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Analysis of the Correlation between Local Field Potentials and Neuronal Firing Rate in the Motor Cortex

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Abstract—**Neuronal firing rate has been the signal of choice for invasive motor brain machine interfaces (BMI). The use of local field potentials (LFP) in BMI experiments may provide additional dendritic information about movement intent and may improve performance. Here we study the time-varying amplitude modulated relationship between local field potentials (LFP) and single unit activity (SUA) in the motor cortex. We record LFP and SUA in the primary motor cortex of rats trained to perform a lever pressing task, and evaluate the correlation between pairs of peri-event time histograms (PETH) and movement evoked local field potentials (mEP) at the same electrode. Three different correlation coefficients were calculated and compared between the neuronal PETH and the magnitude and power of the mEP. Correlation as high as 0.7 for some neurons occurred between the PETH and the mEP magnitude. As expected, the correlations between the single trial LFP and SUV are much lower due to the inherent variability of both signals.**

I. Introduction

Progress in understanding how individual neurons, neural circuits, and systems interact in cortical motor processing depends upon the ability to experimentally and computationally relate action potentials (spikes) generated at cell bodies with the local field potentials (LFPs) generated by dendritic activity. Methods to elucidate the relationship between LFPs and spikes have traditionally fallen in to two categories: using event related potentials (ERP) which average LFPs synchronized to a repeated external behavior [1] or using spike triggered averaging (STA) which time-lock the LFPs to the internal spike representations [2].

In the time domain, researchers have analyzed the evoked local field potentials created by lever presses by averaging the local field potentials synchronized by the external action [3, 4]. They discovered a transient slow wave that modulates in amplitude during planning and execution of the movement. This shows that signatures of the electrical local field produced by the concerted activity of neurons in M1 can indeed be observed by averaging the field potentials. Correlations between movement evoked potentials have also been studied in a trial-by-trail manner by time-averaged cross-correlation methods to discover interhemispheric relations [5][6]. However, Mitzdorf et al. [7][8] claimed that event-related potentials caused by excitatory synaptic mass activities were discordant with conclusions from single-cell studies concerning topography.

In the frequency domain, LFP tuning has been shown to be manifested also, and differentially, in oscillatory activities in different frequency ranges. Oscillations and spiking in sensorimotor cortex in relation to motor behavior in both humans [9,10] and nonhuman primates [5, 11, 12] in the 15–50 Hz range were found to increase in relation to movement preparation and decrease during movement execution [13]. Specifically, in monkeys they appear during tactile exploratory forelimb movements [6, 14] and movement preparation [11, 12, 13]. Other researchers have also described the temporal structure in LFPs and spikes where negative deflections in LFPs were proposed to reflect excitatory, spike-causing inputs to neurons in the neighborhood of the electrode [15]. The connection between different components of the LFP signal to a motor task and comparisons with activity in single units have been studied [1] through correlation [16, 17], which has been shown to be nonstationary [14] or depend on the context [18].

We are particularly interested in determining the most appropriate feature detection method for correlating amplitude modulated (AM) components of the movement evoked local field potentials and single-unit activities recorded at the same electrode across all movement trials. Understanding the functional relationship between these two signals helps the ultimate goal to use both signals in Brain-Machine Interface (BMI) experiments that can extract mesoscopic and microscopic brain activity. In this paper, we propose an analysis based on the 3 different modulations: amplitude, power, and magnitude, of the movement evoked local field potential on the single unit activity for a reaching movement task. The correlation coefficient will be used to evaluate the relationship between the movement evoked LFP and the single-unit activities in the primary motor cortex in part II, followed by analysis and comparison to the correlation calculated in trial-by-trial manner in part III.

II. Data collection and Methods

A. Data collection

We synchronously collect LFP and spike sorted single unit activity from multiple microelectrode arrays (32 channels) chronically implanted in the contralateral forelimb region of the primary motor cortex [13] in rats [19, 20]. Electrodes were configured in 2 x 8 arrays using 50μm polyimide insulated

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tungsten wire with 250μm separation within the 8-electrode row and 500μm spacing between rows.

The animals participated in a two choice go no-go lever pressing task that was synchronized to the neuronal data collection [21]. From the same electrodes recording at 25kHz, the LFPs are separated from the spike trains by digital lowpass filtering and downsampling to 381Hz. Single units are isolated by bandpass filtering between 300 and 6kHz and using template based spike sorting techniques [22].

