34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Decoding Wrist Kinematics from Local Field Potentials of the Ipsilateral Primary Motor and Dorsal Premotor Cortices *

Dong Wang, Yaoyao Hao, Qiaosheng Zhang, Shaomin Zhang, Ting Zhao, Xiaoxiang Zheng，Weidong Chen*

Abstract— **Local field potentials (LFP) are valuable signals for decoding motor kinematics in brain machine interfaces (BMIs). To take full advantage of LFPs, however, more systematic investigation of the relationship between LFPs and ipsilateral limb movement is required. In this paper we investigated the decoding power of LFPs for the ipsilateral wrist movement from two monkeys performing a 2D center-out task. The results show that LFPs could predict the ipsilateral wrist position and velocity with high accuracy, which is comparable to the accuracy of decoding the contralateral kinematics. Furthermore, similar to contralateral decoding, the low (0.3-5 Hz, 5-15 Hz) and high (100-200 Hz, 200-400 Hz) frequency bands resulted in significantly better decoding performance than the medium frequency bands. These results suggest that ipsilateral LFPs could be used to build better BMIs in similar ways of using contralateral LFPs.**

I. INTRODUCTION

Brain machine interfaces (BMIs) link the brain and the external world with a direct communication pathway, which provides a promising way to help restore the damaged motor capabilities of patients with nervous injuries or diseases [1]. A variety of neural signals have been used in BMIs, such as electroencephalogram (EEG), single-unit activity (SUA), multi-unit activity (MUA), and local field potentials(LFPs). Recently, LFPs, which reflect synchronized membrane potentials at dendritic synapses, gained much attention because they provide a good trade-off between spatiotemporal resolution and temporal stability. In particular, since Mehring et al. showed that hand position and velocity could be successfully inferred from low frequency LFPs [2], studies from different groups have consistently shown that LFPs carry rich information of upper limb movements in multiple frequency bands and have been used to decode the kinds of kinematics of the upper limb [3-11]. While most of these studies are focused on contralateral movement decoding, ipsilateral decoding has been relatively ignored, despite that ipsilateral decoding is important for building a bilateral BMI and the pioneering study of Mehring et al. stated that directional tuning for movements clearly existed in ipsilateral LFPs [2]. Only a few studies reported results of ipsilateral decoding [2, 12], and it is yet to be clear how much ipsilateral movement information is contained in LFPs and how such information can be extracted efficiently for better decoding.

In this paper, we investigated how well wrist kinematics in a 2D center-out task could be decoded based on the power of different frequency bands. The results for the first time show that the ipsilateral wrist kinematics could be successfully decoded from LFPs. In addition, decoding on individual frequency band reveals that the frequency dependencies of the decoding power of ipsilateral and contralateral LFPs are remarkably similar, suggesting that we may apply decoding strategies for contralateral LFPs directly on ipsilateral LFP decoding.

II. METHODS

A. Behavior Task and Data Acquisition

Two male macaque monkeys (B01 and B03) were trained to perform 2D center-out task. Following visual cues, each monkey controlled the joystick by turning his wrist to move a red circular cursor on from the screen center to one of the four targets, of which the positions have the same distance to the center and form a cross shape. The monkey had to hold the cursor within the target circle for 300ms to obtain water reward. 10*10 microelectrode arrays (Blackrock Microsystems Inc., USA) were chronically implanted in the primary motor cortex (M1) of the left hemisphere of B01 and the dorsal premotor cortex (PMd) of the left hemisphere of B03 respectively. Although the monkeys were trained to have the ability of successfully performing the task using either the left or right wrist, only the same wrist was permitted to perform the task during each session. Neural activity was recorded using Cerebus multichannel data acquisition system (Blackrock Microsystems Inc., USA) at a sample rate of 30k Hz for each channel. LFP data were collected by band-pass filtering the sample voltage traces within 0.3-500 Hz, and down-sampling them at 1k Hz. 96 channels of signals were recorded for monkey B01, and 64 channels were recorded for monkey B03. Meanwhile, joystick position, which indicates the position of the controlling wrist, was detected by potentiometer and recorded synchronously by an single-chip microcomputer system at a sample rate of 20 Hz. All the procedures conformed to the Guide for the Care and Use of Laboratory Animals (China Ministry of Health) and were approved by the animal care committee at Zhejiang University, China.

