The Neurochip BCI: Towards a neural prosthetic for upper limb function

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***Abstract*—The Neurochip BCI is an autonomously operating interface between an implanted computer chip and recording and stimulating electrodes in the nervous system. By converting neural activity recorded in one brain area into electrical stimuli delivered to another site, the Neurochip BCI could form the basis for a simple, direct neural prosthetic. In tests with normal, unrestrained monkeys, the Neurochip continuously recorded activity of single neurons in primary motor cortex for several weeks at a time. Cortical activity was correlated with simultaneously-recorded EMG activity from arm muscles during free behavior. In separate experiments with anesthetized monkeys we found that microstimulation of the cervical spinal cord evoked movements of the arm and hand, often involving multiple muscles synergies. These observations suggest that spinal microstimulation controlled by cortical neurons could help compensate for damaged corticospinal projections.**

***Index Terms*—Brain-Computer Interface, Motor Cortex, Neural Prosthetics, Spinal Cord Injury**

I. Introduction

HERE we describe work with a battery-powered, implanted computer chip that could potentially serve as a neural prosthetic to aid upper limb function following injury of the spinal cord. Regaining arm and hand function is considered the highest priority by quadriplegic patients [1] and accurate control of these movements depends on corticospinal projections originating largely in primary motor cortex (M1) [2]. Previous research has shown that the activity of cells recorded in M1 can be used to control computer cursors and robotic devices [3,4,5]. We are investigating the possibility of an artificial corticospinal connection using M1 activity to continuously control microstimulation delivered in the spinal cord, which could help to restore function to the patient's own limbs.

We report progress in three areas. First we review the main features of our Neurochip BCI, an implanted Brain-Computer Interface developed for neural recordings and microstimulation in macaque monkeys. The macaque is a good model for human upper limb control since its corticospinal system resembles that of humans. The Neurochip BCI can operate autonomously for extended periods of time in completely unrestrained monkeys, enabling us to study the long-term effects of incorporating prosthetic connections into the nervous system. Next we describe recent experiments in which the Neurochip BCI was used to study the relationship between motor cortex cell firing rate and muscle activity during extended periods of free behavior. We show that this system can obtain stable, movement-related neural activity from M1, a prerequisite for an eventual prosthetic. Finally we summarize experiments demonstrating that low-intensity intraspinal microstimulation can evoke movements of the arm and hand, typically involving multiple muscles.

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II. The Neurochip Brain-Computer Interface

The Neurochip BCI is an autonomous, battery-powered Brain-Computer Interface. Using implantable electronics we are able to collect data in unrestrained monkeys without the high power consumption and short battery life of radio-telemetry systems [6,7]. Onboard spike processing and a stimulator circuit allow for real-time bidirectional interface with the nervous system. Here we give a brief overview of the system and describe recent modifications that allow EMG activity to be recorded simultaneously with neural activity.

The electronic circuitry and battery are enclosed within a percutaneous titanium casing measuring 5.5cm x 5cm x 3cm attached to the monkey's skull; the entire implant weighs 56g. A ⅔AA-sized 3.3V lithium battery powers the circuit for up to 40 hours, depending on the recording configuration. Neural data is acquired from one of 12 microwire electrodes (50 μm diameter teflon-insulated titanium, A-M systems Inc.) chronically implanted in primary motor cortex. Leads run subcutaneously from the head casing to a connector on the monkey's back. Two pairs of stainless-steel wires inserted percutaneously into forearm muscles can be attached to this connecter for recording EMG signals.

Figure 1 shows a schematic of the Neurochip architecture. At the heart of the electronics are two PSoCs (Programmable System-on-Chip, Cypress Semiconductor Corp.) operating in parallel. The primary PSoC samples data from one of the

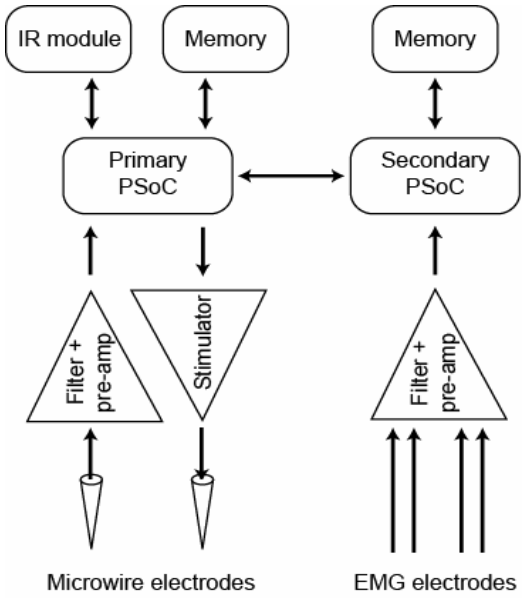

Fig. 1. Schematic of the Neurochip functional blocks. Parallel PSoC microcontrollers record neural and muscle signals to independent memory modules. The primary PSoC also controls a constant-current stimulator circuit and communicates via IR to a PC or hand-held PDA.

