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Improved spindle detection through intuitive pre-processing of electroencephalogram

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HIGHLIGHTS

- This study presents a spindle detection approach which relies on intuitive pre-processing of EEG.
- Techniques include time differentiation, background filtering via empirical mode decomposition and EOG based shortlisting.
- Standard approaches such as wavelets and Fourier transforms performed better when coupled with apt pre-processing.
- Average sensitivities of 96.14 and 92.85% and specificities of 87.59 and 84.85% for Fourier and Wavelets respectively.
- Inter-subject and inter-scorer tunability with data driven thresholds are validated.

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ABSTRACT

Background: Numerous signal processing techniques have been proposed for automated spindle detection on EEG recordings with varying degrees of success. While the latest techniques usually introduce computational complexity and/or vagueness, the conventional techniques attempted in literature have led to poor results. This study presents a spindle detection approach which relies on intuitive pre-processing of the EEG prior to spindle detection, thus resulting in higher accuracy even with standard techniques.
New method: The pre-processing techniques proposed include applying the derivative operator on the EEG, suppressing the background activity using Empirical Mode Decomposition and shortlisting candidate EEG segments based on eye-movements on the EOG.
Results/comparison: Results show that standard signal processing tools such as wavelets and Fourier transforms perform much better when coupled with apt pre-processing techniques. The developed algorithm also relies on data-driven thresholds ensuring its adaptability to inter-subject and inter-scorer variability. When tested on sample EEG segments scored by multiple experts, the algorithm identified spindles with average sensitivities of 96.14 and 92.85% and specificities of 87.59 and 84.85% for Fourier transform and wavelets respectively. These results are found to be on par with results obtained by other recent studies in this area.

1. Introduction

Human sleep has been widely studied with the aid of electroencephalography (EEG) – a non-invasive recording of the brain's electrical activity using scalp electrodes. The various stages of human sleep have been defined mainly based on the characteristic EEG 'features' (Iber et al., 2007; Rechtschaffen and Kales, 1968). One of these features, the sleep spindle, is the focus of this paper.

Sleep spindles are discrete oscillatory bursts of 11–16 Hz waves with a typical duration of 0.5–2 sec and having a specific 'waxing and waning' pattern (Iber et al., 2007; Rechtschaffen and Kales, 1968). Apart from being crucial in sleep staging (as a hallmark of sleep stage 2), sleep spindles were found to be associated with various physiological phenomena such as sleep 'stability' (Dang-Vu et al., 2010), and memory formation (Tamminen et al., 2010; Schabus et al., 2008; Tamaki et al., 2009). Sleep spindles have also been studied in many pathological conditions including major depressive disorders (Plante et al., 2012), epilepsy (Myatchin

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and Lagae, 2007), dyslexia (Bruni et al., 2009) and schizophrenia (Ferrarelli et al., 2010), further raising the interest in their accurate detection and quantification.

Manual scoring of spindles is time consuming, laborious and introduces disparity and biases (Kunz et al., 2000). Hence automated spindle detection has long being studied with numerous papers on this topic. Early works utilized devices such as phase locked loops and waveform detectors (Smith et al., 1975; Broughton et al., 1978). More recent works have utilized computerized signal-processing techniques including band-pass filtering (Bódizs et al., 2009), fast Fourier transform (FFT), fuzzy logic and amplitude detections (Huupponen et al., 2007), multilayer perceptron (Ventouras et al., 2005), support vector machine (Gorur et al., 2002), adaptive neuro-fuzzy methods (Khasawneh et al., 2011), merge neural gas (Estévez et al., 2007), matching pursuit (Żygierewicz et al., 1999; Schönwald et al., 2006), Empirical Mode Decomposition (Causa et al., 2010), sparse bump modeling (Najafi et al., 2011) and Bayesian classification (Babadi et al., 2012). The studies based on conventional techniques such as FFT (Huupponen et al., 2007) and Neural networks (Ventouras et al., 2005) reported sensitivities of 60–80%, while using more recent and involved techniques such as bump modeling (Najafi et al., 2011) and Bayesian classification (Babadi et al., 2012) achieved sensitivities greater than 90% but at the cost of algorithmic complexity and lower specificity. For example, in the recent study by Najafi et al. (2011), which uses bump modeling, a sensitivity of 99.41% was reported but with an error detection ratio (EDR) of 14.5% and no clear specificity reported.

