

Local Field Potential Spectral Tuning in Motor Cortex During Reaching

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Abstract—In this paper, intracortical local field potentials (LFPs) and single units were recorded from the motor cortices of monkeys (*Macaca fascicularis*) while they performed a standard three-dimensional (3-D) center-out reaching task. During the center-out task, the subjects held their hands at the location of a central target and then reached to one of eight peripheral targets forming the corners of a virtual cube. The spectral amplitudes of the recorded LFPs were calculated, with the high-frequency LFP (HF-LFP) defined as the average spectral amplitude change from baseline from 60 to 200 Hz. A 3-D linear regression across the eight center-out targets revealed that approximately 6% of the beta LFPs (18–26 Hz) and 18% of the HF-LFPs were tuned for velocity (p -value < 0.05), while 10% of the beta LFPs and 15% of the HF-LFPs were tuned for position. These results suggest that a multidegree-of-freedom brain-machine interface is possible using high-frequency LFP recordings in motor cortex.

Index Terms—Brain-computer interface (BCI), local field potential (LFP), motor cortex.

I. INTRODUCTION

Most intracortical brain-computer interface (BCI) research to date has focused on extracellularly recorded action potentials for their control signals [1]–[4]. Single-unit activity has the advantage of high spatial resolution and the ability to provide a control signal with multiple degrees of freedom; however, recording single units over a long period of time can be difficult. Encapsulation by glial tissue increases electrical impedance around the electrode tips and essentially eliminates single-unit isolation over time [5], [6]. While single-unit discriminability is quite susceptible to encapsulation issues, the lower frequency intracortical local field potentials (LFPs) are more tolerant of variable electrode impedance and could yield a more stable control signal over time.

Most of the research involving LFPs as a control signal for BCIs has focused on time-domain analysis. Kennedy *et al.* [7] demonstrated that LFPs in humans could be used to control a computer cursor and a virtual finger, with each electrode controlling a separate degree of freedom. Mehring *et al.* [8] compared motor cortex LFPs in the time domain with single unit activity for a two-dimensional (2-D) center-out reaching task with the monkey gripping a pole. They showed limited 2-D LFP tuning in the time domain.

LFP analysis in the frequency domain has focused primarily on the relatively lower frequencies. Murthy and Fetz [9] observed oscillations in the sensorimotor cortex of monkeys in the 20–40-Hz range during wrist and arm movements and found they were not directly correlated with movements. However, LFPs were often synchronized with single and multi-unit activity [10]. Sanes and Donoghue [11] observed oscillations in the motor cortex in the 15–50-Hz range where a desynchronization appeared when the “go” cue appeared and movement-related activity began in motor cortex. Likewise, Donoghue and colleagues

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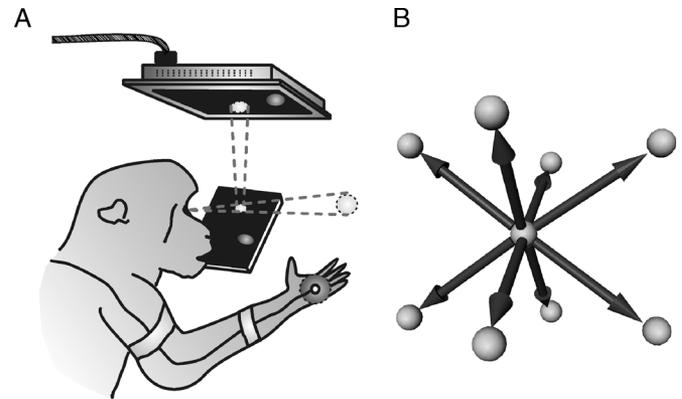


Fig. 1. Virtual reality setup. (a) Subject sits in primate chair looking at image projected onto mirror from 3-D computer monitor. He cannot see his hand, but rather a spherical cursor that represents position of hand in space. (b) For center-out task, subject must hold at central target projected in front of him for short period of time (500–1000 ms). Peripheral target will randomly appear at one of eight corners of a virtual cube and subject will immediately make smooth reach toward peripheral target and hold for set period (500–1000 ms).

