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The detection of epileptic seizure signals based on fuzzy entropy

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HIGHLIGHTS

- A novel FuzzyEn based method of state inspection of epileptic seizures.
- Comparison of the seizure classification performance between FuzzyEn and SampEn.
- Higher performance of our method compared with the existing methods.

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ABSTRACT

Background: Entropy is a nonlinear index that can reflect the degree of chaos within a system. It is often used to analyze epileptic electroencephalograms (EEG) to detect whether there is an epileptic attack. Much research into the state inspection of epileptic seizures has been conducted based on sample entropy (SampEn). However, the study of epileptic seizures based on fuzzy entropy (FuzzyEn) has lagged behind.
New methods: We propose a method of state inspection of epileptic seizures based on FuzzyEn. The method first calculates the FuzzyEn of EEG signals from different epileptic states, and then feature selection is conducted to obtain classification features. Finally, we use the acquired classification features and a grid optimization method to train support vector machines (SVM).
Results: The results of two open-EEG datasets in epileptics show that there are major differences between seizure attacks and non-seizure attacks, such that FuzzyEn can be used to detect epilepsy, and our method obtains better classification performance (accuracy, sensitivity and specificity of classification of the CHB-MIT are 98.31%, 98.27% and 98.36%, and of the Bonn are 100%, 100%, 100%, respectively).
Comparisons with existing method(s): To verify the performance of the proposed method, a comparison of the classification performance for epileptic seizures using FuzzyEn and SampEn is conducted. Our method obtains better classification performance, which is superior to the SampEn-based methods currently in use.
Conclusions: The results indicate that FuzzyEn is a better index for detecting epileptic seizures effectively. The FuzzyEn-based method is preferable, exhibiting potential desirable applications for medical treatment.

1. Introduction

Entropy is a nonlinear index that reflects the degree of disorder of a given system, enabling it to be employed for studies of the chaotic behavior of the brain (Azarnoosh, 2011). Recently, entropy has been broadly applied in the analysis of electroencephalogram (EEG) signals. Furthermore, the concept of entropy has been expanded in several different fields, and some new concepts have emerged, such as sample entropy (SampEn), approximate entropy (ApEn), wavelet entropy (WE), multiscale entropy (MSE), and permutation entropy (PE). All of these indexes have been applied to varying degrees in the analyses of cognitive mental states and sleep states employing EEG signals (Koenig et al., 2009; Korotchikova et al., 2009; Takahashi et al., 2010; Yun et al., 2012). These studies demonstrate that an entropy analysis of the

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brain may be a promising prospect in the field of EEG-based evaluation.

Epilepsy, a chronic disease of the nervous system, is a quite common malady that afflicts people of all classes and backgrounds. The incidence of epilepsy is high, and approximately 1% of the world's population suffers from this condition (Duncan et al., 2006). Epileptic seizures are characterized by paroxysmal, sudden and transient brain disorders induced by the repeated and hyper-synchronous discharges of cerebral nerve cells, which can cause major disruptions to patients' work and lives. Acute seizures can inflict serious injury or death upon the patient. Currently, EEG analysis is the primary method used in the study of epilepsy. Various types of entropy have been calculated from the EEG data, and they are now widely used for identifying the various epileptic states (non-seizure or seizure).

These entropy-based methods for identifying whether an epileptic seizure has occurred are quite similar because the entropy of the EEG signals for different patients at different periods can be calculated and classifications can be performed using a machine-learning algorithm. Kumar et al. (2010) studied the classification of epilepsy signals based on the calculated WE, with a classification accuracy up to 94.5% (Kumar et al., 2010). Using multiple wavelet transformation (WV) and an artificial neural network (ANN), Guo et al. (2010) conducted a classification of epilepsy based on the calculated ApEn, obtaining an accuracy as high as 99%. Using the extreme learning machine (ELM), Song et al. (2012) optimized SampEn for epilepsy classification, and their accuracy was quite high, up to 99%. Ocak et al. (2008) performed epilepsy classifications based upon ApEn using WV, with an accuracy of 94.3%. Using the index of ApEn, Kannathal et al. (2005) performed epilepsy classifications and obtained an accuracy of up to 90%. Wang et al. analyzed the EEG signals of epileptics based on WE, and their prediction accuracy was reported to be 100%. On the basis of PE, Nicolaou and Georgiou (2012) were the first to perform an epilepsy classification using support vector machines (SVM), and their obtained classification accuracy was 94.38%. Using ANN, Akareddy et al. (2013) studied the EEG signals of epileptics based on ApEn, with a classification accuracy of 90%. With the calculated SampEn adopted as the index, Shen et al. (2013) also conducted classifications of epilepsy, and their calculated accuracy was as high as 91.18%. As stated above, favorable classification results have been achieved with the adoption of multiple types of entropy, suggesting that in general, entropy-based methods are promising for the EEG analysis of epilepsy.

