in an artificial arm, in the absence of visual input, thus providing a substrate for better integration of the artificial limb into the amputee's body image. We believe this to be the first demonstration of direct neural feedback from and direct neural control of an artificial arm in amputees.**

Index Terms **– peripheral nerve, neuroprosthetics, amputee.**

I. INTRODUCTION

The overall goal of this project is to develop a Neuroprosthetic Arm: an artificial arm that is controlled by motor commands from nerve fibers (or residual muscles) in the amputee's stump that had originally controlled (or performed) the action desired, and that provides distally referred tactile and proprioceptive sensory feedback by stimulation of sensory nerve fibers in the stump. The potential of neural control of and sensory feedback from a prosthesis is that it would provide the most natural interface for the amputee, with minimal training and conscience effort required in using the prosthesis [1-8].

II. METHODS

Peripheral nerves are somatotopically organized at both fascicular and subfascicular levels. Therefore, we chose Longitudinal Intrafascicular Electrodes (LIFEs) to investigate the functionality of motor and sensory neurons in nerve stumps of human amputees because they can record from small clusters of neurons at a subfascicular level and can selectively activate subsets of nerve fibers within nerve fascicles [9-16]. In addition, LIFEs have been demonstrated to be biocompatible in chronic animal studies, and can be removed without requiring further surgery [17].

CNS reorganization begins almost immediately following nerve section and reaches a peak within 3 to 4 weeks; functional changes in the nerve stumps are most pronounced in the first two months postaxotomy. Therefore, only long term amputees (0.25 to 15 yr, mean of 4 yr post amputation) were invited to participate in the study. By interfacing Longitudinal Intrafascicular Electrodes (LIFEs) with micro-clusters of neurons within severed fascicles of proximal nerve stumps, we investigated, in isolation, the viability of severed motor and sensory neurons and their related central neural connections.

For recording from motor neuron fibers, the subject was directed to make phantom limb movements associated with the missing portion of the amputated limb. Motor signals were recorded in differential mode between a reference and an intrafascicular electrode, amplified, bandpass filtered, sent to a loudspeaker with a noise clipper, and fed through an A/D converter to a battery powered laptop computer. The subject was directed to select a movement that resulted in maximum audible activity. Once the subject had learned to generate motor activity associated with a phantom motion, a simple computer game was used to evaluate his control over the rate of action potential production and, therefore, the ability to modulate a phantom limb motion

Background noise was recorded and displayed on the laptop computer when the subject made no attempt to generate efferent activity related to phantom movement. The experimenter used this data to set a minimum threshold level for detecting neural activity. The subject was then asked to make the phantom movement and the recorded signals were used to set a threshold for detecting volitional motor nerve activity. This set the parameters for a Schmitt trigger to count action potentials within specified bin widths of time. Minimum count corresponded to the subject making no attempt to create a phantom movement. Maximum count was taken by having the subject make the selected phantom movement at a level of effort that generated most amount of neural activity. Once these parameters were set, the subject was asked to control the position of a cursor on the computer monitor to strike and stay within a randomly appearing stationary target. For the

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subject to score a “hit” he had to maintain the cursor in the target for at least 0.5 s [18, 19].

After proficiency in the game was achieved (typically within 5 days), the subject was then tested on his ability to control the position of the elbow joint or force of the gripper on a prosthetic arm and hand.

To investigate whether it is possible to elicit distally referred, natural phantom sensations, each electrode was stimulated separately either with monophasic, capacitively coupled or biphasic, charge balanced rectangular current pulses. If the subject reported a discrete, distally referred sensation, a staircase method of limits was used to identify threshold and upper limit pulse amplitudes for the sensation. Once a stimulus amplitude range was established, a psychometric scaling task was employed to determine the relationship between stimulus frequency and sensation magnitude (e.g., apparent contact force for touch or joint position or rate of movement for proprioceptive sensations) [18]. The subjects were then tested on their ability to gauge joint position or gripper force in a upper limb prosthesis based on feedback provided from sensors placed in the arm and gripper, presented to the subject as pulse frequency modulated stimulus trains.