Male Sprague-Dauley rats were trained to perform go no-go lever pressing task in an operant conditioning cage (Med-Associates, St. Albans, VT). The task involved an LED visual stimulus to press a lever for a minimum of 0.5s to achieve a water reward. Upon achieving the behavioral criteria (lever choice and press time), a 1kHz tone and a 0.04ml water reward were delivered to the animal providing feedback that the task has been achieved.

A combination of threshold and template based spike-sorting techniques yielded neuronal spike firing times from 44 neurons collected from the 32 chronic microwire electrodes. The neuronal firings were binned (added) in non-overlapping windows of 25 ms, which represents the local firing rate for a neuron.

B. Data Analysis

In this section we evaluated the correlation between single unit activity and 3 different modulations: amplitude, power, and magnitude, of the movement evoked local field potential for a reaching movement task.

To construct peri-event time histograms (PETH) of the single unit activity, the neural recordings were time aligned to the onset of the lever press. Peri-event time histograms (PETH) of the spikes binned in a 25 ms nonoverlapping window were represented from 1 second ahead and 1 second after the activation onset respectively across 93 left lever pressings and 44 right lever pressings [23].

In order to evaluate the correlation between LFP and single unit activity recorded synchronously by the same electrode, all the LFP signals were first low-pass filtered with a cutoff frequency of 20 Hz to get rid of high frequency aliasing, then downsampled to 40 Hz. Similar to the peri-event time histogram of the spikes analysis, the LFP signals at each recording electrode were aligned, in the same manner as spike counts, upon the beginning of both left and right lever presses (time zero). The movement evoked local field potentials were calculated as the averaged local field potentials from 1 second ahead to 1 second after the activation onset respectively across both left lever and right lever presses using equation (1)

$$mEP^{\,i}(t) = \frac{1}{N}\sum_{n=1}^{N} LFP^{\,i}_{\,n}(t) \tag{1}$$

where the N is the lever trials number, n is the trial index, t is the time index of 40 Hz during 1 second ahead and 1 second after movement onset, and i is the index for neurons.

To evaluate whether there is a functional modulation between LFP and single unit activities, correlation coefficients can be evaluated in two different manners. One is trial-by-trial [24] between the single unit activity and the local field potential recorded at the same channel. The correlation coefficients are calculated from 1 second ahead to 1 second after each lever pressing, which is shown in equation (2).

$$CC^{\,i}_{\,n} = \frac{\sum_{t=t_1}^{t_2} [LFP^{\,i}_{\,n}(t) - \overline{LFP^{\,i}_{\,n}}]\cdot[PETH^{\,i}_{\,n}(t) - \overline{PETH^{\,i}_{\,n}}]}{\sqrt{[LFP^{\,i}_{\,n}(t) - \overline{LFP^{\,i}_{\,n}}]^2 \cdot [PETH^{\,i}_{\,n}(t) - \overline{PETH^{\,i}_{\,n}}]^2}} \tag{2}$$

where t_1 and t_2 are respectively the beginning time (-1 second) and the ending time (1 second) of movement evoked local field potentials and single unit activity. $\overline{LFP^i_n}$ and $\overline{PETH^i_n}$ are respectively the time average value of LFP and PETH of neuron i and corresponding channel on lever pressing trial n. Then all the correlation coefficients are averaged across all the lever press trials for this neuron by equation (3).

$$CC^{\,i} = \frac{1}{N}\sum_{n=1}^{N} CC^{\,i}_{\,n} \tag{3}$$

Poor correlations were shown in the previous trial-by-trial procedures [24]. In this paper correlations were evaluated between the time averaged SUA peri-event time histograms of 44 neurons and the amplitude of movement evoked local filed potentials of 32 channels recorded at the same electrode across trials in the entire lever pressing experiment. This is because LFP and SUA are both corrupted by random realizations of some unmodeled noise process (the brain's spontaneous activity). By averaging across the lever press trials, we expect to reduce the noise contamination in the signals. The correlation coefficient between the averaged mEP and PETH is computed according to equation (4).

$$CC^{\,i} = \frac{\sum_{t=t_1}^{t_2} [mEP^{\,i}(t) - \overline{mEP^{\,i}}]\cdot[PETH^{\,i}(t) - \overline{PETH^{\,i}}]}{\sqrt{[mEP^{\,i}(t) - \overline{mEP^{\,i}}]^2 \cdot [PETH^{\,i}(t) - \overline{PETH^{\,i}}]^2}} \tag{4}$$

where t_1 and t_2 are respectively the beginning time (-1 second) and the ending time (1 second) of mEP and PETH. Since the LFP is positive and negative while the spike counts are all positive, this may affect the correlations [1]. Therefore, two other different correlation coefficients were calculated and compared between SUA and the power of mEP (the square of the amplitude), and the magnitude of mEP evaluated by equations (5) and (6):

$$mEP^{i}{}_{power}(t) = \frac{1}{N}\sum_{i=1}^{N}[LFP^{i}_{n}(t)]^2 \tag{5}$$

$$mEP^{i}{}_{magnitude}(t) = \frac{1}{N}\sum_{i=1}^{N}|\,LFP^{i}_{n}(t)\,| \tag{6}$$

