A hierarchical structure for human behavior classification using STN local field potentials

Hosein M. Golshan, Adam O. Hebb, Sara J. Hanrahan, Joshua Nedrud, Mohammad H. Mahoor

ECE Dept., University of Denver, Denver, CO, USA
Colorado Neurological Institute (CNI), Denver, CO, USA

ABSTRACT

Background: Classification of human behavior from brain signals has potential application in developing closed-loop deep brain stimulation (DBS) systems. This paper presents a human behavior classification using local field potential (LFP) signals recorded from subthalamic nuclei (STN).

Method: A hierarchical classification structure is developed to perform the behavior classification from LFP signals through a multi-level framework (coarse to fine). At each level, the time-frequency representations of all six signals from the DBS leads are combined through an MKL-based SVM classifier to classify five tasks (speech, finger movement, mouth movement, arm movement, and random segments). To lower the computational cost, we alternatively use the inter-hemispheric synchronization of the LFPs to make three pairs out of six bipolar signals. Three classifiers are separately trained at each level of the hierarchical approach, which lead to three labels. A fusion function is then developed to combine these three labels and determine the label of the corresponding trial.

Results: Using all six LFPs with the proposed hierarchical approach improves the classification performance. Moreover, the synchronization-based method reduces the computational burden considerably while the classification performance remains relatively unchanged.

Comparison with existing methods: Our experiments on two different datasets recorded from nine subjects undergoing DBS surgery show that the proposed approaches remarkably outperform other methods for behavior classification based on LFP signals.

Conclusion: The LFP signals acquired from STNs contain useful information for recognizing human behavior. This can be a precursor for designing the next generation of closed-loop DBS systems.

1. Introduction

Parkinson’s disease (PD) is a debilitating neurodegenerative disorder characterized by motor symptoms such as tremor, rigidity, and bradykinesia (Hebb et al., 2012; Rosin et al., 2011). Although the neurophysiological reason for this phenomenon is not clearly known, the interaction of distinct processing circuits of the basal ganglia and cortex may be involved (Hebb et al., 2012). To treat patients with advanced PD signs, deep brain stimulation (DBS) is often used specifically when pharmacotherapy is no longer effective in tackling the patients’ motor symptoms. DBS has provided a dramatic therapy that can remarkably alleviate motor symptoms of PD. The surgical procedure consists of implanting DBS leads in the globus pallidum (GPI) or subthalamic nucleus (STN) of the brain for...
therapeutic stimulation by a high-frequency (≈130–185 Hz) electrical pulse with a constant pulse width and amplitude (Follett et al., 2010; Moro et al., 2010; Zhuang et al., 2010).

Apart from providing relief of the PD symptom manifestations, DBS gives a unique opportunity to record in vivo the neural activities in deep brain structures through recording local field potential (LFP) signals in surgery (Hebb et al., 2012). This provides an excellent opportunity to investigate the electrical oscillatory activities of the brain (Abosch et al., 2012; Giannicola et al., 2012). Human LFP recordings have been used to characterize activity within cortical regions and subcortical nuclei (Darvas and Hebb, 2014a). In addition, it has been used for studying the effect of neuro-stimulation as well as developing primitive closed-loop DBS systems (Rosin et al., 2011; Santaniello et al., 2011; Little et al., 2013a).

It has been shown (Santaniello et al., 2011; Little et al., 2013a) that a closed-loop DBS system can decrease the side effects (e.g., cognitive and balance disruptions) of the existing open-loop DBS systems, which only use constant stimulation parameters such as frequency, pulse width, and amplitude. Additionally, a closed-loop system may reduce the power consumption of DBS systems by switching off/on the implanted pulse generator (IPG) when needed (Rosin et al., 2011). Currently, the stimulation parameters are set by highly trained clinicians, and the initial programming may require multiple clinical visits over several months before achieving optimal performance. Over the lifetime of the device, the stimulation parameters may need to be adjusted periodically in order to obtain a suitable compromise between maximization of the therapeutic improvement and minimization of the stimulation-imposed side effects (Deuschl et al., 2006; Lee et al., 2010). The static nature of current FDA-approved DBS devices are poorly consistent with the dynamic nature of PD since the Parkinsonian symptoms have typically faster dynamics than those provided by the adjustments of the DBS therapy (Deuschl et al., 2006; Hammond et al., 2007). Hence, developing a closed-loop DBS system capable of adjusting the stimulation parameters automatically has gained much attention in recent years. To this end, classification of the human behavior using the feedback of electrical signals recorded from brain is considered a major stepping stone toward such a device.

