BIOCYBERNETICS AND BIOMEDICAL ENGINEERING 36 (2016) 248–255

Available online at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/bbe

Original Research Article

Automatic sleep scoring using statistical features in the EMD domain and ensemble methods

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
30 October 2015
Accepted 2 November 2015
Available online 21 November 2015

Keywords:
EEG
AdaBoost
Ensemble learning
Sleep scoring
EMD

ABSTRACT

An automatic sleep scoring method based on single channel electroencephalogram (EEG) is essential not only for alleviating the burden of the clinicians of analyzing a high volume of data but also for making a low-power wearable sleep monitoring system feasible. However, most of the existing works are either multichannel or multiple physiological signal based or yield poor algorithmic performance. In this study, we propound a data-driven and robust automatic sleep staging scheme that uses single channel EEG signal. Decomposing the EEG signal segments using Empirical Mode Decomposition (EMD), we extract various statistical moment based features. The effectiveness of statistical features in the EMD domain is inspected. Statistical analysis is performed for feature selection. We then employ Adaptive Boosting and decision trees to perform classification. The performance of our feature extraction scheme is studied for various choices of classification models. Experimental outcomes manifest that the performance of the proposed sleep staging algorithm is better than that of the state-of-the-art ones. Furthermore, the proposed method's non-REM 1 stage detection accuracy is better than most of the existing works.

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1. Introduction

Sleep is a widespread biological phenomenon that affects the whole human body [1]. Sleep related ailments deteriorate the quality of lives of humans – the commonest ones being hypersomnia, insomnia, circadian rhythm disorder, narcolepsy and parasomnias. Sleep related complaints are second only to complaints of pain as a cause to seek medical attention [2]. On the other hand, the function of mammalian sleep is mostly unknown. So research based on analysis of sleep data is of paramount importance not only for diagnosis of sleep disorders but also to augment our understanding about sleep. Traditionally, all night polysomnographic (PSG) recordings are visually scored by experts based on Rech-tschaffen and Kales's (R&K) recommendations [3] or a new guideline developed by the American Academy of Sleep Medicine (AASM) [4]. Our study uses six sleep stages in accordance with R&K standard: Awake (AWA), Non-Rapid Eye Movement stages 1–4 (S1–S4) and Rapid Eye Movement (REM). The 5-state stages of sleep combine S3 and S4 of 6-state as Slow Wave Sleep (SWS) and the 4-state stages combine S1 and S2 of 5-state. The 3-state and

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http://dx.doi.org/10.1016/j.bbe.2015.11.001

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2-state stages of sleep include: AWA, NREM, REM and AWA, Sleep (S1-S4 and REM) respectively.

Electroencephalogram (EEG) signals are widely used for sleep data analysis. As multichannel EEG equipments place limitations on the subject's movement, recent studies [5–7] on sleep staging are focusing more on using single-channel EEG for sleep staging. Since a large number of epochs have to be screened visually, manual sleep scoring is onerous for sleep scorers. This also makes the whole process prone to human error. An automatic sleep scoring scheme can not only assist the clinical staff but also speed up the diagnosis of various sleep disorders. Moreover, if the patient has to come to the laboratory for a PSG examination, the sleep quality of the subject can be reduced due to the unfamiliar environment. A portable sleep quality monitoring system integrating an embedded system for EEG acquisition and the automatic sleep staging method with reduced channel requirement is of paramount importance for home care [8]. An automatic sleep scoring algorithm can ensure wearability and portability of sleep quality evaluation at home. Again, excessive wire connections for polysomnography is often a problem that causes sleep disturbance. Automatic sleep scoring based on single channel EEG can also reduce sleep disturbance caused by recording wires [6].