* Manuscript received March 15, 2012. This work was supported by grants from the National Natural Science Foundation of China (No. 61031002, 61001172). National High Technology Research and Development Program of China (No. 2012AA011602). Zhejiang provincial key science and technology program for international cooperation(No. 2011C14005)

Dong Wang, Yaoyao Hao and Qiaosheng Zhang are with the Qiushi Academy for Advanced Studies, and the Department of Biomedical Engineering and Instrument Science, Zhejiang University, Hangzhou, China

Shaomin Zhang, Ting Zhao and Xiaoxiang Zheng are with Qiushi Academy for Advanced Studies, Zhejiang University, Hangzhou, China.

Weidong Chen is with Qiushi Academy for Advanced Studies, Zhejiang University, Hangzhou, China. (Phone: +86 571 87952838; Fax: +86 571 87952865; e-mail: qaas@zju.edu.cn).

B. Feature Selection and Frequency Band

The raw LFP waveform was firstly digitally filtered (band pass with low cutoff edge at 0.3 Hz and high cutoff edge at 450 Hz, notch filter at 50 Hz), and then any signal value above three standard deviations from the signal mean was set to zero so as to reduce the noise. We use the power as the LFP feature in this study. To calculate the LFP spectrogram, the LFP time series of an entire session were segmented into time windows of 500 ms with 400 ms overlapped. The multitaper spectral estimation approach [13] was employed to obtain the power spectrum in each window of all the channels. Here we used Slepian taper functions with nine tapers, which yield optimal localization in the frequency domain.

The frequency spectrum of LFP signal (0.3-400 Hz) was further partitioned into the seven different frequency bands defined in [7]: δ (0.3-5 Hz), $\theta \sim$ (5-15 Hz), β (15-30 Hz), $\gamma 1$ (30-50 Hz), $\gamma 2$ (50-100 Hz), $\gamma 3$ (100-200 Hz) and the broad high frequency band (bhfLFP: 200-400 Hz). For each frequency band, the power spectrum in each time window was computed by summing up all the estimated power values within the particular frequency band. The power spectrum of different frequency band was later used to decode contralateral or ipsilateral wrist movement.

C. 2D Center-out Kinetics Decoding

Kalman Filter (KF) [14] was employed to estimate the position and velocity of the wrist in the 2D center-out task here. It is a Bayesian decoder, which provides optimal state estimates along with the associated confidence regions for a linear Gaussian dynamic system. The Kalman Filter was based on the following generative model and system model:

$$z_k = A_k x_k + p_k \tag{1}$$

$$x_{k+1} = H_k x_k + q_k \tag{2}$$

where $x_k = [x, y, v_x, v_y]_k^T$ represents the position and velocity of wrist at time $t_k = k\Delta t$ ($\Delta t =$ 100 ms in this study). z_k, the power spectrum of the LFP channel in the particular frequency band is computed in a 500 ms time window starting at t_k . A is the observation matrix that linearly relates the wrist state to the power spectrum of LFP, H is the state matrix that linearly relates the wrist kinematics at time t_{k+1} to the state at time t_k . $p_k \sim N(0,T)$ and $q_k \sim N(0,W)$ are the observation and state Gaussian noise respectively with covariance matrices T and W . Least square estimation was used to train the decoder. The power spectrum of LFPs and wrist kinematics were normalized by z-score before they were used in the decoder.

D. Performance Assessment

To assess the decoding performance, we choose correlation coefficient (CC) and mean square error (MSE) to quantify the decoding accuracy. These metrics measure the similarity between the predicted kinematics and the corresponding actual values. A five-fold cross-validation scheme was performed to reduce the impaction of training data. The process of cross-validation is as follows. The data were evenly partitioned into 5 segments. Of the five segments, a single segment is retained as the test data set for the decoder while the remaining four segments are used as training data. The final result is obtained by averaging five results from the folds after each of the five segments is used exactly once as the test data.

