Computer Methods and Programs in Biomedicine 140 (2017) 77–91

Contents lists available at ScienceDirect

Computer Methods and Programs in Biomedicine

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

A comparative review on sleep stage classification methods in patients and healthy individuals

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ARTICLE INFO

Article history:
Received 7 August 2016
Revised 17 November 2016
Accepted 5 December 2016

Keywords:
Sleep stage classification
Wavelet transform
Random forest classifier
Entropy

ABSTRACT

Background and objective: Proper scoring of sleep stages can give clinical information on diagnosing patients with sleep disorders. Since traditional visual scoring of the entire sleep is highly time-consuming and dependent to experts' experience, automatic schemes based on electroencephalogram (EEG) analysis are broadly developed to solve these problems. This review presents an overview on the most suitable methods in terms of preprocessing, feature extraction, feature selection and classifier adopted to precisely discriminate the sleep stages.
Methods: This study round up a wide range of research findings concerning the application of the sleep stage classification. The fundamental qualitative methods along with the state-of-the-art quantitative techniques for sleep stage scoring are comprehensively introduced. Moreover, according to the results of the investigated studies, five research papers are chosen and practically implemented on a well-known public available sleep EEG dataset. They are applied to single-channel EEG of 40 subjects containing equal number of healthy and patient individuals. Feature extraction and classification schemes are assessed in terms of accuracy and robustness against noise. Furthermore, an additional implementation phase is added to this research in which all combinations of the implemented features and classifiers are considered to find the best combination for sleep analysis.
Results: According to our achieved results on both groups, entropy of wavelet coefficients along with random forest classifier are chosen as the best feature and classifier, respectively. The mentioned feature and classifier provide 87.06% accuracy on healthy subjects and 69.05% on patient group.
Conclusions: In this paper, the road map of EEG-base sleep stage scoring methods is clearly sketched. Implementing the state-of-the-art methods and even their combination on both healthy and patient datasets indicates that although the accuracy on healthy subjects are remarkable, the results for the main community (patient group) by the quantitative methods are not promising yet. The reasons rise from adopting non-matched sleep EEG features from other signal processing fields such as communication. As a conclusion, developing sleep pattern-related features deem necessary to enhance the performance of this process.

1. Introduction

Sleep covers almost one third of human lifespan. Due to the direct relationship among sleep quality and humans' physical and mental performance, sufficient night sleep is crucial. As a result of machinery and stressful life, sleep disturbance is increasing in modern societies. In addition, research findings suggest that several psychological and neurological disorders can deteriorate normal sleep patterns [1]. According to the international classification of sleep disorders (ICSD-II) criteria [2], eighty four different sleep disorders are defined. Sleep disorders not only cause a reduction in physical performance during the day, but also leave negative effects on cognitive functions such as attention, learning and memory, in long-term [3]. For instance, beside the significant side effects of obstructive sleep apnea syndrome (OSAS) including the increased risk of cardiovascular diseases; neurocognitive decline and excessive daytime sleepiness are considered as potential consequences [3].

To achieve the right diagnosis and treatment based on the various biological records, accurate sleep scoring is deemed to be a crucial part of the process. Up to now, the conventional

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http://dx.doi.org/10.1016/j.cmpb.2016.12.004
0169-2607/

visual scoring method is still the most acceptable approach, though it involves visual data interpretation of different signals [4]. Qualitative scoring, however, subject to some pitfalls including experts' experience which might result in different scoring results by different experts [5,6]. In an optimistic view, the agreement between the obtained results by two experts, in average, is 83 ± 3 % [7] which is not convincing. Moreover, visual inspection is a time-consuming process for a whole night EEG labeling. Therefore, automatic scoring is deemed to be an efficient approach [8,9].

Several research teams have recently proposed various methods to automate the process of sleep classification (sleep scoring). Several signal processing techniques along with machine learning algorithms are adopted to obtain useful information from biological signals [10]. Such methods are divided into two categories, i.e. multi-channel and single-channel processing. In the former approach, the combination of various biological signals such as multi-channel EEG signals, electromyogram (EMG) [11] and electrooculogram (EOG) are utilized to extract informative features [12–18]. While the use of multi-channel signals leads to the higher performance [19], it imposes a considerable cost to patients, especially in home sleep testing [5]. Moreover, excessive number of wire connections during the recording process might per se result in sleep disturbance [20].

On the other hand, single-channel EEG based analysis is a cheap way of automatic sleep scoring. EEG contains valuable and interpretable information resembling the brain activities which is not only used in extensive research contexts pertaining to the brain, but also to diagnose and consequently treat neurological disorders [21]. Sleep neurology is a progressively-evolving subspecialty field in which the sleep EEG signals are utilized to study the function of the brain during sleep, also to diagnose various types of disorders based on sleep stage analysis. There are many single-channel approaches for automatic sleep stage classification in the literature [9,15,22–24]. According to the available evidence [23], EEG signals are almost sufficient for reliable scoring.

