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Review

Automated seizure prediction

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ABSTRACT

In the past two decades, significant advances have been made on automated electroencephalogram (EEG)-based diagnosis of epilepsy and seizure detection. A number of innovative algorithms have been introduced that can aid in epilepsy diagnosis with a high degree of accuracy. In recent years, the frontiers of computational epilepsy research have moved to seizure prediction, a more challenging problem. While antiepileptic medication can result in complete seizure freedom in many patients with epilepsy, up to one-third of patients living with epilepsy will have medically intractable epilepsy, where medications reduce seizure frequency but do not completely control seizures. If a seizure can be predicted prior to its clinical manifestation, then there is potential for abortive treatment to be given, either self-administered or via an implanted device administering medication or electrical stimulation. This will have a far-reaching impact on the treatment of epilepsy and patient's quality of life. This paper presents a state-of-the-art review of recent efforts and journal articles on seizure prediction. The technologies developed for epilepsy diagnosis and seizure detection are being adapted and extended for seizure prediction. The paper ends with some novel ideas for seizure prediction using the increasingly ubiquitous machine learning technology, particularly deep neural network machine learning.

1. Introduction

Seizures are due to the sudden change in the brain's electrical activity which results in alteration of awareness, often with associated involuntary abnormal movements [1–3]. Seizures occur as a result of hypersynchronous firing and propagation of abnormal neural networks [4–6]. Epilepsy is defined by having two or more unprovoked seizures or one unprovoked seizure with increased risk for future unprovoked seizures [7–9]. According to the World Health Organization (WHO), nearly 50 million people have epilepsy [10].

The etiology of epilepsy can be categorized as structural, genetic-mediated, metabolic, or unknown [11]. Patients with epilepsy who experience loss of consciousness and convulsive movements are at risk of serious physical injury. Patients with uncontrolled generalized tonic–clonic seizures are also at increased risk of the fatal complication sudden unexplained death in epilepsy (SUDEP) [12]. These patients are restricted from operating a motorized vehicle and unable to obtain meaningful employment because of uncontrolled seizures.

There is also strong evidence that people with long-standing uncontrolled epilepsy are at increased risk for permanent memory impairment, depression, anxiety, suicide, and other psychiatric disorders [13]. These factors negatively affect the quality of life of patients living with epilepsy. They also affect the lives of family and caretakers and represent an economic burden in terms of healthcare cost to their family members [14].

Following the seminal work of Adeli et al. [15], significant advances have been made on automated electroencephalogram (EEG)-based diagnosis of epilepsy and seizure detection in the past fifteen years [16,17]. A number of innovative algorithms have been introduced that can perform epilepsy diagnosis and seizure detection with a high degree of accuracy [18–21]. Faust et al. [22] presented a review of wavelet-based techniques [23–25] for computer-aided seizure detection and epilepsy diagnosis. They conclude that a "*multi-paradigm approach through the adroit integration of wavelets, nonlinear dynamics and chaos theory, and neural networks advanced by Adeli and associates is the most effective method for automated EEG-based diagnosis of epilepsy*."

In recent years, the frontiers of computational epilepsy research have moved to seizure prediction, a more challenging problem. Therefore, the focus of this paper is a review of recent literature on automated seizure prediction. Fig. 1 depicts a block diagram of the proposed seizure prediction system employing the use of machine learning techniques for forecasting of seizures by identifying the

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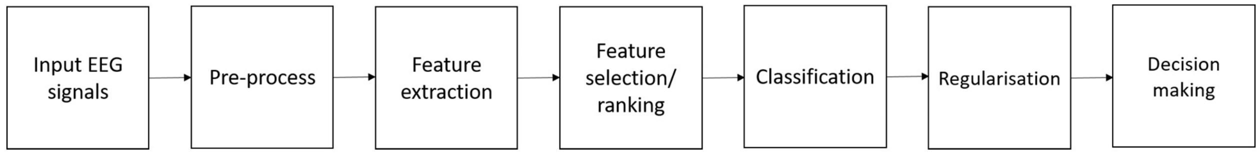

Fig. 1. Block diagram for an automated seizure prediction system.

different episodes of seizure states in the EEG signals. In seizure prediction, the preictal EEG signal appearing a few minutes or a few hours before the seizure is predicted. In contrast, seizure detection is the classification of the EEG signals into seizure or nonseizure classes using the salient features in the EEG signals [26].