The performances reported in the above works are adequate for routine sleep study and staging, especially given the comparable inter-scorer agreement. However, a higher sensitivity and specificity in spindle detection can aid in studying the role of spindles during various physiological phenomena. Apart from few studies such as Babadi et al. (2012), a simple but reliable approach for spindle detection with above 90% sensitivity as well as specificity has not yet been proposed. It is in this context that we argue that simple but intuitive pre-processing of the EEG prior to spindle detection can greatly improve the performance of the algorithms without the need for complex signal processing techniques. In this paper, we propose the use of three pre-processing techniques to increase accuracy of standard techniques: (1) taking the direct time derivative of the EEG signal, (2) suppressing the background activity using empirical mode decomposition and (3) using the electrooculogram (EOG) to identify regions of specific interest in the EEG. This paper describes the results obtained from the use of these three different pre-processing approaches in conjunction with different spindle detection tools such as wavelets and Fourier transforms, based on their reliable performance observed in previous studies (Ahmed et al., 2009; Huupponen et al., 2007). Further, in our implementations, we propose the use of only data-driven thresholds to ensure that the approach is tunable to individual subjects and scorers. The results obtained are compared with previous studies to illustrate the improvement in performance.

The rest of this paper is divided in six subsections. In Section 2, a mathematical model for a sleep spindle has been proposed. This model serves as the basis for our spindle processing rationale. The implementation details of the proposed pre-processing methods are then explained in Section 3. The details of the dataset used for validation can be found in Section 4 followed by the results obtained by our approach in Section 5. The paper concludes after discussing implications of the findings and comparing it against previous studies in Section 6.

2. Sleep spindle model

A sleep spindle has been defined as a relatively sinusoidal burst, occurring during AASM sleep stages two to three, predominantly in stage two, and recorded on the central regions of the scalp. In the Rechtschaffen and Kales manual, it is defined as 12–14 Hz bursts of activity lasting at least half a second, typically about a second or two (Rechtschaffen and Kales, 1968). The 2007 AASM definition of a sleep spindle has extended the frequency range and states that a sleep spindle is "A train of distinct waves with frequency 11–16 Hz (most commonly 12–14 Hz) with a duration of >0.5 s, usually maximal in amplitude using central derivations" (Iber et al., 2007).

Given the sinusoidal, waxing and waning form of sleep spindles, we hypothesize that they can be modeled by a windowed sinusoidal function given by

$$x(t) = w_i(t, f) \cos\ (2\pi f_n t + \theta_i) \quad (1)$$

where the sinusoidal has a frequency of f_n between 11 and 16 Hz. The windowing function $w(t,f)$ can also be modeled as a time and frequency-varying function that limits the duration of the spindle so it lasts at least 0.5 sec and provides the spindle with a rising and falling envelope. In this model, given the short duration of the spindle, we have assumed that the frequency content of the sinusoidal

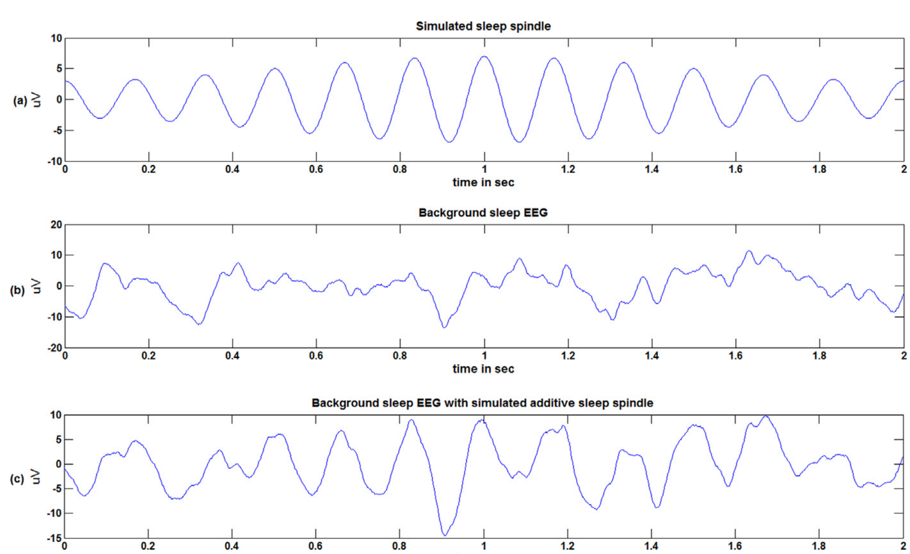

Fig. 1. (a) A mathematically simulated spindle, (b) a sample of stage 2 sleep EEG background and (c) the simulated spindle superimposed on the background EEG.