Electroencephalography (EEG) and LFP signals have been used to decode human behavior. However, accurate classification based on the acquired brain signals can be considerably challenging due to the poor signal-to-noise ratio (Blankertz et al., 2011; Lotte et al., 2007). Different EEG-based methods have been developed for human task classification/detection purposes (Sheikh et al., 2003; Millán et al., 2004a; Wolpaw et al., 2000; Wolpaw et al., 2002). Event-related potential (ERP)-based classification has been used to develop suitable brain computer interface (BCI) (Treder and Blankertz, 2010; Bostanov, 2004). Support vector machine (SVM) has successfully been utilized for EEG classification applications (Kaper et al., 2004; Li et al., 2008). By imposing L2-norm constraint, Muller et al., (Muller et al., 2004) proposed regularized Fisher’s discriminant analysis (RFDA) for motor imaginary EEG classification. A sparse version of the FDA for recognizing finger movement has been introduced in (Blankertz et al., 2002), resulting in better classification performance compared to SVM. Hoffmann et al., (Hoffmann et al., 2008) presented a Bayesian LDA (BLDA) for ERP classification, which has shown suitable performance in BCI applications. Common spatial pattern (CSP) has been one of the most successful algorithms for single-trial EEG classification (Pfurtscheller et al., 1999; Guger Schlogl et al., 2001; Blanchard and Blankertz, 2004; Dornhege et al., 2003; Dornhege et al., 2004) (i.e., single-trial analyses provide a systematic mapping between the brain activity and subject’s behavioral variability). Neural Networks and SVM-based classifiers together with wavelet-domain feature extraction have been used in detecting human behavior (Subasi and Ercelebi, 2005; Wu et al., 2010; Li et al., 2009). Furthermore, many studies have focused on the real-time detection of behavior using EEG and electrocorticography (ECoG) data such as P300 detection for spelling (Scherer et al., 2004; Panicker et al., 2011), brain-switch based on motor imagery (Townsend et al., 2004; Muller–Putz et al., 2010), and self-regulation of rhythm (Millán et al., 2004b).

Most recently, classification of the human behavior using LFP signals has been addressed in some studies, aiming at providing basis for behavior-adapted closed-loop DBS systems. Considering the oscillatory nature of the STN-LFPs, Loukas and Brown (Loukas and Brown, 2004) proposed an algorithm to predict self-paced hand-movements. A pilot research was done by Santaniello et al., (Santaniello et al., 2011) in which a closed-loop DBS system capable of adjusting the stimulation amplitude was developed. The LFP signals from ventral intermediate nucleus (VIM) of the thalamus were used as the control variable in their closed-loop system. Time-frequency analysis of the β frequency range (≈10–30 Hz) of the LFP signals has been used in different studies (Niketeghad et al., 2014; Golshan et al., 2016; Golshan et al., 2017) to drive SVM or multiple kernel learning (MKL)-based SVM classifiers for human behavior recognition purposes. An adaptive learning approach using LFP signals was proposed in (Zaker et al., 2014), where the authors developed a hybrid model for human behavior clustering based on combining SVM and hidden Markov model (HMM). In (Mahoor et al., 2016; Niketeghad et al., 2015), a non-linear regression method was developed to measure the inter-hemispheric connectivity between LFP signals, aiming at detecting motor activity, like finger movement of the PD patients.

In this paper, we focus on human behavior classification using LFP signals recorded from the STN regions of the brain. The wavelet decomposition of the acquired signals within the β frequency range is used to generate a more distinctive feature space for representing different human behaviors (Hebb et al., 2012; Niketeghad et al., 2014). In contrast to the previous works (Golshan et al., 2016; Golshan et al., 2017) in which just a single or a pair of the bipolar signals are employed in the classification step, we propose to utilize all recorded bipolar LFP signals (three bipolar LFP signals are recorded from each STN using all four contacts of implanted DBS leads, resulting in six bipolar LFP signals from two STNs) to feed an MKL-based SVM classifier for behavior recognition purposes. We develop a hierarchical structure capable of performing the behavior classification at different levels of resolution, ranging from a coarse level (e.g., action recognition) to a finer level (e.g., a sub-category of the motor activity, like finger movement). Such a coarse-to-fine scheme provides a flexible classification interface that can easily be terminated at each level of resolution defined by the user. As a consequence, it enhances the discrimination ability of the classifier since a fewer number of classes requires to be analyzed at each level.

However, using all six available LFPs potentially tends to increase the computational burden due to the size of the feature vectors. To overcome this problem, we alternatively propose a parallel classification scheme that takes advantage of all available data at each level of the hierarchical scheme while the computational burden still remains low. To this end, considering the synchronized aggregate activity of the LFP signals acquired from the basal ganglia (Loukas and Brown, 2004; Darvas and Hebb, 2014b; Mamun et al., 2015; Little et al., 2013b) and inspired by the classification method presented in (Golshan et al., 2017), we use an FFT-based synchronization approach to pair up the recorded LFP signals, making three pairs out of six available signals for each trial and driving three classifiers in parallel. Finally, three predicted labels of a single trial are fused through a decision function to estimate the label of the input trial at each level of the hierarchical scheme. With this parallel approach, the computational burden decreases considerably while the classification performance remains relatively unchanged.
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