Direct Neural Sensory Feedback and Control of a Prosthetic 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 implant, prosthetic limb control, sensory feedback.**

I. Introduction

IT IS generally agreed 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 [1]–[8]. In addition, it has been reported that phantom limb pain, which can affect up to 80% of amputees, can be ameliorated in some cases by sensory training that limits the extent of somatosensory cortical reorganization [9]–[12]. Although different sensory feedback systems have been tried, including whole nerve stimulation, none of them have been widely adopted clinically, presumably because they have not provided discrete, natural, distally referred sensations [13]–[19]. Similarly, control strategies for artificial arms generally require that the user translate some unrelated motion into the intended motion of the arm (but see [20] for a recent exception). We believe that these problems can be solved by a direct neural interface with nerve fibers in the peripheral nerve stumps that allows feedback information to be provided through sensory pathways originally associated with the missing parts of the arm, and that allows control signals to be derived from neural activity generated by the amputee in attempting to move the missing elbow, wrist, or fingers.

The intent of the present study was to demonstrate that appropriate, distally referred sensory feedback about joint position and grip force from an artificial arm could be provided to an amputee through stimulation of the severed peripheral nerves, and that motor command signals appropriate for controlling joint position and grip force could be obtained by recording motor neuron activity from these nerves. As a feasibility study, issues of optimizing sensory discrimination through nerve stimulation or motor control ability through nerve recording were not addressed, but have been left for future work.

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II. Methods

Longitudinal intrafascicular electrodes (LIFEs) [21]–[23] were implanted within fascicles of severed nerves in six male, long term (range 10–360 months, average 96 months post-amputation), upper limb (amputation level at or below elbow) human amputees. The electrodes were exteriorized percutaneously, and connected to external circuitry interfaced with a laptop computer. Following completion of the study, the electrodes were removed percutaneously by applying gentle longitudinal traction. Institutional Review Board approval was obtained for the study, all amputees were given adequate time to consent to the study, and all signed an approved, written consent form.

A. Electrodes

Details of electrode design, fabrication, recording and stimulation properties have been extensively presented previously [21]–[29]. LIFEs were fabricated from commercially available 25-μm-diameter, Teflon insulated platinum-iridium wire (A-M Systems #7750). Each electrode consisted of a 20–30-cm-long wire from which insulation was removed over a 1 mm length, approximately 5 cm from the leading end of the electrode. Platinum black was electrodeposited on this recording/stimulating zone to produce a low impedance interface (1–3 kΩ at 1000 Hz). To insert the flexible LIFE into the nerve fascicle, a 50-μm-diameter tungsten needle was chemically bonded to the leading end of the electrode using cyanoacrylate adhesive. The other end of the LIFE was connected to saddle connector, which was adhered to the skin surrounding the point where the percutaneous electrodes exited the arm. This connector was used to interface outside circuitry (recording and stimulation hardware) to the electrodes.

B. Electrode Implantation, Evaluation of Electrode Function, and Subject Training

Surgical procedures, mapping of motor and sensory electrode functions, evaluation of stimulation and motor control parameters, and subject training with computer controlled stimuli and simulated tasks have also been described in detail elsewhere [30], [31], so only a brief description will be provided here.

To insure that recordings could be made from motor neurons innervating the extrinsic muscles of the hand, the electrodes were implanted in the median nerve above the point where motor fibers start branching to those muscles [32]–[34] in four of the subjects. Electrodes were implanted in the median nerve in the forearm for the other two subjects, who were not used for evaluation of motor control. Following limited external neurolysis to visualize the Bands of Fontana, the tungsten needle was used to thread the LIFE into a given fascicle, centering the 1-mm recording/stimulating zone in the fascicle. The needle was then cut off and the distal end of the electrode was tacked in place using a 8-0 nonabsorbable suture. A reference electrode having the same physical dimensions and electrical properties as the LIFEs was placed at the level of implantation but outside the nerve fascicles. Four to eight electrodes were implanted in each subject.

Sensory feedback channels were identified by applying short duration (500 ms) pulse trains with varying current-controlled pulse amplitudes at a fixed pulsewidth (300 μs) to individual electrodes. This identified which electrodes could be used to elicit distally referred sensations of touch/pressure or proprioception, and defined the threshold and upper current limit for the sensation. Once these parameters were identified, psychophysical testing was done to map the relationship between stimulus frequency and sensation intensity (or perceived position of a joint). Stimulation frequencies of 250 and 500 Hz were found to be upper limits for position and pressure sensations, respectively. The minimum stimulus frequency was 10 Hz. In all subjects, one or more electrodes were capable of providing sensory input.

