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Ipsilateral Directional Encoding of Joystick Movements in Human Cortex.

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Abstract—**The majority of Brain Computer Interfaces have relied on signals related to primary motor cortex and the operation of the contralateral limb. Recently, the physiology associated with same-sided (ipsilateral) motor movements has been found to have a unique cortical physiology. This study sets out to assess whether more complex motor movements can be discerned utilizing ipsilateral cortical signals. In this study, three invasively monitored human subjects were recorded while performing a center out joystick task with the hand ipsilateral to the hemispheric subdural grid array. It was found that directional tuning was present in ipsilateral cortex. This information was encoded in both distinct anatomic populations and spectral distributions. These findings support the notion that ipsilateral signals may provide added information for BCI operation in the future.**

I. Introduction

To date, Brain Computer Interfaces (BCIs) have been put forth as novel engineering approaches to enhance communication and control for patients who have intact cortex but lack motor control due to brain stem stroke, spinal cord injury, or peripheral neuro-muscular dysfunction. With requisite improvements in performance and robustness, these systems have the potential to help tens of thousands of motor disabled subjects. The majority of BCI methodologies are based on a functioning motor cortex that is capable of controlling the contralateral limb. In recent years, there has been an evolving appreciation of how motor and motor related areas participate in same-sided, or ipsilateral, motor movements.[1-3] These findings have prompted further exploration into the underlying cortical physiology as a possible substrate for neuroprosthetic application.

Wisneski et al. utilized electrocorticography (ECoG) to more definitively define this physiology in six motor intact patients undergoing invasive monitoring for seizure localization. Electrocorticographic signals were recorded while the subjects engaged in specific ipsilateral or contralateral hand motor tasks. Spectral changes were identified with regards to frequency, location, and timing. This study showed that ipsilateral hand movements were associated with electrophysiological changes that occurred in lower frequency spectra (average 37.5Hz), at distinct anatomic locations (most notably in premotor cortex), and earlier (by 160 ms) than changes associated with contralateral hand movements. Given that these cortical changes occurred earlier and were localized preferentially in premotor cortex compared to those associated with contralateral movements, the authors postulated that ipsilateral cortex is more associated with motor planning than its execution. Additionally, these changes were quite distinct from those changes associated with contralateral motor movements which were more dominantly associated with higher gamma rhythms (average 106.9 HZ). The group further demonstrated that brain derived control of a computer cursor could be achieved by using the anatomic sites or the lower frequency amplitude changes distinctive to ipsilateral movements which was comparable to contralateral derived control.[4]

In previous studies, ECoG signals have been found to carry very specific information about contralateral joystick, hand, and finger movements.[5, 6] Additionally, these distinct signals have been able to provide for more complex multidimensional device control.[7] Though the cortical physiology associated with ipsilateral motor movements has been found to be different than that associated with contralateral movements, it has not yet been defined to what extent more complex motor information is present. Using a classic center out task in three invasively monitored patients this study set out to examine whether similar levels of complex motor movements could be decoded from the ipsilateral hemisphere.

II. Methods

A. Subjects

The subjects in this study were three patients (ages 36, 48, and 58 years) with intractable epilepsy who underwent temporary placement of intracranial electrode arrays to localize seizure foci prior to surgical resection. All had normal levels of cognitive function, were right handed, and had left hemispheric 8x8 electrode grid arrays. All gave informed consent. The study was approved by the Washington University Human Research Protection Office. Each patient studied was in a sitting position (semi-

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recumbent), approximately 75 cm from a video screen. In all experiments, we recorded ECoG from up to 64 electrodes using the general-purpose BCI system BCI2000 [8]. All electrodes were referenced to an inactive intracranial electrode, amplified, bandpass filtered (0.5-500 Hz), digitized at 1200 Hz, and stored.

B. Behavioral Paradigm

The subjects performed a two dimensional center out reaching task using a Microsoft Sidewinder force feedback joystick operated by the left hand (ipsilateral to the intracranial grid array). The subject would be cued to move a cursor from the center of the screen to one of eight targets placed radially and equidistant around the center point on the periphery. The center was approximately 5 inches from any of the targets. Random delay periods ranging from 300 - 1200 msec were added between cue and target presentation to dissociate attention and intentional effects from movement effects. The targets were presented in a pseudo randomized order. All subjects were presented each target a minimum of 8 times per run and the number of runs for each subject varied from 4 - 10 depending on patient compatibility.