III. Results and Analysis

The correlation coefficients were calculated between peri-event time histograms of single unit activities of 44 sorted neurons and the 3 different functions of movement evoked potential of the corresponding 32 channels. The neurons were sorted according to descending correlation coefficients corresponding to mEP, the power of mEP, and the magnitude of mEP.

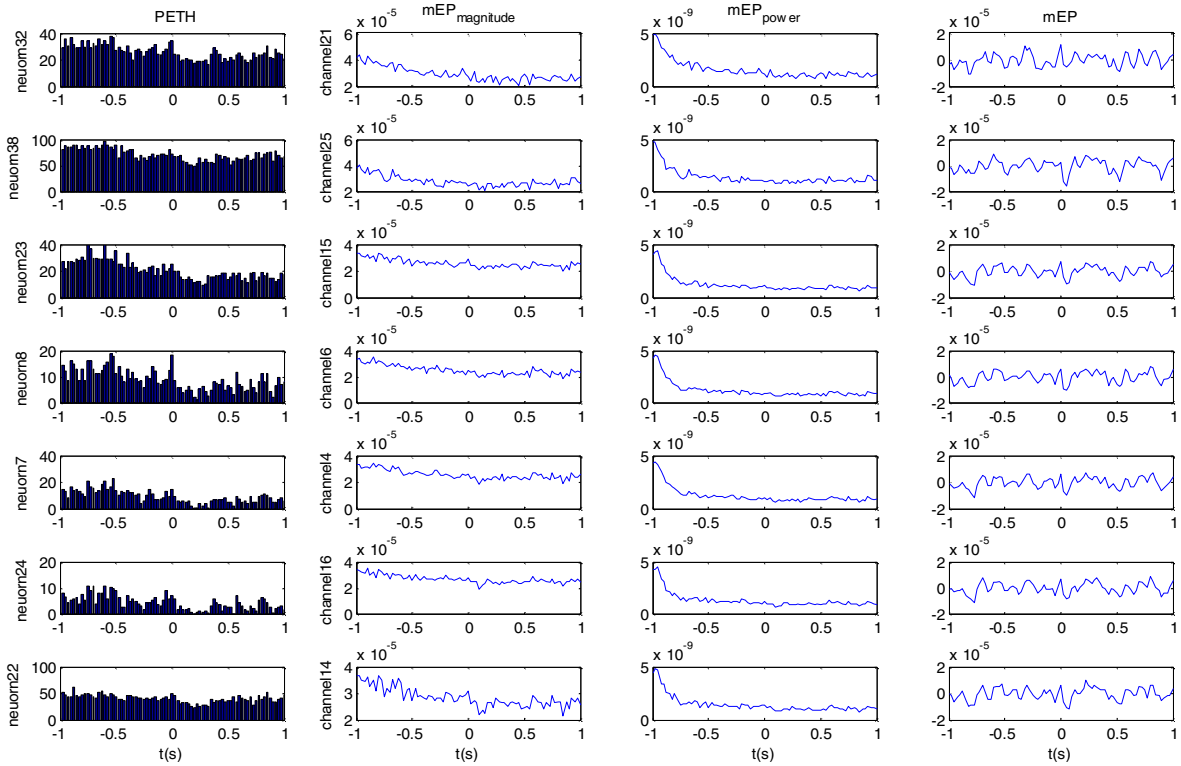

Figure 1. The signals of 7 pairs of neurons and corresponding channels

The maximum correlation coefficient between peri-event time histograms of single unit activities and the raw movement evoked potential was 0.2860, which was close the result mentioned in [1], and the mean correlation coefficient across all 44 neurons was 0.0783 with standard derivation of 0.0634. The maximum correlation coefficient between peri-event time histograms of single unit activities and the power of movement evoked potential was 0.6174, and the mean correlation coefficient across all 44 neurons was 0.2387 with standard derivation of 0.1568, which is higher than the results for amplitude of mEP. The correlation coefficient between peri-event time histograms of single unit activities and the magnitude of the movement evoked potential performed the best with a maximum value of 0.7066, and the mean value 0.3251 with standard derivation of 0.1985 across all 44 neurons.