[12] observed an increase in power in the 35–50-Hz range and a decrease in power at the lower frequencies. Other groups have compared LFP activity with spikes in parietal cortex during memory reaching and saccade tasks [13]–[15] where they found increases in gamma band activity during the memory period. Andersen *et al.* [5] also discusses the promise of using the local field potential as a control signal for neural prosthetics. However, few studies have looked at high gamma frequencies (100–200 Hz) in LFP during movement. Our initial results in human electrocorticographic (ECoG) recordings taken from the surface of the brain suggested that high-frequency ECoG recordings show directional effects during movement [16]. We later showed that high-frequency intracortical LFPs were cosine tuned in a three-dimensional (3-D) reaching task in monkeys [17], which has subsequently been confirmed by others using a 2-D reaching task [18]. In this paper, we examine the spectral tuning of both low (10–60 Hz) and high-frequency (60–200 Hz) LFPs recorded in motor cortex during a standard center-out reaching task with arm kinematics and compare the results with simultaneously recorded single-unit activity [19], [20].

II. METHODS

Three macaque monkeys were trained using operant conditioning to perform a standard 3-D center-out reaching task. The subject sat in a primate chair with its head fixed, facing a 3-D computer monitor. An optical tracking system (Optotrak, Northern Digital) monitored the position of the monkey’s hand during all reaches. The monkey saw a green ball representing the target and an orange ball representing the current position of its hand in space [see Fig. 1(a)].

For the center-out task, a target (center sphere) would appear in the center of the workspace. The monkey was then required to move the cursor sphere to the center sphere and hold it there for 500–1000 ms (hold A). The center sphere would then disappear and a target sphere would immediately appear at one of eight positions at the corner of a virtual cube centered at the position of the center sphere [Fig. 1(b)]. The length of each edge of the cube was 100 mm, thus each reach was approximately 87 mm. Once the target sphere appeared, the monkey had 600 ms to move its hand to the target. Reaction time was defined as the time from when the target sphere appeared to when the monkey moved his hand from the center sphere. Movement time was the period from when the monkey left the center sphere to when it reached the