To the best of our knowledge, the reported classification accuracies of the suggested methods are mostly obtained from healthy subjects [22,24,25]. Only a few methods in the literature are tasted on patients with various sleep disorders [26]. However, it should be noted that automatic sleep scoring methods should gain acceptable performance on analyzing EEG signals in sleep disorders. Sleep disorders (such as sleep-disordered breathing, REM behavioral disorder and sleep-related movement disorders) impose disruptive effects on the recorded signals. In these cases, sleep signals behave more irregular containing higher movement artifacts. In addition, drugs consumption may also change sleep patterns [6]. Such pitfalls may also influence both manual and automatic sleep scoring processes and the issue tends to be more profound in automatic methods. Inaccurate sleep scoring leads to mis-diagnosis; consequently, the treatment based on this wrong diagnosis cause negative consequences on patients' disorder outcome and well being [6]. A few reports confirm that due to irregularity of sleep EEG among patients, the scoring accuracy do not exceed 75% which is considered below expected standards [1].

This paper reviews most of state-of-the-art automatic sleep scoring methods with their pros and cons being discussed. Such insights would be expected to help implementing several single-channel methods and apply them to normal and patient groups in order to assess the performance of published methods in different circumstances. To our knowledge, thus far, no comprehensive review on sleep EEG scoring is performed to compare the results of state-of-the-art single-channel methods on both patients and healthy subjects. Moreover, the performance of different classifiers are compared to find the best classifier for this application. In addition, to assess the robustness of these methods, Gaussian noise is added by different signal-to-noise-ratio (SNR) values and their performance are measured in presence of the noise.

Table 1
The frequency range of sleep EEG bands and events.

Freq. band	Freq. range (*Hz*)
Delta	0.5–4
Theta	4–8
Alpha	8–13
Beta	13–30
Sleep spindles	12–14
K-complex	0.5–1.5

Later in this report Section 2 explains the qualitative and quantitative sleep stage assessments. Section 3 describes several single-channel based methods in detail. In Section 4, results of these methods on both normal and patient data are demonstrated. The final Section is dedicated to the discussion and conclusion.

2. Methodology

Sleep stages can be qualitatively/quantitatively analyzed. In this Section, first visual sleep stage scoring criteria (qualitative methods) are explained. Then, several quantitative sleep scoring methods are introduced in detail.

2.1. Polysomnographic data and qualitative assessment

Sleep medicine uses polysomnography (PSG) as an efficient method to record several biological signals to evaluate the sleep quality. PSG recordings generally involve overnight monitoring of patients sleep EEG, airflow through the nose and mouth, respiratory rate, blood pressure changes, electrocardiogram (ECG) signals, blood oxygen level, EOG signals, as well as the chin and legs surface EMGs [26,27].

The qualitative analysis (visual inspection) of a whole night PSG recordings is performed through one of the two available standards [28] including the traditional Rechtschaffen and Kales (R&K) [29] and the more recently-developed standards laid down by the American academy of sleep medicine (AASM) [30]. Based on both the R &K and AASM criteria, EEG signal is the most informative signal compared to others. Experts analyze the EEG signals visually within successive 30 second intervals (epochs) mainly based on its standard rhythms (frequency bands). They assign a sleep stage as a label to each epoch successively [28]. The standard sleep EEG rhythms are categorized as Delta, Theta, Alpha, Beta bands (Table 1). Moreover, two important events happening through sleep EEGs are Sleep Spindles and K-complexes, where both exclusively occur in the second sleep stage.

For almost three decades, the R&K sleep classification manual was the only widely-accepted standard to describe the human sleep process [31]. According to the R&K criterion, sleep study comprises seven stages including: wakefulness (W), non-rapid eye movement (NREM) including stage 1, stage 2, stage 3, and stage 4, rapid eye movement (REM) and movement time (MT). Although the recommended setup is brief and instruction is easy to follow, many issues in sleep study still remain unresolved [32].

Regarding the most recent AASM manual, at least 3 electrodes should be placed on frontal, central, and occipital head regions to record EEG signals [30]. The criteria concerning sleep-wake transition, sleep stages, sleep spindles, K-complexes, micro arousals, slow wave and REM sleep are revised. Unlike the R&K recommendations, in the new manual, stages 3 and 4 are merged into N3 and the MT stage is retracted from analyses. The trend transition from R&K rules to new AASM standards, left only a minor influence on total