III. RESULT

LFPs data and wrist position were recorded from two monkeys in a total of 22 25-minute sessions (12 from B01 and 10 from B03). Among these sessions, 10 of them (6 from B01 and 4 from B03) correspond to ipsilateral coding, i.e. the monkeys performed the task using the wrist ipsilateral to the implanted hemisphere. 96 channels of LFPs were used to be analyzed for monkey B01 while 58 channels of LFPs were good enough to be analyzed for monkey B03 (the neural signal of the remaining 6 channels was mainly the noise). All decoding analysis and results describe below were based on the five-fold cross-validation scheme.

A. Wrist Position and Velocity Decoding

Fig. 1 shows an example of the synchronously recorded 2D joystick data and one channel of LFPs within 150s from B01. X-position and y-position are plotted in Fig. 1(a), and the same data are illustrated in the two dimensional coordinate system in Fig. 1(b). 96 channels of LFPs were recorded while the monkey B01 was performing the task and Fig. 1(c) only shows one channel of LFPs.

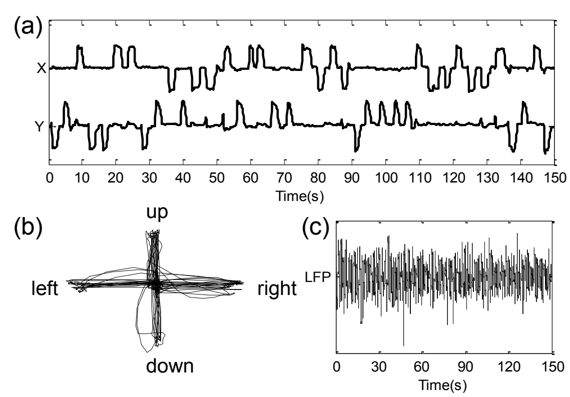

Fig. 1 Movement data of 2D joystick and the corresponding LFP data (a) X-position and y-position of joystick (corresponding to wrist) recorded in 150 s at a sample rate of 20 Hz. (b) Joystick position recorded in x-y plane. (c) One channel of LFPs (0.3-500 Hz) recorded at a sample rate of 1 kHz.

The Kalman Filter was employed to decode the kinematics of the wrist from the power of multichannel LFPs. Fig. 2 summarizes the decoding performance of different frequency band of LFPs about ipsilateral and contralateral wrist kinematics including position and velocity. The results here show the statistics of decoding performance for ipsilateral kinematics across 10 sessions from two monkeys and the statistics of decoding performance for contralateral kinematics across 12 sessions from two monkeys respectively. From Fig. 2 we find that the position and velocity could be predicted with high accuracy using low (δ and $\theta \sim$) and high ($\gamma 3$ and bhfLFP) frequency bands regardless of whether ipsilateral or contralateral wrist kinematics were decoded. Low CC and high MSE were obtained while the middle frequency bands (β , $\gamma 1$ and $\gamma 2$) were used. Overall the decoding performance for ipsilateral wrist movement based on each frequency band was similar to the contralateral decoding based on the same frequency band. These results reveal that the low and high frequency bands not only provide substantial information for decoding contralateral wrist movement but also for decoding the ipsilateral wrist movement.

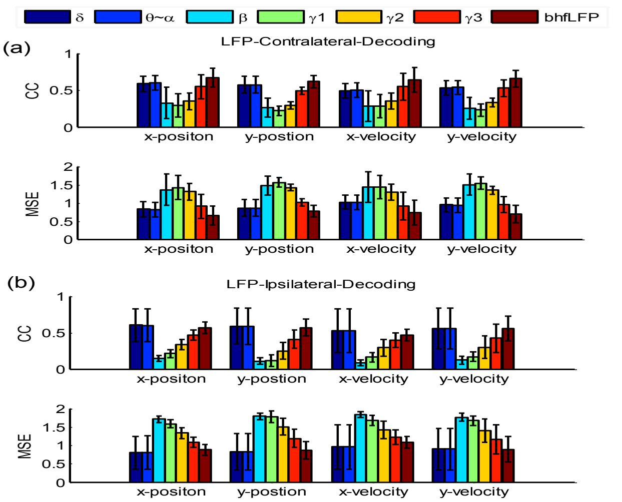

Fig. 2 Decoding performance of LFP power in each frequency band for ipsilateral and contralateral wrist kinematics. Error bars represent the standard deviation. (a) the contralateral wrist kinematics was decoded based on each frequency band and the results were displayed by CC and MSE respectively. (b) CC and MSE were shown respectively for decoding ipsilateral wrist kinematics.