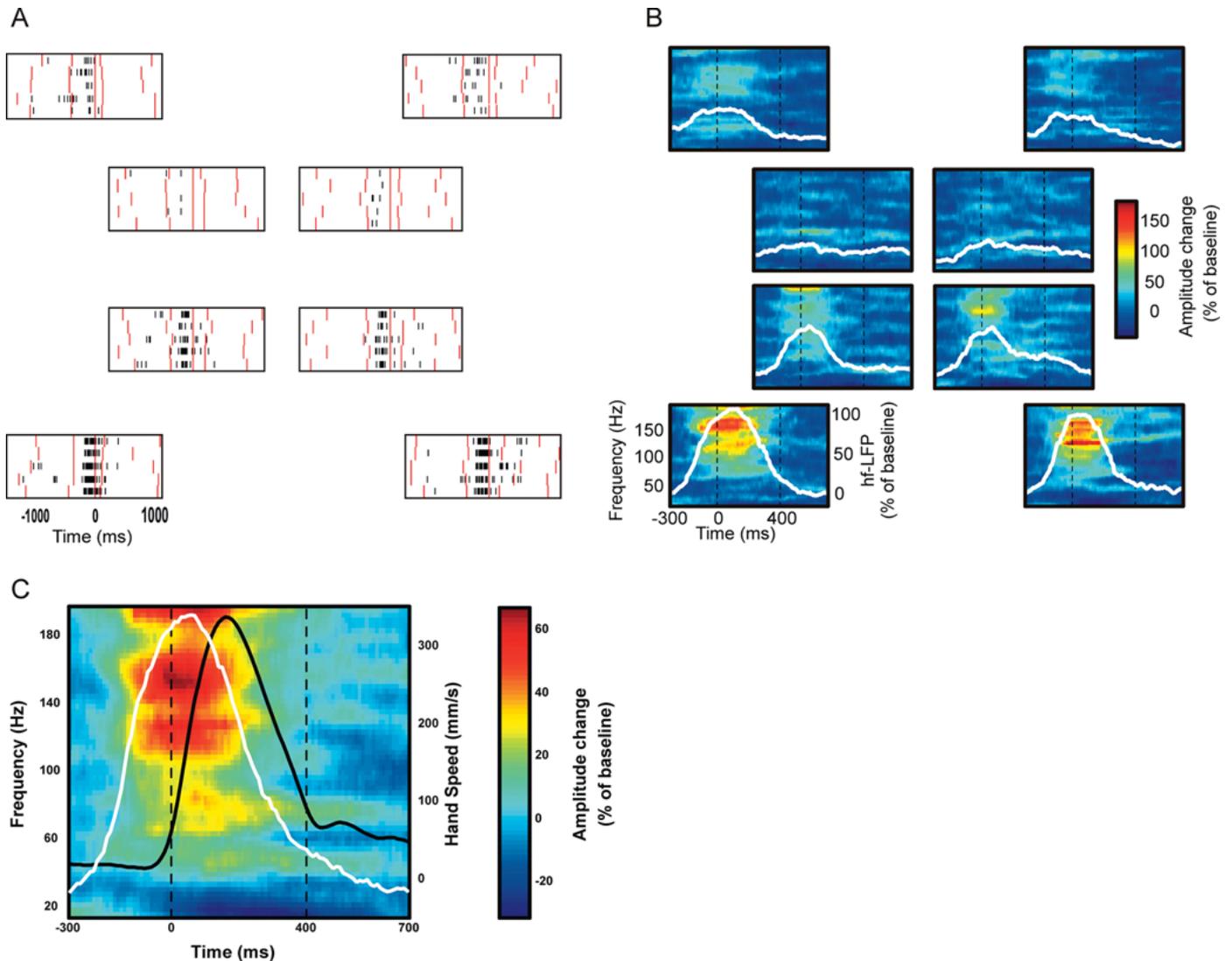


Fig. 2. (a) Spike rasters for five repetitions of reaches to each of eight targets in center-out task. Four inner plots represent reaches to four targets farthest from subject, while four outer plots represent reaches to four targets closest to subject. Reaches are aligned by onset of movement. Each black line represents a spike and red lines indicate task periods as follows: central target is first acquired, peripheral target appears, subject begins to reach for peripheral target, peripheral target is acquired, and finally reward is given. Cell has preferred direction near lower left proximal target. (b) Spectral amplitude as percent change from baseline of LFP recorded on same electrode while cell in (2a) was recorded. White line represents average spectral amplitude of LFP from 60–200 Hz (HF-LFP). HF-LFP has similar tuning to cell recorded simultaneously. (c) Average LFP spectral amplitude for same channel shown in (b). Sharp increase in HF-LFP precedes movement and decrease in beta LFP. Black line is subject's average hand speed, while white line is average HF-LFP. Hand velocity lags HF-LFP activity by approximately 140 ms.

target sphere. The monkey then had to hold his hand in the target sphere for a random interval of 500–1000 ms (hold B). A liquid reward was given after the hold B time was completed. The monkey performed five reaches to each of the eight targets in a random block design.

A standard cylindrical recording chamber (16 mm inside diameter) was implanted in the skull over motor cortex. Intracortical local field potentials and single units were recorded using tungsten microelectrodes with impedances ranging from 1–2 $M\Omega$. LFPs were filtered using a fourth-order low-pass Butterworth filter with an attenuation of 12 dB at 200 Hz and sampled at 500 Hz. Electrodes were arranged in a 16×1 linear array (300- μm spacing) and driven independently by a Thomas Recording Eckhorn microdrive. Each day, a different recording location was chosen in order to well sample the entire chamber region over a period of several weeks.

The spectral amplitude of each LFP was calculated in 3-Hz bins over the range 12 to 200 Hz using an autoregressive model [21]–[23]. The spectral amplitude was calculated in a 300-ms sliding window (150

TABLE I

	Beta	Gamma	HF
Increase	7.9 %	76.1 %	80.0 %
Decrease	62.0 %	4.4 %	5.7 %
Velocity Tuned	5.8 %	8.8 %	17.6 %
Position Tuned	10.5 %	12.5 %	14.9 %

ms before and 150 ms after) for each time point. The movement time was normalized to 40 equally spaced time points having an average spacing of approximately 10 ms (i.e., 400-ms movement time). The high-frequency LFP (HF-LFP) is defined as the average spectral amplitude from 60–200 Hz. The baseline LFP was calculated as the spectral amplitude of the LFP while the monkey was holding its hand in the central target.