Motor control channels were identified by connecting individual electrodes and the reference electrode to a differential amplifier (gain of $\sim$20 000, bandpass filter 0.3–4 kHz), the output of which was fed to a loudspeaker (Fig. 1). The subject was instructed to attempt a missing limb movement (such as finger flexion) while listening to the nerve activity over the loudspeaker. In each of the subjects implanted in the upper arm, one or more electrodes provided motor signals. For an electrode from which motor nerve activity could be recorded in response to such attempts, recorded signals were fed via a 16 bit digital-to-analog converter to a laptop computer and the amount of neural activity associated with a given limb movement was quantified. The subject was asked to control the position of a cursor on the computer screen by modulating this motor activity. The position of the cursor was linearly related to the level of motor activity: minimal output placing it at the left end of the screen, maximal output placing it at the right edge of the screen. The goal was to place the cursor and make in stay within a randomly appearing stationary target for a specified period of time (e.g., 0.5 s). Subjects were scored on the percentage of time they succeeded in this task in a given block of trials. As performance improved above a set level, the task was made more difficult by changing target size or changing the time constraints.

Fig. 1. Experimental setup. Shown is a photograph taken during a typical motor control training session. Percutaneous intrafascicular electrodes implanted in the median nerve of the subject's amputated arm were connected by a cable to a multichannel, differential amplifier. Switches allowed any given electrode to be connected to any one of the amplifiers. Outputs from two of the amplifiers were supplied to loudspeakers so the subject and the experimenter could monitor recorded neural activity by ear. The outputs from the amplifiers were fed into a laptop computer via 16 bit analog-to-digital converters. In the present experiments, only one amplifier channel was used at a time. Initial phase of training consisted of using the loudspeaker monitor to identify electrodes on which neural activity could be recorded while the subject attempted to move individual fingers or the wrist of the amputated hand. Once a suitable electrode was identified, the subject's task was use this activity to control the position of a cursor on the computer screen as described in the text. Next, the subject was instructed to modulate the motor activity to control the position of the elbow of the artificial arm or the force exerted by the hand. During testing, once training was over, the subject was turned facing away from the equipment and was blindfolded to eliminate any visual cues as to the task or his performance. Loudspeakers were disconnected so there were no auditory cues. For sensory feedback, stimulus waveforms generated by the computer were fed via a digital-to-analog converter to a current controlled stimulus isolation unit which was connected to the desired intrafascicular electrode.

C. Nerve–Arm Interface

Computer-aided training studies were conducted for up to 7 days [31]. Experiments with a modified Utah Artificial Arm (Motion Control Inc.) were conducted over a one week period immediately following the training period (Fig. 1). A force (strain gauge) sensor in the thumb of the hand and a position (angle) sensor in the elbow of the prosthesis were used to provide sensory feedback. Input from one or the other of these sensors was logarithmically mapped to the stimulus frequency delivered to the selected stimulating electrode (tactile sensation for force, proprioception for position), within the frequency limits determined in the psychophysical evaluations described above [30], [31].

Actuators in the elbow and hand were controlled in torque and force mode, respectively. Neuronal firing rate recorded from a motor control electrode was used to control these actuators. The control signal was generated by a process equivalent to leaky integration of the neural firing rate with a linear decay rate.

Specifically, recordings of activity during rest and maximal voluntary effort at making the intended movement were used to set a threshold level for detecting neural events (spikes). Each spike added a fixed increment to the output control signal, which decayed linearly over a selected time period (typically 0.5 s). The net control signal was thus the linear sum of the contributions from each spike detected within this decay period. The gain of the control signal was set so that a slightly submaximal effort produced full elbow flexion or full grip force.

D. Sensory Input

Due to constraints on the time available to work with individual subjects, three of the subjects were used for tactile and proprioceptive sensory feedback evaluation. In each of these subjects, one tactile and one proprioceptive electrode were selected for testing. Prior to the testing, training paradigms involved three and then five different force or position matches with visual feedback. Varying levels of indentation or force were applied to the strain gauge sensor on the thumb and the subject was asked to rate them, without the visual feedback, by using an open numerical scale for indentation [31], [35] or by squeezing a pinch force meter for force. For joint position sense, the elbow of the artificial arm was moved to different positions and the subject was asked to match the perceived angle of elbow flexion/extension, again without the visual feedback, through movements of the contralateral, intact arm.

E. Motor Output

Motor control was assessed in the other three subjects, using only one of the available motor channel electrodes in each. This was done by asking the subjects to control grip force (two subjects) or elbow position (one subject), without visual feedback. Prior to testing, each subject was given adequate time to acquaint and train himself for a given movement, usually for a period of up to 30 min, on a daily basis. For grip force control, the subjects were asked to match three levels of force (typically 22, 44, and 67 N) and then, after successfully matching more than 70% of the target values, five force levels (typically ranging from 13 to 67 N). Subjects had to match the target value within 5 s and the steady state read out was taken as the value for applied force. The matched position was assigned to the nearest target. Following proficiency at five levels, the subjects were asked to control force applied by the hand for any value set randomly in the range 22–67 N. For elbow position control, a similar training paradigm was used following which the subject was directed to match various randomly set angles of his intact arm with the artificial arm.