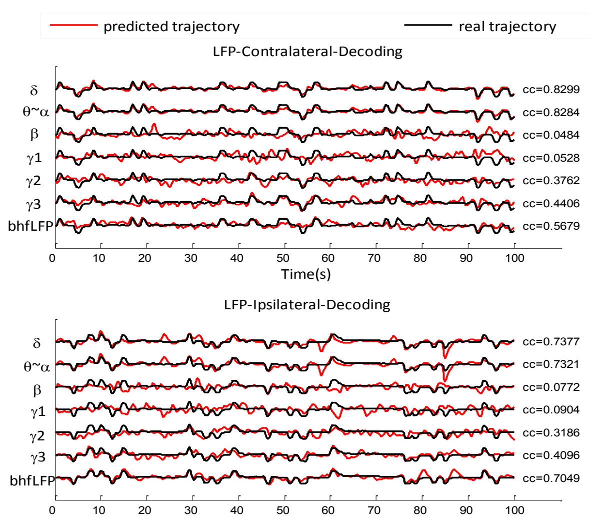

Fig. 3 Decoding y-position of the wrist based on different frequency band of LFPs from two sessions of monkey B01 (one session for the ipsilateral wrist and the other for the contralateral wrist). (a) y-position of the contralateral wrist was decoded based on the seven frequency band. (b) y-position of the ipsilateral wrist was decoded based on the seven frequency band.

Decoding examples of y-position of the contralateral and ipsilateral wrist based on each of the seven frequency band selected here were shown in Fig. 3. From the figure, we can see that y trajectory predicted close match to the actual trajectory using the low and high frequency bands regardless of whether in contralateral or in ipsilateral decoding. The intermediate frequency bands almost could not rightly reconstruct the trajectory. Similar results were obtained for decoding the other kinematics (x-position, x-velocity and y-velocity). Furthermore, when considering reconstruction of 2D wrist trajectory as demonstrated in Fig. 4, we found that accuracy of ipsilateral wrist position decoding was also substantial and only a little worse than the contralateral wrist decoding. All these results indicate that the low and high frequency bands of LFPs could reliably and continuously represent ipsilateral wrist movement as well as contralateral wrist movement.

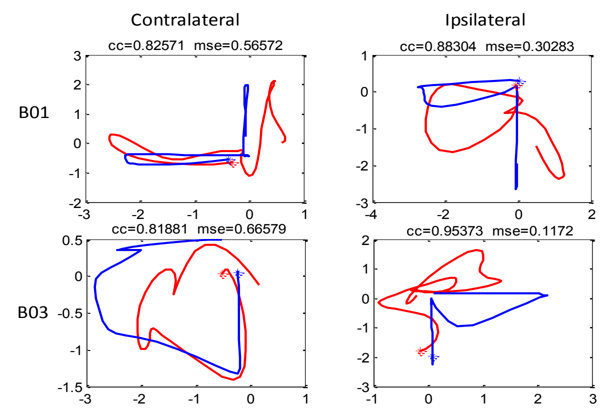

Fig. 4 2D wrist position reconstruction based on bhfLFP decoding. Blue lines represented the actual trajectoris and red lines represented the decoded trajectories based on bhfLFP. Stars indicated the beginning of the trajectory. Four figures here shows the sample segments (each segment lasted about 5s) extracted from much longer trajectories. The position had been normalized here. The CC and MSE shown were avaveraged across x and y.