cortical microwires at 11.7ksps and handles infrared (IR) communication. A secondary PSoC multiplexes and samples two differential, rectified EMG signals at 2ksps per channel. Inter-PSoC communication for synchronizing recordings and relaying data is handled by an asynchronous serial bus. Front-end signal processing includes band-pass filtering and amplification (500Hz – 5kHz, 1500x with a further 1-48x variable gain for neural signals; 20Hz – 2kHz, 250x with further 1-48x followed by full-wave rectification for EMG). Each PSoC stores data to independent 8Mb Flash memory chips. The Neurochip BCI also incorporates stimulation circuitry capable of delivering biphasic constant-current stimuli of up to 100μA to a different microwire electrode [7].

Each PSoC has an 8-bit microprocessor core, used to detect action potentials in the neural signal, calculate firing rate and EMG envelopes, store data and control stimulation. The spike discrimination algorithm consists of a threshold level which the signal must exceed, followed by two adjustable time-amplitude windows through which the signal must pass. Spike rate and average EMG level can be calculated and stored over a user-defined time-bin, resulting in considerable memory savings. The primary PSoC's 8Mb memory bank can hold 85s of raw neural data sampled at 11.7ksps while the secondary PSoC's memory bank can hold 256s of dual-channel raw EMGs sampled at 2ksps. However, if spike rate is compiled for consecutive 100ms bins along with simultaneous average EMGs, the Neurochip can store over 27 hours of continuous data. Short sections of raw signal can be interspersed during the recording period, allowing discrimination quality to be confirmed throughout. The Neurochip operates autonomously after the recording, discrimination and stimulation parameters have been set via the IR link. Typically we download data via IR and replace the battery daily for continuous operation over many months. In one animal this system has been recording data for over 16 months.