The mean LFP spectral amplitude was calculated over the reaction and movement times for each trial and averaged over the five repetitions

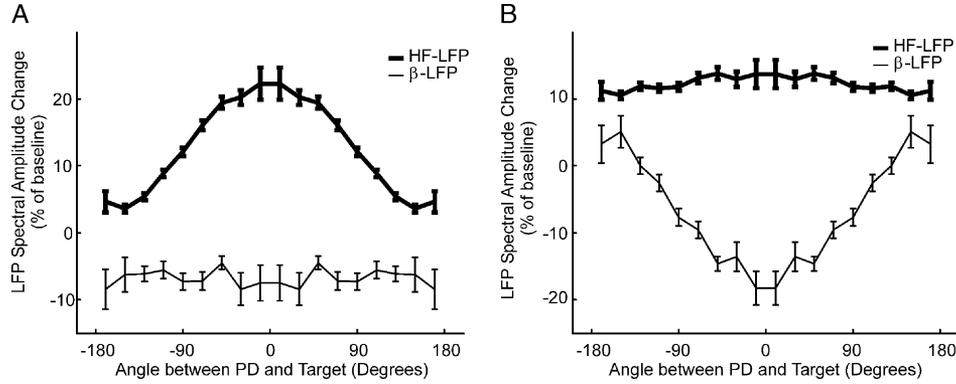


Fig. 3. Generalized LFP spectral tuning. LFP spectral amplitude during reaction time and movement were averaged and are plotted as function of angle between actual reaching direction and preferred direction of that channel. Tuning curves are aligned by HF-PD in (a) and beta-PD in (b). Lengths of error bars are standard errors.

to each target. The hand velocity and hand position were regressed to the LFP spectral amplitude using the following models:

$$\bar{P} = B_{p,0} + B_{p,x}\bar{x} + B_{p,y}\bar{y} + B_{p,z}\bar{z} \quad (1)$$

$$\bar{P} = B_{v,0} + B_{v,x}\bar{x} + B_{v,y}\bar{y} + B_{v,z}\bar{z} \quad (2)$$

where \bar{P} is the averaged LFP spectral amplitude, \bar{x} , \bar{y} , and \bar{z} are the hand positions (coordinates) during the hold times, and \bar{x} , \bar{y} , and \bar{z} are the average hand velocity components during the movement. $B_{p;x,y,z}$ are the positional regression coefficients and $B_{v;x,y,z}$ are the velocity regression coefficients with $B_{v,x}$ and $B_{v,y}$, and $B_{v,z}$ being the preferred direction vector of the LFP. The bars above the variables in (1) represent time averages taken over the reaction and movement times. Applying the regression model to each electrode and frequency band generates a “preferred direction” (PD) for each “feature” (i.e., electrode–frequency band combination) as well as a coefficient of determination (r^2) and p-value corresponding to the fit of the model. Features with p-values less than 0.05 were considered significantly tuned.

III. RESULTS

LFPs were recorded from 823 sites in the motor cortices of three monkeys. In approximately half these recording sites, a single-unit motor cortical cell was simultaneously discriminated on the electrode. In addition, approximately 25% of the sites had two discriminable single units isolated on the electrode and the remaining 25% had no discriminable single-unit activity. Fig. 2 shows a typical example of single unit tuning to movement direction (2a) along with the corresponding power spectrum of the LFP over time (2b). Fig. 2(b) suggests that the high-frequency power spectra of the LFP are tuned to both movement direction and speed. In fact, by averaging all the high-frequency spectra for all eight targets together and comparing it to hand speed (2c), an accurate prediction of hand speed is seen in the cortical activity approximately 140 ms beforehand. Also, note that in Fig. 2(c) the LFP spectral amplitude decreases during movement in the beta frequencies (18–26 Hz).

A one-way ANOVA test was used to determine how many LFPs in various frequency bands significantly increased or decreased during movement. The upper section of Table I shows the percent of features with significant increases/decreases of spectral amplitude during movement ($p < 0.05$, beta: 18–26 Hz, gamma: 30–80 Hz, and HF: 60–200 Hz).