Figure 1 shows a block diagram of the setup used to evaluate neural control of and neural sensory feedback from the prosthesis. A Utah myoelectric arm and gripper were modified to allow independent, continuous control of the elbow, wrist and gripper. For the experiments described here, only a single degree of freedom was tested at any one time. Sensors placed in the elbow and wrist provided information about joint position, and a force transducer on the end of the thumb of the gripper provided information about grip force. Again, for the work reported here, only a single sensory channel was used at any one time.

Action potentials in motor nerve fibers were recorded from a LIFE, amplified and filtered, and sent to the control computer through an analog-to-digital converter. At the same time, position and force information from the Utah arm were also monitored by the computer. For control of joint position or force, the recorded motor signals from the nerve were mapped into an appropriate level control signal by the computer and fed to the actuator controller in the Utah arm through a digital-to-analog converter. Sensor information from the prosthesis was transformed into a pulse frequency code by the computer and fed as charge balanced, biphasic stimuli through a digital-to-analog converter to a stimulus isolation unit. The output of the latter stimulated one or more sensory nerve fibers through one of the implanted LIFEs.

For evaluation of motor control, blindfolded subjects were asked either apply a specified force with the gripper, or to match the angle of the prosthesis elbow to an angle of the contralateral, intact elbow set by the experimenter. For sensory feedback evaluation, the opposite tasks were performed: identifying the amount of force applied to the end of the gripper, or matching a set angle of the elbow of the prosthesis with their intact elbow.

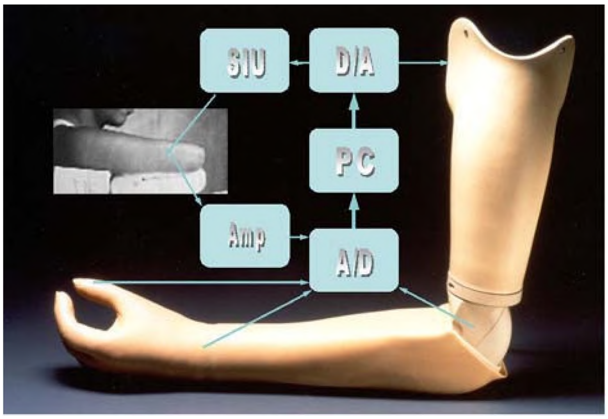

Fig. 1 Block diagram of the experimental setup. Motor nerve fiber signals were picked up by implanted, intrafascicular electrodes, amplified, filtered and fed to a laptop computer through an analog-to-digital converter. Sensors in the prosthesis provided information to the computer about gripper force, wrist and elbow position. The computer generated drive signals for the actuators in the prosthesis and pulse trains fed through a stimulus isolation unit (SIU) to electrodes implanted in the fascicles of the amputee's nerve stump.

III. RESULTS

All of the subjects were able to generate motor activity associated with missing limb movements once they had established a phantom arm image. At the point when they were able to generate repeated bursts of motor activity, they could immediately control the cursor position in the computer game, but with varied success in scoring hits. Pooled data from all the subjects showed that there was a monotonic, positive relationship between the precision of cursor control and the time taken to achieve this control. This was consistent over different trials, implying that, as with normal limbs, the more precise the movement, the greater the time for execution.

The overall frequency of recorded motor potentials varied from 29 to 130 Hz, with a mean of 89 Hz. In general, subjects that could generate higher frequencies showed greater control over cursor position. Even when the subjects failed to score a “hit”, they could still position the cursor near the target. This behavior was typical of all the subjects even when their success rate was limited. Neither the time taken to score a “hit” nor the success rate over consecutive trials showed any statistically significant positive or negative trend, implying that the subjects were using an innate sense of motor control, not something newly learned to deal with an unnatural experience.