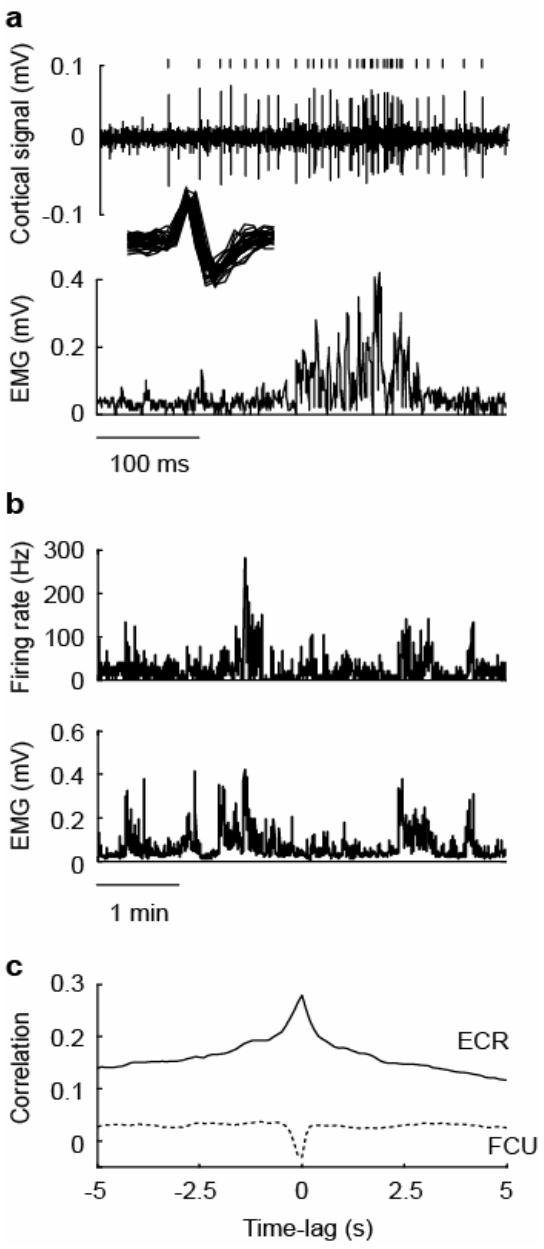

Fig. 2. a. Raw recording from a microwire electrode in M1 and simultaneous rectified EMG from *extensor carpi radialis* muscle (ECR) recorded with the Neurochip. Discriminated action potentials are marked with ticks above and the superimposed waveforms are inset. b Longer section of data recorded as mean firing rate and rectified EMG over consecutive 100ms time-bins. c Cross-correlation between spike firing rate and ECR activity over 6 hours of unrestrained behavior. Also shown is the cross-correlation with *flexor carpi ulnaris* muscle (FCU, dashed line).

III. Neural and EMG recordings during natural behavior

The relationship between motor cortical activity and movements has traditionally been studied in awake animals by recording neural spiking during the performance of repetitive, trained tasks under restrained conditions [2,8,9]. This approach offers technical and methodological advantages. Stable recordings can be obtained most easily with the head fixed, while mains-powered rack amplifiers and acquisition systems can be used to collect data. Furthermore, limiting the range and dimensionality of possible movements aids the interpretation of task-related cortical activity. By contrast, a neural prosthetic intended to restore a wide range of motor behavior would need to extract signals from cortical neurons across a wide range of behavior. Toward this end we used our Neurochip system to investigate the relationship between neural and EMG activity during extended periods of free behavior in two monkeys.

Fig. 2a shows a neural signal sampled by the Neurochip from a microwire electrode in M1, and rectified EMG activity recorded simultaneously from a wrist extensor muscle. Fig. 2b shows five minutes of spike firing rate and mean EMG level during free behavior. This section was taken from a longer record covering 12 hours of day and nighttime activity.

The relationship between cortical and EMG activity can be revealed by cross-correlation methods based on simple linear regression analysis. The plot in Figure 2c is compiled from 6 hours of continuous daytime firing rate and average rectified EMG activity, recorded over the same consecutive 100 ms bins. The regression coefficient (r) was calculated between the aligned signals (zero-lag) and for the EMG shifted forwards or backwards in time relative to the firing rate by up to 5s. A positive correlation peak around zero-lag (r=0.28) is seen between this cell and activity of the wrist extensor muscle (ECR), as well as a negative correlation trough with an antagonist wrist flexor (FCU). Most cells showed peak correlations with arm and extrinsic hand muscles of $0.1<r<0.4$, with cell firing leading muscle activity by 0-100ms, consistent with a causal role in generating motor commands. These correlation coefficients are slightly lower than those typically obtained during repetition of trained tasks in a restricted workspace, which are usually in the range of 0.2-0.6 [9]. Nevertheless, for our proposed neural prosthetic it is encouraging that robust correlations can be observed between single motor cortex neurons and individual arm muscles over long periods of completely unrestrained behavior.

Using the Neurochip BCI we were able to continuously monitor the activity of single cells for periods of several weeks at a time. Correlations between cell firing and muscle activity remained consistent from day to day, although in some cases the overall firing rate of a cell could drift slightly over extended periods of time.

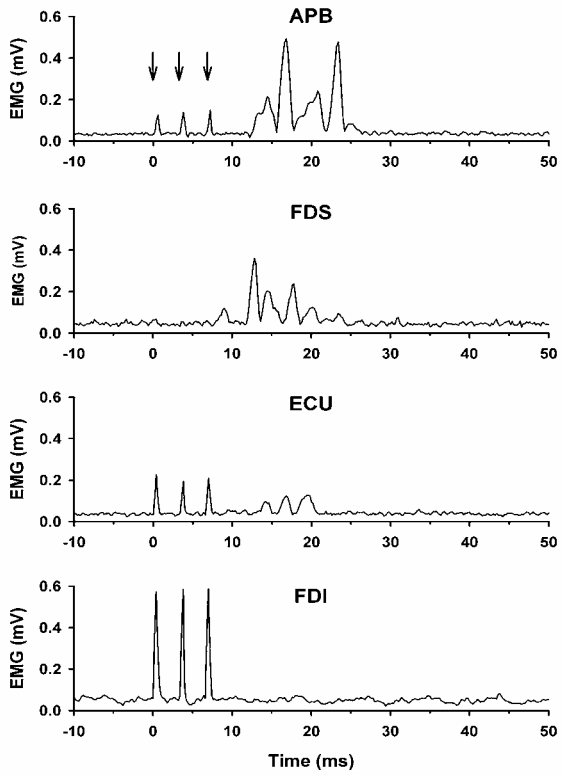

Fig. 3. Muscle activity evoked by microstimulation of lamina VII in the rostral C7 segment of the spinal cord. A train of three biphasic current pulses at 20μA (arrows) is just above threshold for eliciting a visible gripping movement of the monkey's hand. Multiple EMG responses in muscles controlling the wrist (ECU), fingers (FDS) and thumb (APB) are seen.