We picked the top 7 pairs of neurons and corresponding channels with correlation coefficient over 0.5 across all trials on left lever pressings, and show in Figure 1 all signals of the 7 pairs of neurons and corresponding channels. The most left column of the figure is the peri-event time histogram of the single unit activity. The next 3 columns are respectively, from left to right, the mean of the mEP magnitude, the mean of mEP power, and the mEP. The mean of mEP power, the third column, shows a large slope, which means a big variance of the magnitude of the mEP at 1 second ahead of the movent. From the figure, we cannot see the correlations between PETH and the other 3 functions of mEP directly, because they were signals with different variance in different scales. We use the correlation coefficients as the metric to evaluate the functional relationship so that the computation can self-normalize the signals to zero mean and unit standard derivation. Figure 2 shows the normalized PETH (cyan bar) of neuron 32, the normalized mEP (grey dot), the normalized mEPmagnitude (blue solid) and the normalized mEPpower (red dash) of the corresponding channel 21.

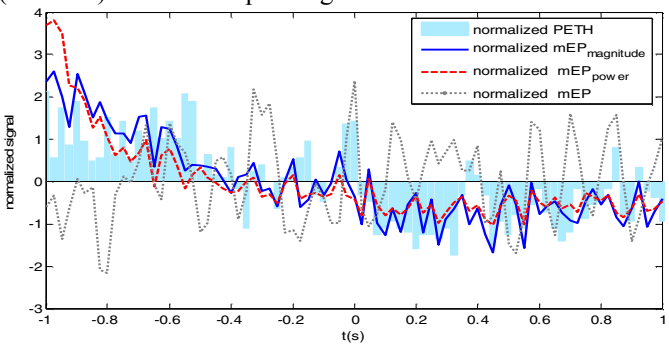

Figure 2. Normalized PETH of neuron 32 and three normalized features of mEP of channel 21

From figure 2, we can easily see that after normalization, the PETH (cyan bar) has a higher correlation (0.70662) with the magnitude of the mEP (solid blue) than with the other two LFP features. We can also observe that the normalized mEP (grey dash dot) marked the movement onset (time 0) as PETH, which has been reported before [1].

The correlations between PETH and the 3 mEP features of all the 7 picked pairs of neurons and corresponding channels are shown in Table 1. From Table 1, we can see that the correlation between the PETH and the mEP magnitude always gave the best performance when compared with the mEP itself.

We also compared the results with the correlation coefficients computed by the trial-by-trial procedure [24] evaluated by equation (2) and (3). The correlation coefficients calculated in this manner gave very poor performance even when we calculate the average correlation coefficients

between the SUA and the magnitude of the LFP. For example, the averaged correlation coefficient across all 93 lever pressing trials between neuron 32 and the magnitude of LFP of channel 21 was only 0.1052. It means that for each lever press trial, the single unit activity and the LFP are very noisy. It is hard to find clear functional relationship from each trial. After the peri-event histograms of the single unit activities and movement evoked local field potentials, we actually averaged the signals and reduced the noise. In this way, we found much higher correlations between them.

Table 1. Correlation Coefficients between SUA and LFP

CC between		PETH and mEP_{mag}	PETH and mEP_{power}	PETH and mEP
neuron	channel			
32	21	0.70662	0.61744	0.021183
38	25	0.70201	0.57943	-0.11655
23	15	0.68482	0.45694	-0.08474
8	6	0.6167	0.45512	0.11944
7	4	0.60322	0.42059	-0.04195
24	16	0.56958	0.41498	0.03493
22	14	0.55543	0.44642	-0.16542

IV. Conclusion and Discussion

Here we tested feature detection analysis based on the correlation between the amplitude modulated movement evoked local field potentials and single unit activity recorded during a reaching movement task. Since amplitude modulations play a significant role for SUA used in BMIs, it is encouraging that correlation as high as 0.7 was obtained for some neurons between the single unit activities and the mEP magnitude. This indicates that the extracellular dendritic potentials contain indicators of the level of neuronal output. The degree to which this relationship exists must be studied in the future from a spatial perspective using both dendritic and somatic electrodes.

A critical aspect of extracting the relationship was the process of averaging the LFP and single unit activity across the lever press trials that reduced the noise contamination caused by the random realization of unmodeled brain spontaneous activities. Additional studies are necessary for reducing the noisy contamination of single trial extraction of mescopic and microcscopic brain activity in Brain-Machine Interfaces (BMI) experiments.

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