C. Analysis

The analysis algorithm consisted of the following steps: converting the time domain signal into the frequency domain, correlating ECoG spectra to joystick kinematics data for position and velocity encoding, and statistical evaluation to quantify significant results. ECoG signal has been previously shown to include sharp changes in the time domain and hence to fit spectra with sharp features and increase the frequency resolution, the Maximum Entropy Method (MEM) was used.

The MEM is an Auto-Regressive (AR) filter model which does not reconstruct the power spectra but estimates it based on the input parameters. It estimates the power spectrum of the input signal using the following mathematical expression:

$$P(f) = \frac{a_0}{\left|1 + \sum_{k=1}^{M} a_k z^k\right|^2}$$

The parameters that determine the estimation are model order (M), sample data and the sampling frequency at which the data is acquired. The coefficients a_k are computed from the autocorrelation function of the sample data. The parameter z of the power spectrum is defined as $z = e^{2\pi i f \Delta}$ (where f represents the frequency and Δ is the sampling interval) and can be used to resolve the power spectrum to the required frequency resolution.

Movement period spectra generated using MEM was normalized by comparing to the baseline signal spectra. Normalized spectra was regressed with the position coordinates of one of four targets (positioned at 0, 90, 180, and 270 degrees) on a trial by trial basis. Their correlation to the ECoG spectra was computed using the MATLAB function *regress* which evaluates the linear correlation coefficients as described by Georgopoulos et al. [9] The regression analysis is performed for individual electrodes over the complete frequency spectrum. We next measured the strength of correlation using the Depth of Modulation (DOM) of the cosine tuning curve, which is defined as the percent change in activity from baseline during movement in the preferred direction. The following expression demonstrates the regression and cosine tuning analysis:

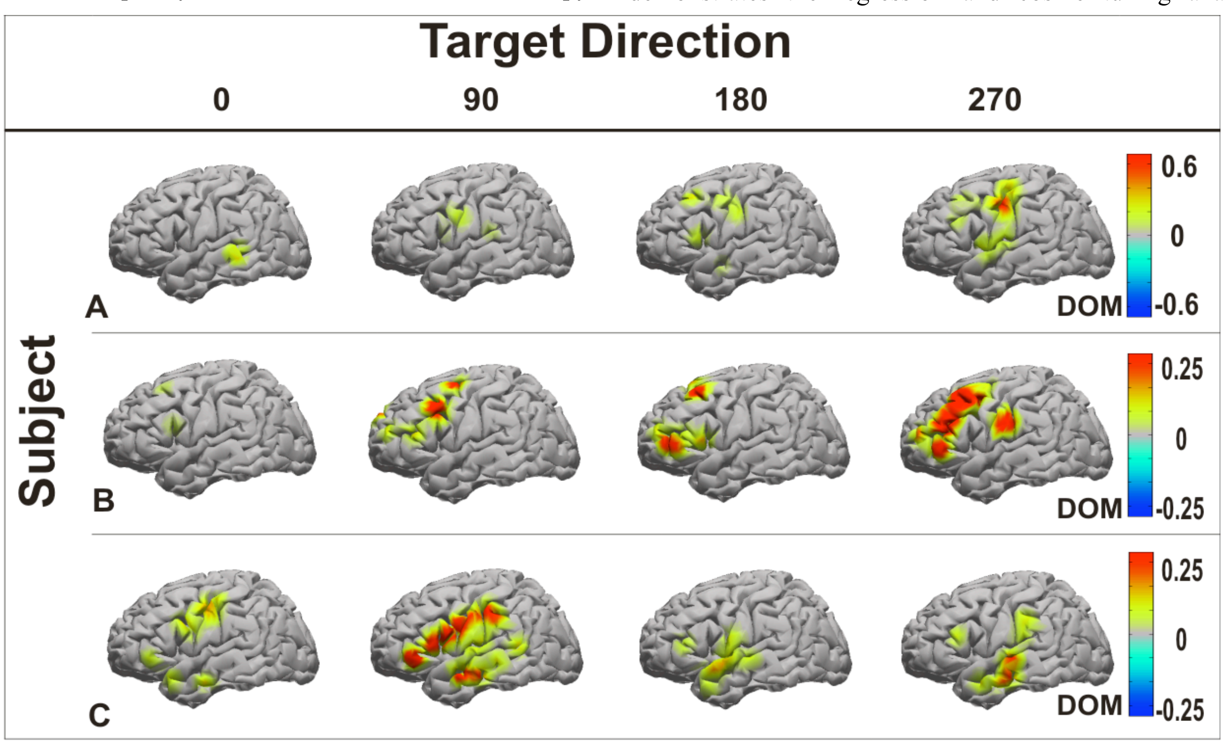

Figure 1. Cortical regions demonstrating statistically significant ($p < 0.05$) Depth of Modulation (DOM) across frequencies between 0.5-275 Hz for joystick movements towards four different targets positioned ninety degrees apart around a central starting point. Each subject demonstrates different cortical distributions of DOM for the given directional movement.

$$\overline{P_j} = b_0 + b_x \overline{x_j} + b_y \overline{y_j} = b_0 + DOM \cos(\theta_{PD-M})$$

where P_j is the normalized activity spectra in the movement direction, x_j and y_j are position coordinates of final target positions, b's are the regression coefficients, DOM is the depth of modulation and θ_{PD-M} is the angle between the preferred direction and movement direction **Error! Reference source not found.**. Features (frequency band at certain electrode location) were assessed to be statistically significant if the DOM is greater than 0.05 and the p-value (strength of fit to the tuning curve) is less than 0.05.

D. Anatomic Reconstructions

Radiographs were used to identify the stereotactic coordinates of each grid electrode [10], and cortical areas were defined using Talairach's Co-Planar Stereotaxic Atlas of the Human Brain [11] and a Talairach transformation database (http://ric.uthscsa.edu/projects/talairachdaemon.html). We obtained a template 3D cortical brain model from the AFNI SUMA web site(http://afni.nimh.nih.gov/afni/suma). Stereotactically defined electrode locations were then mapped to this template brain model. We then created DOM activation plots for each patient using a customized MatLab program. For each plot, only electrode sites with a p value of less than 0.05 were considered. The resulting map showed the activation at each point on the brain model for the target direction considered.

III. Results

In this study, each of the three subjects tested showed significant cortical changes that were specifically tuned to one of the four directions during joystick movement. Of the 176 total electrodes recorded over the three patients, 85 showed statistically significant tuning to one or more directions (0, 90, 180, and 270 degrees). As shown in Figure 1, there was a distinct anatomic pattern of cortical activation for each target when examined across all frequencies between 0.5-275 Hz. These populations were somewhat heterogeneous between subjects. This likely is accounted for by the variability in grid placement between individual subjects and the 1 cm electrode spacing which is coarse from a functional standpoint. For each of the subjects there was directional tuning in all frequencies (See Figure 2)

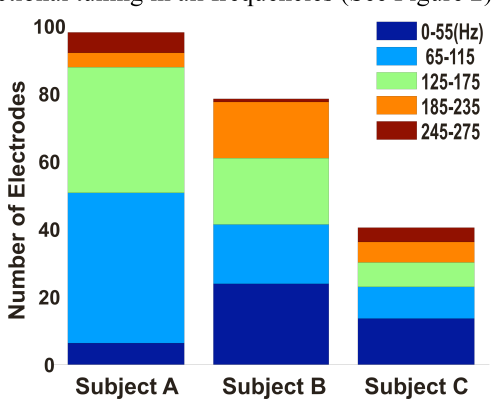

Figure 2. The frequency spectra demonstrating significant Depth of Modulation (DOM) for any of the four directions. The degree to which a frequency was represented was measured by the number of electrode sites that showed significant DOM at a frequency within the respective ranges. The majority of spectra showing directionally tuned DOM were below 175 Hz.

Beyond cortical populations, there was also distinct directional tuning at individual sites. Individual electrode sites showed tuning for up to three of the four independent directions. Figure 3A shows the number of electrode sites that showed tuning for one, two, and three directions. The majority (33.5%) of tuned electrodes showed tuning to a single direction. A smaller subset of sites however showed tuning for more than one direction (14.8%). Figure 3B shows an example of an electrode and its associated directional tuning to multiple directions. The separable directional tuning was based on distinct frequency bands showing independent depth of modulation. Figure 3C shows the respective frequency bands that had significant DOM for the associated directional tuning. When a single direction was encoded, it appears a broad distribution of frequencies where represented. As a site showed a higher number of encoded directions the frequency range between 65-115 Hz became much more prominent.

