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An Optimal Data-Driven Method for Controlling Epileptic Seizures

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Introduction

Neurological disorders such as epilepsy and Parkinson's disease have been associated with excessive neural synchronization. Mathematical knowledge of the brain synchronization principles may be utilized to guide therapeutic approaches, whether pharmaceutical or neurostimulation, in targeting brain areas to control brain dynamics optimally. The Kuramoto model (KM) is a fundamental and abstract form that may be used to simulate the dynamics of brain oscillations [1]. In this paper, we utilize a data-driven method for controlling the phase of Kuramoto oscillators as well as a minimum-cost driver node selection strategy along with exact controllability method to guarantee network controllability. Then we implement this procedure on the extended KM for brain oscillators to desynchronize the oscillations, assessing its effectiveness in suppressing epileptic seizures.

Background and Methods

KM: The KM is a mathematical explanation of the phenomena of synchronization in a population of coupled oscillators. Some alterations and adaptations are needed in order to increase the KM's neurobiological relevance. By adding those neurological factors to the original KM, we obtain the following equation for an N-coupled oscillator system [2]:

$$\frac{d\theta_i(t)}{dt} = \omega_i + \frac{K}{N}\sum_{j=1}^{N} a_{ij}\sin\left(\theta_j(t) - \theta_i(t)\right) + \eta_i(t)$$

Synchrony measure: According to KM, the following measure can be used to evaluate the synchronicity between phases of oscillators at time t:

$$R(t) = \frac{1}{N}\left|\sum_{j=1}^{N} e^{i\theta_j(t)}\right|$$

Node Selection: Controllability is the ability of a control system to go from an initial state to a specific state in a certain amount of time, given proper inputs. In this paper, we used the exact controllability method [3] to calculate the minimum number of driver nodes in the network to reach full controllability. In order to choose the optimal set of driver nodes to control the network, we used the minimum-cost node selection method by solving the following optimization problem using the projected gradient method along with Monte-Carlo scenarios.

$$\min B \quad E(B) = tr\left(W_B^{-1} e^{At_f} e^{A^T t_f}\right)$$
$$\text{s.t.} \quad tr(B^T B) = M$$

Data-Driven Control: The optimal input can be obtained by using the following equation. The matrices are calculated by applying random inputs and recording the obtained output of the network. Q and R are the matrices that penalize output deviation and input signal energy, respectively [4].

$$u^{\star}_{0:T-1} = argmin_{u_{0:T-1}} y^T_{1:T-1} Q y_{1:T-1} + u^T_{0:T-1} R u_{0:T-1}$$

Results

We used a healthy brain network in order to test our proposed method. The brain structural connectivity and delay matrices are shown in Fig. 1. According to this model, the brain network consists of 80 regions. We simulated the network for a total of 600 seconds, where seizure is mimicked during $200 < t < 400$. The results of the simulation are shown in Fig. 2. The red color represents the uncontrolled response, the blue represents the controlled response, and the highlighted area illustrates the epileptic phase.

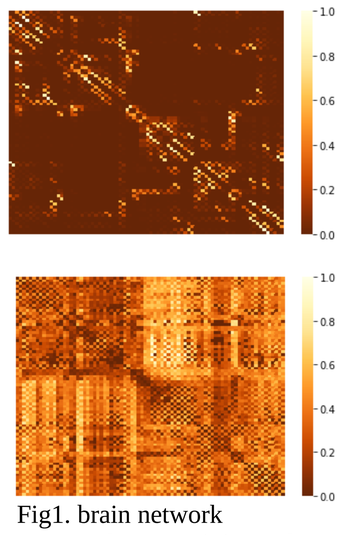

Fig1. brain network structural connectivity and delay matrices

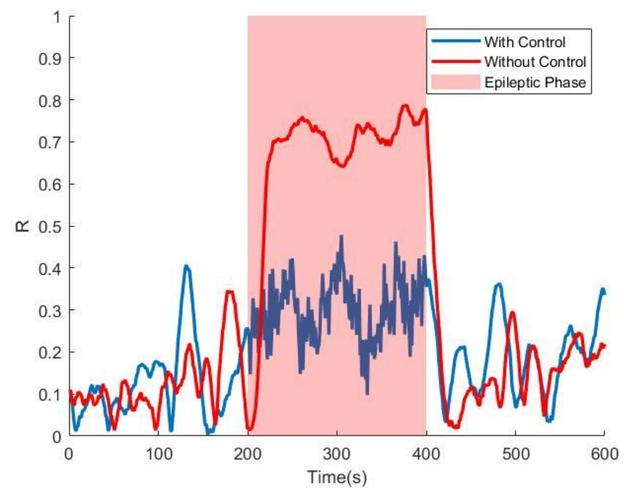

Fig2. the brain synchronization measure during simulation

Conclusion

In this paper, we presented a novel method of controlling brain synchronization. Our method is unique in three ways. The first is the data-driven control approach, the second is the optimal selection of driver nodes, and the third is the utilization of the modified KM. We showed that this framework would be effective in desynchronizing the aberrant synchronization of neuronal activity observed during an epileptic seizure phase. So we believe that our proposed method would be beneficial for treating diseases where abnormal synchronization is responsible for them.

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