IV. Microstimulation of the spinal cord

To study the output effects evoked by intraspinal microstimulation we conducted mapping experiments in three sedated primates. These experiments will guide the placement of chronically indwelling stimulating electrodes [10] that may be controlled in awake animals by the Neurochip BCI.

During an initial surgery, a laminectomy over four cervical vertebrae was covered by a recording chamber attached by screws in the lateral masses [11]. In subsequent sessions with the monkeys lightly sedated, we delivered brief trains of biphasic, constant-current stimuli through tungsten microelectrodes advanced through successive sites in the cord, recording correlated EMG signals at the minimum current that elicited a visible movement. Low movement thresholds (10-90μA) within the range of our Neurochip stimulator [7] were obtained throughout most of the lower cervical spinal cord (79% of stimulation sites). Fig. 3a shows responses to three stimuli of 20μA evoked in multiple hand and forearm muscles, associated with a brief gripping movement of the hand. Longer trains of stimuli produced a sustained contraction. Stimuli commonly evoked synergetic responses in multiple muscles, probably due to activation of local spinal circuitry in addition to direct excitation of motoneurons. At threshold for movement, stimuli evoked responses in a single

muscle at only 14% of effective sites, whereas two to six muscles were simultaneously activated at 47% of sites. Finger movements were the most commonly evoked, occurring at 59% of effective sites.

V. Discussion

Successful creation of a neural prosthetic to aid upper limb function following injury depends on solving several technical and scientific problems. Here we have described progress in three areas: recording stable single-unit activity from primary motor cortex during unrestrained behavior, relating this activity to muscle patterns, and evoking movements of the hand and arm by intraspinal microstimulation. Clearly, a BCI system to restore the normal range of complex motor behaviors remains a formidable challenge. Arm and hand movements are performed in a high-dimensional, multi-joint space with control signals distributed over large populations of cortical neurons [5]. As the computational power of the PSoC increases, it may be possible to record multiple neural channels on one chip. Alternatively, the parallel architecture that we have implemented for simultaneous spike and EMG recording could be expanded to incorporate multiple PSoCs running as independent modules. Such a system would have greater flexibility and computational power, with expansion limited primarily by space and battery considerations. Furthermore, the finding that useful functional muscle synergies can be evoked by spinal stimulation [cf. 10] may reduce the required dimensionality of control signals.

An unresolved issue concerns the appropriate transformation between cortical signals and stimulation parameters. Linear correlation between single cells and muscle activity typically yielded modest regression coefficients. The activity of multiple cells allows calculation of a better fit of EMG envelopes [5,12,13] in repetitive tasks, although generalization to an unrestricted range of movements remains untested. Thus, a major factor in successful prosthetic control is the degree to which neural activity can be appropriately modified under closed-loop conditions in which the consequences of this activity are immediately evident. Previous operant conditioning studies have shown that the requisite flexibility exists for motor cortex neurons. Given biofeedback showing the degree to which cortical cell activity met criteria for reinforcement, monkeys learned within minutes to modify cell activity in various ways in order to drive a meter arm toward reinforcement threshold [14]. Cortical cells and arm muscles that were normally co-activated could be readily dissociated within minutes [15]. Cortical firing patterns have been shown to adapt during control of BCIs [4,5], and over longer periods of time this flexibility may well facilitate adaptation to changed motor demands, such as that which occurred with chronic cross-innervation of antagonist forelimb muscles [16]. Because the Neurochip BCI allows long-term, continuous operation, we should be able to test the degree to which monkeys can learn to appropriately control motor cortical activity that directly evokes spinal microstimulation in order to generate coordinated movements. This approach also holds clinical promise: patients could learn to compensate for impaired corticospinal connections or spinal cord injury through a Neurochip BCI allowing cortical cell activity to directly evoke or facilitate movement.

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