For elbow control, there was a linear relationship between target and matched elbow flexion/extension angles (Fig. 2). There was a significant increase in the slope and decline in the variance of residuals around the regression line with time for this subject.

For grip force control, linear regression provided the best fit for the correlation between the target and the applied force. Analysis of the variance around the regression lines indicated a significant reduction with time in both subjects, with no significant change in the slopes of the regression lines.

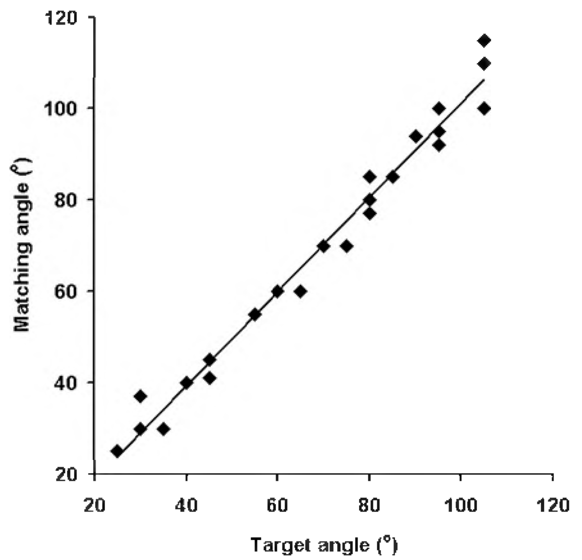

Fig. 2 Position of the artificial arm elbow set by subject versus target position of the contralateral, intact elbow set by the experimenter. Data were collected in random order.

Tactile sensations were readily elicited by nerve stimulation. They were distally referred, mainly to digit tips, localized to small receptive fields, and generally consistent with findings from microneurographic activation of single sensory units in intact nerves. Increasing the intensity of stimulation led to a spread of the sensation or caused it to take on a shock-like character. Proprioceptive sensations initially tended to be more vague, but with practice the subjects soon learned how to bring them into focus as either movements of the whole digit or of individual joints, or a feeling of a change in joint position. Individual finger joint sensations usually began with sensation of distal interphalangeal joint movement, and with increasing stimulus charge progressed to proximal interphalangeal and then metacarpophalangeal joint movements. Cessation of stimulation led to a perception that the joint had returned to its starting or "rest" position.

With practice, the subjects could give reliable reports of elbow position based strictly on sensory feedback from the joint position sensor in the prosthetic arm. Force judgment for the gripper was less successful. We believe this was largely due to the use of a single, small pressure sensor located on the thumb of the gripper.

IV. DISCUSSION

Although the subjects were able to control elbow position or gripper force in the modified Utah arm, this control was not as precise or smooth as desired. We attribute this to three sources: non-optimal signal processing, the nature of the control algorithm used, and the mechanical response properties of the arm. The arm was run in open loop mode, with the expectation that final joint position or gripper force would be a linear function of the command signal. The command signal itself was generated by mimicking the response properties of human muscle to neural stimulation: basically the command was the result of a leaky integration of the pulse rate of the signals recorded from the amputee's nerve stump. However, the arm did not respond like human muscle. It had a large "dead-band" due to gear train friction and so required an extra burst of activity to start moving, and once a desired position was achieved, a much lower rate of firing was required to maintain that position. The gripper operated in open loop mode, and so its position in the absence of a compliant load could not be well controlled without constant visual feedback.

While single channel input appeared adequate for making joint position judgments, single channel input from a simple pressure transducer on one digit of the gripper was not adequate for good estimates of grip force. More sophisticated force transducers, and possibly more input channels, are needed to provide adequate perceptions for this sensory modality.

These results and our work with amputees using computer-based tasks provide grounds for optimism in developing an artificial arm in which the prosthesis behaves in response to "natural" movement intentions on the part of the amputee much like a "normal" arm would, and in which "normal" sensations of touch, position and movement are present. Ideally, this would result in the amputee feeling that the arm is part of his/her body and using it without conscious effort or thought.

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