Using the directional analysis outlined in the Section II, the lower section of Table I shows the percentage of LFPs that were significantly tuned ($p < 0.05$) to either hand position (1) or hand velocity (2) for the different frequency ranges in the three monkeys.

A fair number of features tune to both hand position and velocity; however, the number of significantly tuned high-frequency features is

three times larger than the lower frequency Beta ranges. Since a p-value of 0.05 was used to test for significance and only 6% of the beta LFPs were found to be significant, it could be well argued that nearly none of the beta LFPs were, in fact, truly tuned to 3-D movement direction.

In order to determine the correlation in tuning between high-frequency features versus low-frequency features, a generalized tuning curve for was constructed for the features. Fig. 3 shows generalized tuning curves for all significantly tuned features. In Fig. 3(a), the tuning curves are aligned by the high-frequency preferred direction; while, in Fig. 3(b), the tuning curves are aligned by the beta preferred direction.

IV. DISCUSSION

As shown in Fig. 2, there is a strong increase in the HF-LFP accompanied by a moderate decrease in beta-LFP preceding movement. The low-frequency results are consistent with what previous researchers have found in low-frequency LFP analyses (e.g., [12]). The increase in the HF-LFP power leads the hand velocity in a similar fashion to the concurrently recorded binned single unit activity (i.e., firing rate of single cortical neurons [20]). Likewise, nearly 18% of all recorded HF-LFPs were significantly cosine tuned to movement direction [Fig. 3(a)]. The HF-LFP was defined in this paper as the average spectral amplitude 60–200 Hz, since the increases in power in the high frequencies appeared to be broad and not at a specific frequency.

Fig. 2 compares the directional tuning of a typical motor cortical cell and its simultaneously recorded LFP. When an electrode is near a spiking single neuron, the HF LFP is more likely to be cosine tuned and its properties (e.g., preferred direction) tend to be correlated to the single unit tuning properties. For instance, 20% of the LFP channels containing a tuned single unit were themselves tuned. While only 10% of the channels with no discriminable single units had significantly tuned LFPs. Future analyses into the correlation between single-unit signal-to-noise ratio and HF-LFP tuning is needed to determine the influence of spiking activity on local field potential tuning. However, these preliminary results suggest that the HF-LFP reflects local spiking activity and are not correlated with low-frequency LFP oscillations (e.g., mu and beta activity). As seen in Fig. 3(a), when the generalized tuning curves are aligned by the HF-LFP preferred direction, the beta-LFP curve essentially averages out into a flat line. Similarly, Fig. 3(b) shows the converse: when aligned by the beta-LFP, the HF-LFP generalized tuning curve “washes out.” Since there are three times as many significantly tuned HF-LFPs, adding HF-LFP data to a low-frequency BCI signal should increase the information content four fold. With tuning properties similar to single unit activity, the high-frequency components of intracortical LFPs appear to be a viable control signal for a neural prosthetic device.

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Classifying EEG and ECoG Signals Without Subject Training for Fast BCI Implementation: Comparison of Nonparalyzed and Completely Paralyzed Subjects

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Abstract—We summarize results from a series of related studies that aim to develop a motor-imagery-based brain-computer interface using a single recording session of electroencephalogram (EEG) or electrocorticogram (ECoG) signals for each subject. We apply the same experimental and analytical methods to 11 nonparalyzed subjects (eight EEG, three ECoG), and to five paralyzed subjects (four EEG, one ECoG) who had been unable to communicate for some time. While it was relatively easy to obtain classifiable signals quickly from most of the nonparalyzed subjects, it proved impossible to classify the signals obtained from the paralyzed patients by the same methods. This highlights the fact that though certain BCI paradigms may work well with healthy subjects, this does not necessarily indicate success with the target user group. We outline possible reasons for this failure to transfer.

Index Terms—Amyotrophic Lateral Sclerosis (ALS), brain, brain-computer interface (BCI), computer interface human factors, electrocorticography, electroencephalography, locked-in state, paralysis, pattern classification.

I. INTRODUCTION

We report the results from experiments in which auto-regressive (AR) models, support vector machine (SVM) classification, and recursive channel elimination (RCE) were applied to electroencephalogram (EEG) or electrocorticogram (ECoG) signals in order to implement

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