B. N-channel Decoding Performance

All the results above were obtained based on all the channels recorded (96 channels for monkey B01 and 58 channels for monkey B03). We also examined the dependency of the decoding performance on the number of channels for ipsilateral wrist kinematics for each monkey. Firstly, the decoding power of individual channel was calculated based on the different frequency band to investigate how much the choice of the channel matters. Because of the intermediate frequency bands with low decoding accuracy, so we only focus on the low (δ and $\theta \sim$) and high ($\gamma 3$ and bhfLFP) frequency bands. The single channel decoding performance of y-position based on the δ band as an example was shown in Fig. 5. It is obvious that CC and MSE varied broadly with the selected channel: CC could reach values greater than 0.45 for the best channel, and also could reach values smaller than 0.05 for the worst channel. So it matters which channels are selected, and then the relationship between the decoding power and channel number was analyzed by randomly adding single channel, once at a time, and decoding the kinematics using the channels added until all the channels were added. This procedure was repeated 50 times, and then the averaged curve, which describes the decoding power as a function of the channel number, was obtained to decrease the impact of the selection of the channels. The results based on the low (δ) and high (bhfLFP) frequency bands for y-position of ipsilateral wrist were demonstrated in Fig. 6. For both monkeys, the CC increases with the addition of LFP channels which is consistent with the decreasing MSE. This finding was also common for other kinematic variables. And we also found that 40 randomly selected channels could achieve about 90% of the best CC.

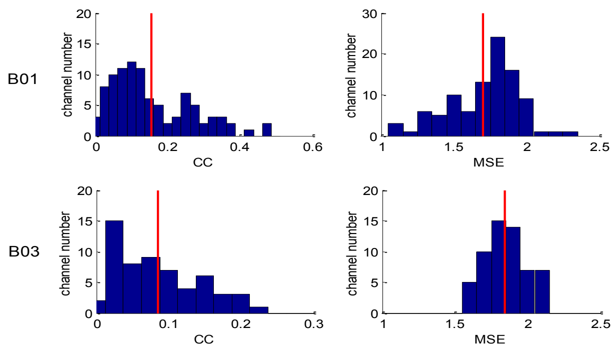

Fig. 5 Single channel LFP decoding performance based on δ band for y-position. Distribution of decoding power for individual channel for y-position of ipsilateral wrist (96 channels for monkey B01, 58 channels for monkey B03). Vertical red lines represent the mean.

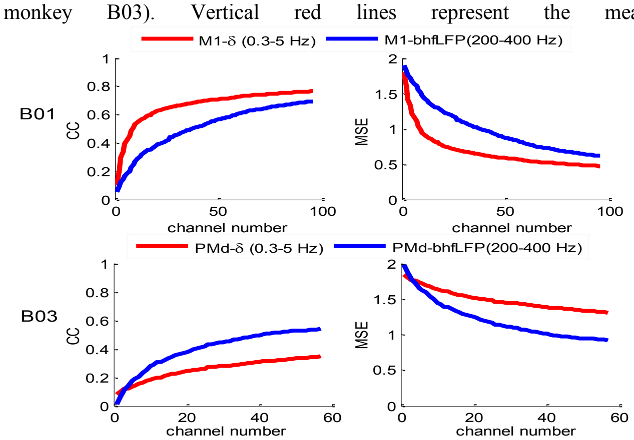

Fig. 6 The relationship between the decoding performance and the number of channels based on the low and high frequency bands for y-position of ipsilateral wrist.

IV. DISCUSSION AND CONCLUSION

In this paper, we have investigated the decoding performance of LFPs for ipsilateral wrist kinematics based on the each of seven frequency bands here in a 2D center-out task. We successfully decoded ipsilateral wrist movement from the power of LFPs and the results showed that the low (δ and $\theta\sim$) and high ($\gamma 3$ and bhfLFP) frequency bands of LFPs achieved good performance and the decoding power could be comparable to the same band of LFPs for the contralateral kinematics. And the results presented here also suggest that the LFPs from the ipsilateral hemisphere could be analyzed in the same way as the contralateral LFPs and could be incorporated into decoding the limb kinematics for better performance. These findings also bring benefit for the patients suffering from extensive unilateral brain injury, and the LFP from the remained intact hemisphere could be used to control the ipsilateral limb movement. And with the characteristics of stable and durable recording, LFPs from bi-hemisphere could be combined and used to build bilateral BMIs which would improve the overall performance of practical BMIs in the future.