Various single or multichannel based methods for automated sleep scoring have been reported in the literature. Agarwal et al. [9] segmented five-channel PSG data in quasi-stationary components, computed features such as amplitude, dominant rhythm, spindles, frequency weighted energy etc. and used k-means clustering to classify sleep states. Held et al. [10] presented a neuro-fuzzy classifier to classify sleep states of healthy infants from four-channel PSG recordings. Berthomier et al. [11] presented a fuzzy logic based iterative method to classify sleep states from single channel EEG data. Karkovska et al. [12] extracted many features such as average amplitude, variance, spectral powers, coherence, fractal exponent etc. from data collected from six EEG channels, two EOG channels and one EMG channel and performed the classification using quadratic discriminant analysis. Charbonnier et al. [13] utilized EEG, EMG and EOG to devise a multichannel-based two stage classification scheme. Liang et al. [6] used multiscale entropy and autoregressive model parameters as features and linear discriminant analysis as classifier for single-channel automatic sleep scoring. Ronzhina et al. [14] proposed a power spectrum density and artificial neural network based method that used single channel EEG signal. Renyis entropy based features extracted from various time-frequency distributions were used in [15] for sleep stage identification from single channel EEG. Six energy features and Elman neural network were proposed in [16] which put forward a single channel based method to classify sleep stages. Zhu et al. [7] generated difference visibility graph (VG) and horizontal VG from single channel EEG signal and extracted nine features from them to classify using support vector machine. Imtiaz [5] utilized spectral edge frequency, absolute and relative power of the signal for REM sleep detection from single channel EEG. Koch et al. [17] put forward a Latent Dirichlet Allocation topic model based method that uses four-channel EEG and EOG signals for sleep staging.

Recently, Empirical Mode Decomposition (EMD) has emerged as a useful means of analyzing nonlinear and non-stationary signals such as EEG [18,19]. The major advantage of EMD is that it is data-driven and hence does not require a prior basis function. However, research reported in the literature on sleep scoring using EMD is rather limited. In the present article, we classify sleep stages from single channel EEG signal using statistical features in the EMD domain and an ensemble learning based classifier, namely – Adaptive Boosting (AdaBoost). To the best of our knowledge, none of the existing works on automatic sleep scoring attempts to employ ensemble learning algorithms. This study therefore opens up new possibilities of research where various novel variants of boosting algorithms can be applied to further ameliorate the classification performance. Further, the appropriateness of the statistical features is demonstrated via p-values obtained from Kruskal–Wallis test [20]. We also investigate the sleep scoring performance of a number of classifiers for the proposed features including AdaBoost. Finally, the performance of the proposed method is compared with those of the state-of-the-art techniques. It is shown that in general we achieve better accuracy than existing works for the classification of various sleep stages. In fact, from 3-state to 6-state sleep stage classification, the accuracies of the proposed scheme are by far the best accuracies reported using more than 10,000 epochs from the public sleep EEG data-set.

2. Materials and methods

2.1. Subjects and recordings

The data used for evaluation of the proposed scheme are taken from Physionet Data Bank's [21] Sleep-EDF Database [22,23] which is publicly available and widely used in the literature [15,16,6,7,24,25]. The recordings were obtained from Caucasian males and females (21–35 years old) without any medication. The first four recordings (sc4002e0, sc4012e0, sc4102e0, sc4112e0) were obtained in 1989 from ambulatory healthy volunteers during 24 h in their normal daily life. The last four data recordings (st7022j0, st7052j0, st7121j0, st7132j0) were obtained in 1994 from subjects who had mild difficulty falling asleep but were otherwise healthy. They contain horizontal EOG, Fpz-Cz and Pz-Oz EEG data, each sampled at 100 Hz. EEG signal from Pz-Oz channel yields better classification performance than that of the Fpz-Cz channel [11,6,14,7]. So in our study Pz-Oz channel EEG signal is used.

Expert scoring of the EEG data is obtained from [22]. Each 30 s of EEG data was scored in accordance with the R&K recommendations [3]. The duration of each epoch is 30 s having ($30 \times 100 =$)3000 data points. Each epoch was scored by expert scorers in one of the eight classes: AWA, S1, S2, S3, S4, REM, MVT (Movement Time) and 'Unscored'. Table 1 summarizes the number of epochs of different classes that are used in this work. Fig. 1 shows sample EEG epochs of each of the six sleep states.

2.2. Feature extraction in the EMD domain

Once the epochs are generated, the next step is to compute EMD of each of them. Empirical Mode Decomposition (EMD) aims to generate highly localized time-frequency estimation of a signal in a data-driven fashion by decomposing it into

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