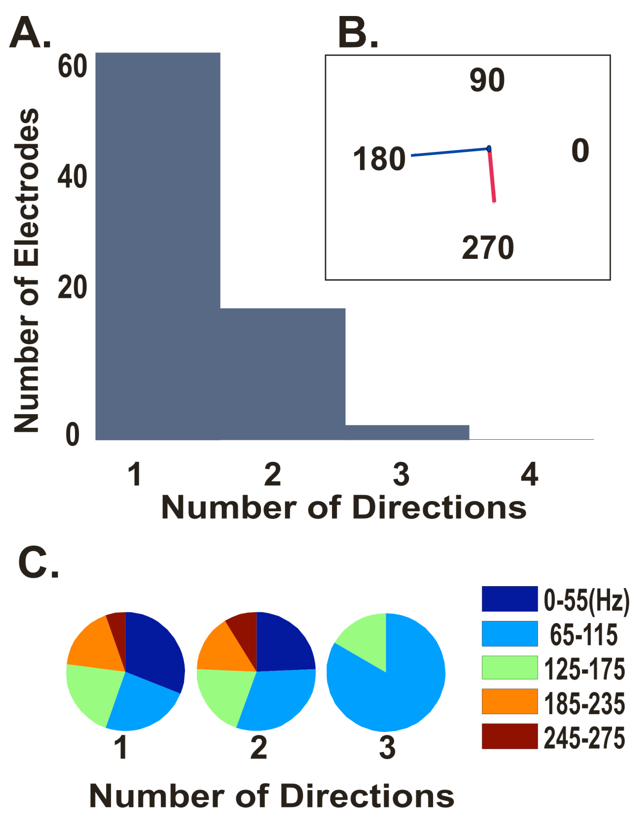

Figure 3. A. Number of electrode sites showing significant Depth of Modulation (DOM) for a single direction and multiple directions (across all patients). B. Demonstrates an example of how a single site encodes for multiple directions. A significant DOM of one spectral band is tuned to one direction (blue), while another spectral band is tuned to another direction (red). C. The frequency distribution showing significant DOM for sites encoding one, two, and three different directions. As a site encodes more directions the frequency range between 65-115 Hz predominates in spectra showing tuned DOM.

IV. Discussion

This study demonstrates that two-dimensional information is present in electrocorticographic signals taken from cortex ipsilateral to the hand operating a joystick. This information is encoded by distinct cortical populations demonstrating tuned depth of modulation in specific frequency bands to specific directions. These cortical populations are represented in distinct anatomic locations (e.g 45Hz DOM tuned to the 90 degree target at several distinct cortical locations) and, for a given location, there is further directional encoding present in distinct frequency spectra (e.g. for a single site, 70 Hz DOM encodes for a target at 180 degrees and a 110Hz DOM encodes for a target at 270 degrees) For sites encoding a single direction there appears to be a diverse range of frequency representations, as single sites encode more numerous directions, the frequency bands that are tuned to multiple directions predominantly range between 65-115 Hz.

These findings build upon the current understanding of ipsilateral motor physiology and ECoG based neuroprosthetics. There have been numerous studies demonstrating that ipsilateral limb movements have been associated with a distinct and separable cortical physiology. [1, 3, 12, 13] Initially this was felt to be the result of transcallosal inhibition.[14, 15] More recent findings have demonstrated this to be an active phenomenon thought to be more involved with motor planning.[16, 17] Additionally, this separable physiology as measured with ECoG has been utilized for simple BCI device control. [4] Using ECoG, Schalk et al demonstrated that two dimensional joystick movements could be decoded from cortex contralateral to the operating hand.[18] Later this same group demonstrated two-dimensional control was indeed possible using ECoG. [7] In this study, the results show for the first time that two dimensional information is also present with ipsilateral joystick movements. This study supports the notion that multidimensional control may also be possible using ipsilaterally derived cortical physiology.

Further evaluation will be required to define the independence of these cortical signals encoding ipsilateral directional information to that of contralateral derived directional information. If separable, this ipsilateral kinematic information could potentially provide a parallel set of features for control that would be complementary to signals derived from classic motor physiology associated with contralateral movement imagery. Beyond the potential increase in degrees of freedom of control, these findings provide important preliminary evidence that a BCI could achieve "bisomatic" control—a unilateral neuroprosthetic that could enable a single hemisphere to facilitate control of both sides of the body. This could substantially improve the control capabilities of an ECoG based BCI for motor impaired patient populations.

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