REFERENCES

[1] [1] M. A. Lebedev and M. A. Nicolelis, "Brain-machine interfaces: past, present and future," Trends Neurosci, vol. 29, pp. 536-46, Sep 2006.

[2] [2] C. Mehring, J. Rickert, E. Vaadia, S. C. de Oliveira, A. Aertsen, and S. Rotter, "Inference of hand movements from local field potentials in monkey motor cortex," Nature Neuroscience, vol. 6, pp. 1253-1254, Dec 2003.

[3] [3]J. Rickert, S. C. de Oliveira, E. Vaadia, A. Aertsen, S. Rotter, and C. Mehring, "Encoding of movement direction in different frequency ranges of motor cortical local field potentials," Journal of Neuroscience, vol. 25, pp. 8815-8824, Sep 2005.

[4] [4] I. Asher, E. Stark, M. Abeles, and Y. Prut, "Comparison of direction and object selectivity of local field potentials and single units in macaque posterior parietal cortex during prehension," Journal of Neurophysiology, vol. 97, pp. 3684-3695, May 2007.

[5] [5] R. L. Spinks, A. Kraskov, T. Brochier, M. A. Umilta, and R. N. Lemon, "Selectivity for Grasp in Local Field Potential and Single Neuron Activity Recorded Simultaneously from M1 and F5 in the Awake Macaque Monkey," Journal of Neuroscience, vol. 28, pp. 10961-10971, Oct 2008.

[6] [6] N. F. Ince, R. Gupta, S. Arica, A. H. Tewfik, J. Ashe, and G. Pellizzer, "High Accuracy Decoding of Movement Target Direction in Non-Human Primates Based on Common Spatial Patterns of Local Field Potentials," Plos One, vol. 5, Dec 2010.

[7] [7] J. Zhuang, W. Truccolo, C. Vargas-Irwin, and J. P. Donoghue, "Decoding 3-D Reach and Grasp Kinematics From High-Frequency Local Field Potentials in Primate Primary Motor Cortex," IEEE Transactions on Biomedical Engineering, vol. 57, pp. 1774-1784, Jul 2010.

[8] [8] Bansal, "Relationships among low-frequency local field potentials, spiking activity, and three-dimensional reach and grasp kinematics in primary motor and ventral premotor cortices (vol 105, pg 1603, 2011)," Journal of Neurophysiology, vol. 106, pp. 1599-1599, Sep 2011.

[9] [9] A. K. Bansal, W. Truccolo, C. E. Vargas-Irwin, and J. P. Donoghue, "Decoding 3-D reach and grasp from hybrid signals in motor and premotor cortices: spikes, multiunit activity and local field potentials," J Neurophysiol, Dec 7 2011.

[10] [10] E. Stark and M. Abeles, "Predicting movement from multiunit activity," Journal of Neuroscience, vol. 27, pp. 8387-8394, Aug 2007.

[11] [11] D. A. Heldman, W. Wang, S. S. Chan, and D. W. Moran, "Local field potential spectral tuning in motor cortex during reaching," Ieee Transactions on Neural Systems and Rehabilitation Engineering, vol. 14, pp. 180-183, Jun 2006.

[12] [12] K. Ganguly, L. Secundo, G. Ranade, A. Orsborn, E. F. Chang, D. F. Dimitrov, J. D. Wallis, N. M. Barbaro, R. T. Knight, and J. M. Carmena, "Cortical representation of ipsilateral arm movements in monkey and man," J Neurosci, vol. 29, pp. 12948-56, Oct 14 2009.

[13] [13] D. B. Percival and A. T. Walden, Spectral analysis for physical applications: multitaper and conventional univariate techniques: Cambridge Univ Pr, 1993.

[14] [14] W. Wu, M. J. Black, D. Mumford, Y. Gao, E. Bienenstock, and J. P. Donoghue, "Modeling and decoding motor cortical activity using a switching Kalman filter," Biomedical Engineering, IEEE Transactions on, vol. 51, pp. 933-942, 2004.