However, few studies have been conducted that compare these classification results directly using calculated entropy with different definitions. Fuzzy entropy (FuzzyEn), which has been proposed based upon the theory of fuzzy mathematics, is a nonlinear index used to evaluate the probability of newly generated modes. In 2007, Chen et al. (2007) performed modifications of the SampEn-based algorithm and, from this, proposed a definition for FuzzyEn. Since then, the index of FuzzyEn has been successfully applied in feature extraction and in the classification of surface electromyography (EMG) signals. The FuzzyEn-based algorithm retains several characteristics of the SampEn-based algorithm, such as the relative uniformity and the suitability for the processing of short datasets. Additionally, by making the similarity measurement formula fuzzy, the FuzzyEn-based algorithm precludes the limitations of the SampEn definition, as FuzzyEn can transit smoothly through varying parameters. Recently, limited studies have been reported on the detection of epilepsy using the index of FuzzyEn, but almost no related comparative studies have been performed for EEG analysis using the two indexes, SampEn and FuzzyEn. In the present study, we used two open-source databases, provided by CHB-MIT and BONN, and we studied the detection of epileptic seizures using both the FuzzyEn and SampEn calculations. The performance of these two methods in epilepsy detection using EEG signals was compared with several other classification indexes, to determine the accuracy, specificity and sensitivity of our methods.

2. Data and methods

2.1. The open-source EEG data from epileptics

Two open-source EEG datasets from epileptics were used in our study. One is the CHB-MIT database (http://physionet.org/cgi-bin/atm/ATM), and the other is the Bonn database (http://www.meb.uni-bonn.de/epileptologie/science/physik/eegdataold.html). The CHB-MIT database is from a group of epileptic children, with EEG data provided by the Massachusetts Institute of Technology (MIT), USA. These data were collected from 23 subjects at Boston's Children's Hospital. With data integrity taken into account, the data from 18 subjects (4 males and 14 females) were used, whose ages ranged from 1.5 to 22 years. Each subject was required to stop medicinal treatment one week before data collection, and the data were collected successively for 916 h, with a sampling frequency of 256 Hz. During the recording process, any position changes that may have occurred in the EEG electrodes did not affect the results. According to expert judgments, the duration, start time and end time of each seizure have been labeled explicitly in the data. For each subject, the numbers and durations of seizure events varied. The EEG signals in the database reflect the occurrence of 198 individual epileptic seizure episodes.

The above data were recorded from scalp electrodes; in this study, we also used a data set of intracranial electrodes provided by the department of epileptology of Bonn University for our comparison. The whole dataset consisted of five sets (denoted as *Z*, *O*, *N*, *F* and *S*), each containing 100 single-channel EEG segments of 23.6 s duration, with a sampling rate of 173.6 Hz. Sets *Z* and *O* were carried out in five healthy volunteers. Sets *N*, *F* and *S* originated from an EEG archive of pre-surgical diagnosis. Segments in set *F* were recorded from the epileptogenic zone, and those in set *N* were recorded from the hippocampal formation of the opposite hemisphere of the brain. While sets *N* and *F* contained only activity measured during seizure-free intervals, set *S* only contained seizure activity. All EEG signals were recorded with the same 128-channel amplifier system, using an average common reference. The data were digitized at 173.61 samples per second using 12-bit resolution, and they were recorded at the spectral bandwidth of the acquisition system, which varied from 0.5 Hz to 85 Hz. In this study, we used this dataset to carry out two classification experiments, one based on the *N* and *S* datasets (denoted as *N*/*S*), and another based on the *F* and *S* datasets (denoted as *F*/*S*).

2.2. Principles of analysis method

Fig. 1 shows the procedure for the detection of epileptic seizures based on entropy. First, the entropy (SampEn or FuzzyEn) of all of the EEG electrodes was extracted, and second, features were selected to form classification eigenvectors. Usually, in this step, we selected those electrodes whose entropy exhibited significant variation during the seizure and non-seizure periods as features (labeled as s_1, $s_{2,\ldots}$, s_m, respectively); the entropy values of these selected electrodes then constituted the eigenvectors. Finally, the classifier was trained using support vector machines (SVM), an algorithm for classification training. In this step, all training samples composed of eigenvectors together with their labels (seizure free or seizure) were input into the SVM to train a classifier. Once a classifier was obtained, those sample eigenvectors with no labels could be labeled by this classifier; therefore, we could use this classifier