III. Results

A. Sensory Input

All three subjects could judge changes in indentation or force applied to the thumb sensor [Fig. 2(a)]. The slopes of linear regression lines fit to the data were significantly different from zero ($p < 0.001, r^2$ values ranged from 0.80 to 0.87 at the end of the experimental period). The regression slopes showed a significant increase with time in one subject ($p < 0.05$) but not in the other two ($p > 0.1$). There was a significant decline in the variance of residuals around the regression lines in two of the amputees ($p < 0.01$), but not in the third ($p = 0.1$).

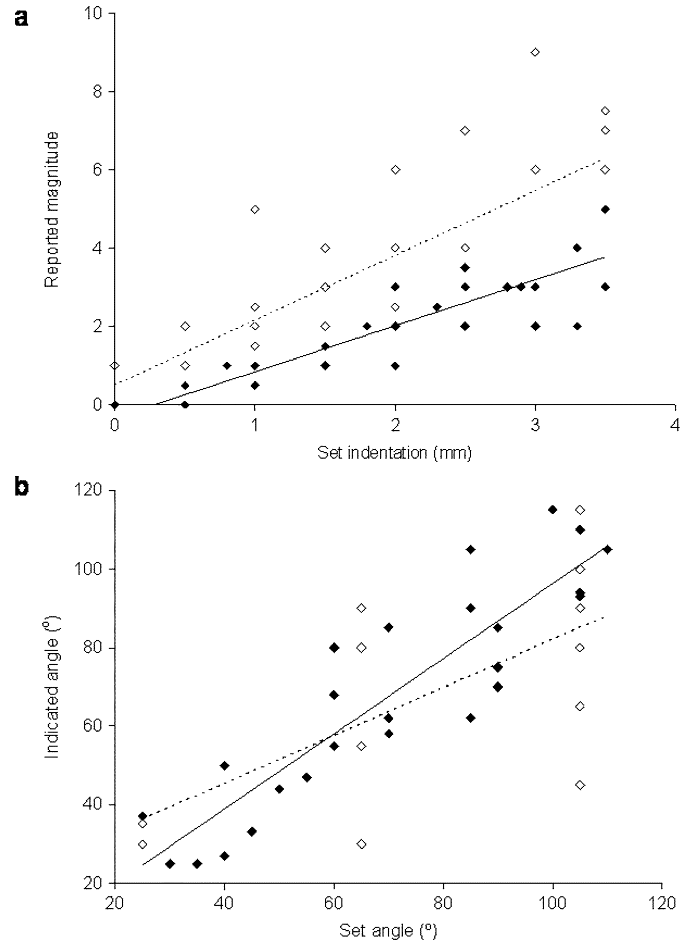

Fig. 2. Sensory input. (a) Psychometric sensation magnitude reported by subject 4532 (on an open scale) versus indentation applied to the thumb sensor by the experimenter on day 1 (open symbols, dotted line) and day 7 (filled symbols, solid line). (b) Matching position of the contralateral, intact elbow set by subject 8726 versus position of the artificial arm elbow set by the experimenter on day 1 (open symbols, dotted line) and day 4 (filled symbols, solid line). Data were collected in repeated up and down sequences on the first day and in random order on the last day.

The subjects could also consistently judge the static position of the elbow joint in the artificial arm [Fig. 2(b)]. Linear regression ($p < 0.05$ for the first run, $p < 0.001$ subsequently) best described the relationship between actual and sensed joint positions of the artificial arm. There was a general increase in the slopes of the regression lines with time, which was statistically significant ($p < 0.05$) in two of the three subjects. A statistically significant ($p < 0.05$) decline in the variance around the regression lines with time was seen in only one subject.

B. Motor Output

For grip force control, linear regression ($p \gg 0.05$ for non linearity), with a significant nonzero slope ($p < 0.001$), provided the best fit for the correlation between the target and the applied force (r^2 values of 0.86–0.90, at the end of the testing period). Sample data from one of the two subjects is shown in Fig. 3(a): the other subject gave similar results. Analysis of variance around the regression lines indicated a significant