A computer-aided prediction (CAP) system is developed using signal processing and machine learning techniques [27–29]. It consists of preprocessing, feature extraction, feature selection and ranking, and classification steps (see Fig. 1). In this review, reviewed articles are divided into studies conducted using EEG data collected primarily from animal (rats and canine, summarized in Table 1) and human (summarized in Table 2) subjects.

2. Seizure prediction using animals

2.1. Signal processing

Typically, the data collected are preprocessed for the removal of artifacts and noise before extraction of features. The power-line interference of 50 to 60 Hz is filtered to obtain a clean EEG signal for analysis.

2.2. Feature extraction

The EEG signals, in general, are highly chaotic with small signal magnitudes in millivolts. Usually, nonlinear feature extraction methods are preferred for feature extraction [26]. These nonlinear parameters can effectively capture the hidden information and minute characteristics in the EEG signals [26]. Nevertheless, some researchers still use the frequency and time–frequency domain feature extraction methodologies for development of a CAP. The features employed by researchers in Table 1 are discussed in this section briefly.

2.2.1. Nonlinear features

The largest Lyapunov exponent (LLE) [33,71] parameter is an estimation of the chaos level of the EEG data. It can distinguish the different chaotic episodes present in the EEG data.

2.2.2. Frequency domain features

The spectral power analysis [72] is used to evaluate the frequency in each power spectrum. This technique is useful in investigating the subtle changes due to seizures in the EEG signals. The short-time Fourier transform [34] was also used to design a CAP system with the EEG data collected from 23 patients with intractable seizures.

2.2.3. Time–frequency domain features

The wavelet transform is usually applied to decompose the EEG signals into its respective frequency components to represent the signal information as a function of time. Typically, in wavelet transforms, a mother wavelet is first selected depending on the nature of the signal. Then, the EEG signals are decomposed according to the morphology of the mother wavelet. The wavelet transformation is a useful technique to analyze the components of a time-varying and chaotic signal such as the EEG signal.

2.3. Feature selection and ranking

The aim in this step is to eliminate redundant features and select only characteristic features for classification. Principal component

Table 1
Summary of works conducted on automated seizure prediction using animal subjects.

Authors	Year	Objective of study	Database/methodology	Time of prediction	Performance
Ouyang et al. [30]	2007	• To develop a novel wavelet-based nonlinear similarity index to predict seizures	• Rat EEG recordings • Freiburg database • Wavelet and nonlinear dynamic measures	• 2.24 min (rats) • 6.98 ± 1.50 min (Freiburg database)	• Wavelet approach is effective in predicting seizures.
Rajdev et al. [31]	2010	• To propose a real-time automated seizure prediction system developed from rats	• Rat EEG recordings • Computer-aided prediction algorithm • Adaptive Wiener prediction technique	• 6.7 s	• Sensitivity: 92%
Varatharajah et al. [32]	2017	• To investigate the possibilities of a seizure prediction using machine learning techniques	• Canine EEG recordings • Computer-aided prediction algorithm → Power in band features → Time domain → Spectral coherence → PCA → PLS → SVM, ANN, RF classifier	• 1 min	• Machine learning techniques portrayed possible seizure prediction capabilities.
Shafique et al. [33]	2018	• To discuss the process of developing nonlinear parameters with the help of big data to predict seizures	• Rat EEG recordings • LLE • The Wolf's algorithm • The Rosenstein–Kantz algorithm • Big data	• 10 s	• The use of Lyapunov exponents may refine the dependency of seizure prediction algorithm.
Truong et al. [34]	2018	• To design a seizure prediction model using convolutional neural networks (CNN)	• Canine EEG recordings • Freiburg and CHB-MIT database • Short-time Fourier transform • CNN	• 30 s	• Sensitivity: 75%