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Estimate the effective connectivity in multi-coupled neural mass model using particle swarm optimization

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HIGHLIGHTS

- A new model inversion framework for estimating effective connectivity from measured data is introduced in this manuscript.
- The neural mass model along with the particle swarm optimization algorithm forms our framework.
- The framework and the results may be fundamentally important for epilepsy detection and treatment.

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ABSTRACT

Assessment of the effective connectivity among different brain regions during seizure is a crucial problem in neuroscience today. As a consequence, a new model inversion framework of brain function imaging is introduced in this manuscript. This framework is based on approximating brain networks using a multi-coupled neural mass model (NMM). NMM describes the excitatory and inhibitory neural interactions, capturing the mechanisms involved in seizure initiation, evolution and termination. Particle swarm optimization method is used to estimate the effective connectivity variation (the parameters of NMM) and the epileptiform dynamics (the states of NMM) that cannot be directly measured using electrophysiological measurement alone. The estimated effective connectivity includes both the local connectivity parameters within a single region NMM and the remote connectivity parameters between multi-coupled NMMs. When the epileptiform activities are estimated, a proportional–integral controller outputs control signal so that the epileptiform spikes can be inhibited immediately. Numerical simulations are carried out to illustrate the effectiveness of the proposed framework. The framework and the results have a profound impact on the way we detect and treat epilepsy.

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1. Introduction

Brain processing is the result of interactions among several brain regions or neural populations (such as cortical columns, the basic units of the cortex), which are reciprocally interconnected and functionally integrated. Abnormal brain connections appear to occur in abnormal brain activities [1], including epilepsy disease, which is the focus of this study. Epilepsy is a neurological disorder defined by recurrent seizure. Seizure is characterized by aberrant hyper-synchronic activity at several brain regions (generalized seizures) or just in a circumscribed brain region (focal seizures). Unless other neurological disorders, patients with epilepsy typically have normal neurological activity during interictal stage [2]. Approximately thirty percent epilepsy patients cannot be cured by advanced medical treatments, including pharmacology and surgical methods. The mechanism of epilepsy has not been completely understood, but a common proposed underlying theme considers the

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transition from normal neural activity to seizure is because of the abnormal connectivity between neuronal populations [2,3], and [4]. An improved understanding of the neurophysiological basis underlying seizure initiation, spread, and termination will therefore be conducive to therapeutic strategies and medical management.

Neuroimaging technologies have enabled to monitor functional relationships between brain regions and to gain a deeper understanding on how the brain works [5]. Non-interventional methodologies, for example, electroencephalogram (EEG), magnetoencephalogram (MEG), or functional magnetic resonance imaging (fMRI) data have all been used to evaluate connectivity in epileptic patients. Among these imaging modalities, EEG captures high temporal resolution [6], and [7], and is thus a powerful tool for estimating temporal dynamics of brain connectivity and seizure electrophysiology [8–11], and [12].

Mathematical models especially network models make a contribution to better expound the relationship between brain electric activities varying from health to disease. A network model consists of nodes and links. The node can be an individual neuron or a population of structured neurons depending on the spatial scale of interest [13]. The observations of the network model are the micro- or macro-electrical recordings from each node. The directional links between the nodes are able to represent the effective connectivity and causal interaction, which can be inferred through the observations and the causal model.

This paper is built on the studies for brain connectivity and reverse modeling [7,9], and [14]. A new model-based framework is presented for estimating the effective connectivity and model status in a neural network model. This estimate scheme is applicable to many alternate neural biophysics models where effective connectivity corresponds to the connection parameters of the network model.

Effective connectivity describes the causal effects that one neural system exerts on another one, either at a synaptic or population level [15], and [16]. An improved understanding considers effective connectivity as “the simplest possible brain circuit that would reproduce the temporal relationship as observed experimentally between recorded regions” [17]. This indicates that the analysis of effective connectivity can be reduced to model interaction or coupling [16]. In order to infer the effective connectivity, knowledge about the network model is needed in addition to observed data. At the same time, a major challenge lays in utilization the functional imaging data is reverse modeling. The framework presented in this paper is a feasible program to this challenge.

Unlike previous studies are based on a single region population model, this study use a multi-coupled neural mass model (NMM) to infer effective connectivity from observed data. In the context of this study, the local interactions are described by the connectivity strength parameters between neural sub-population (i.e., pyramidal neurons and interneurons) within the circuitry of a functional processing unit (cortical region or cortical column) and the remote effective connectivity are described by the connection strength parameters between brain regions.

Inversion means using recorded data to estimate the neural states (average membrane dynamics of various neural population subtypes) and parameters (defining connectivity strengths) [9]. Estimation of system variables provides new information about underlying population dynamics and physiological properties that cannot be directly measured using neuroimaging methods. In systems’ theory, the model-based approach of estimating the unmeasured states and parameters from a measurement is commonly known as ‘observer’, ‘filter’ or ‘estimator’ [18,19]. Numerous estimation formulations exist for fitting multi-coupled NMM to observation data.

The inversion method outlined in this paper is particle swarm optimization (PSO) algorithm, which is very promising for parameter estimation. PSO is first introduced by Kennedy, Eberhart and Shi based on the swarm theory [20,21], and [22]. PSO is able to perform global optimization through calculation of the objective function in the parameter space. Comparing with Kalman filters, PSO method is not very sensitive to the initial parameter setting, does not need derivatives of the objective functions, and can be used in multi-parameters problems. PSO technique can generate a high-quality solution within short calculation time and stable convergence characteristic than other stochastic methods PSO has found wide spread application in solving complex nonlinear optimization problems, owing to its flexibility, simple concept, easy implementation and quick convergence. Many works have already reported the use of PSO method to perform parameter estimation and data reconciliation [23,24], and [25]. Here we apply PSO algorithm to estimate effective connectivity parameters and neural membrane dynamics from observed data. To the best of our knowledge, this is the first research to apply PSO to infer effective connectivity of multi-coupled NMM.

The paper is organized as follows: We first introduce the formulation of the NMM, the multiple regions NMMs and the PSO algorithm. And then, a model-based states and parameters identification framework from electrophysiological signal is presented. Next, example simulations and results are provided that validate the framework for both single and multiple cortical areas. In addition, we show the framework can be used to identify seizure onset, evolution and termination in simulated EEG data. What is more, when PSO method detects the epileptiform abnormalities, an external electric control is introduced to suppress the epileptiform discharges and maintain normal electrophysiological behavior. The final section is the conclusion.

2. Model and method

2.1. Neural mass model

Neural mass model is a simplified canonical cortex column (the unit in neocortex) model, which exhibits an adequate compromise between simplicity and physiological reliability. NMM is primitively proposed by Lopes da Silva, Freeman, Jansen and Rit [26,27], and [28], considering of the interconnected excitatory and inhibitory neurons. The behavior of the

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