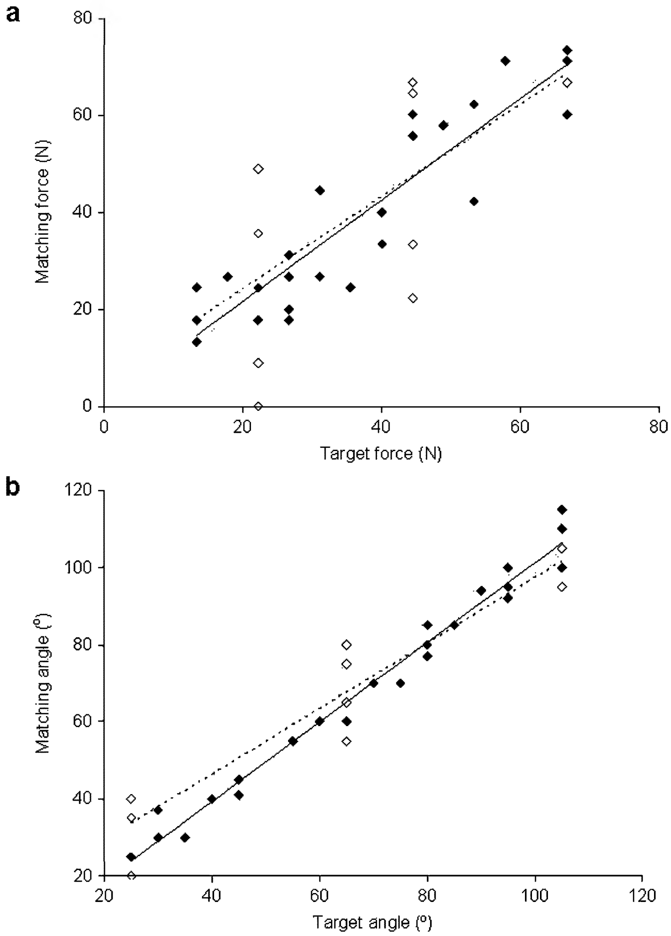

Fig. 3. Motor output. (a) Hand force applied by subject 9018 versus target force set by the experimenter on day 1 (open symbols, dotted line) and day 6 (filled symbols, solid line). (b) Position of the artificial arm elbow set by subject 8276 versus target position of the contralateral, intact elbow set by the experimenter on day 1 (open symbols, dotted line) and day 5 (filled symbols, solid line). Data were collected in repeated up and down sequences on the first day and in random order on the last day.

$(p < 0.01)$ reduction with time in both subjects, with no significant change in the slopes of the regression lines.

For elbow control, linear regression ($p \gg 0.5$ for non linearity), with a significant nonzero slope ($p < 0.04$ for day one, otherwise $p < 0.001, r^2$ up to 0.98), described the relationship between target and matched elbow flexion/extension angles [Fig. 3(b)]. There was a significant increase in the slopes $(p < 0.01)$ and decline in the variance of residuals around the regression line $(p < 0.01)$ with time for this subject.

IV. Discussion and Conclusion

These results indicate that appropriate, graded, distally referred sensations can be provided through stimulation of amputee nerve stumps with intrafascicular electrodes and that these sensations can be used to provide feedback information about grip strength and limb position. In addition, control of grip strength and limb position can be effected by recording volitional motor activity from the peripheral nerve stumps with these electrodes. Indications of improved performance (reduced variance and increased regression line slopes), in at least some of the subjects over the short period tested, suggest that further training would provide even better feedback and control. The extent to which this can reverse the cortical plastic changes seen after amputation is still to be determined, but evidence from studies of the effects of experience on cortical representation of sensory and motor information [36]–[38] suggest that it will have a significant impact, and may help provide a pain-free integration of the artificial arm into the amputee's body image.

As a feasibility study with a limited number of subjects and relatively short duration, this work did not address issues of optimization of sensory stimulation paradigms, optimal processing of motor control signals, different training regimes, or improving the operational characteristics of the artificial arm. Nor did we explore closed-loop, nonvisual control of the artificial arm. However, the data presented here do provide an adequate rationale and basis for pursuing these issues.

On the hardware side, things to be considered include provision of either an implanted, bidirectional telemetry system or a viable, permanent percutaneous connector system as an interface to the intraneural electrodes. An artificial arm and hand needs to be designed with continuous, simultaneous, neural control of multiple degrees of freedom and continuous sensory feedback of limb position and tactile events. A method of accommodating or eliminating stimulus artifacts while simultaneously stimulating and recording from peripheral nerve stumps needs to be implemented. All of these are within the grasp of current technology, although design constraints on weight and power supply requirements make designing a new generation of artificial arm that meets these criteria an interesting challenge.

Once an adequate hardware platform is in place, the stage will be set to explore closed-loop control of an artificial arm based solely on neural control and feedback. This would include optimizing stimulation parameters and motor control strategies to minimize the number of channels (electrodes) needed, and exploring different training approaches to maximize the functional utility of the neuroprosthetic arm. In particular, one would like to develop a system that allows the amputee to practice movements and acquaint him/herself with pseudonatural sensory feedback from the prosthesis in the home and work environment. The end result of which, ideally, would be to get the amputee to the point of feeling that the arm is part of his/her body and using it without conscious effort or thought.

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