Biomedical Signal Processing and Control 26 (2016) 117–125

Contents lists available at ScienceDirect

Biomedical Signal Processing and Control

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

A new automatic method for the detection of limb movements and the analysis of their periodicity

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ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form 12 January 2016
Accepted 14 January 2016

ABSTRACT

We present a new algorithm for the automatic detection of periodic and non-periodic limb movements in polysomnographic (PSG) sleep recordings. A set of 70 PSG recordings obtained in the course of common practice were randomly selected for the validation of the proposed approach. The dataset includes 35 recordings that were acquired in ambulatory conditions and 35 that were carried out under the supervision of clinicians at our sleep centre. The algorithm includes robust mechanisms to handle the presence of artefacts, and has the ability to adjust its detection thresholds to dynamically adapt to changing signal conditions. The validation results in our dataset, which also include the comparison with another two automatic methods available in the literature, support the validity of our approach, and its utility as a valuable tool to help the clinician in the scoring task.

1. Introduction

Periodic limb movements (PLMs) are considered as a fundamental and objective physiological marker for the diagnosis of different conditions such as Restless Legs Syndrome (RLS)/Willis–Ekbom disease [1] or Periodic Limb Movement Disorder (PLMD) [2]. RLS is a common neurological, sensorimotor disorder which is estimated to affect about 2–3% of the adult population. It is characterized by the urge to move the legs (mostly, although it may affect also other body parts), usually in response to uncomfortable and unpleasant sensation. Current diagnostic criteria establishes the following five points which all must be met: (i) an urge to move the legs usually but not always accompanied by, or felt to be caused by, uncomfortable and unpleasant sensations in the legs; (ii) the urge to move the legs and any accompanying unpleasant sensations begin or worsen during periods of rest or inactivity such as lying down or sitting; (iii) the urge to move the legs and any accompanying unpleasant sensations are partially or totally relieved by movement, such as walking or stretching, at least as long as the activity continues; (iv) the urge to move the legs and any accompanying unpleasant sensations during rest or inactivity only occur or are worse in the evening or night than during the day; and (v) the occurrence of the above features is not solely accounted for as symptoms primary to another medical or a behavioural condition (e.g., myalgia, venous stasis, leg edema, arthritis, leg cramps, positional discomfort, and habitual foot tapping) [1]. PLMD, on the other hand, is considered a sleep disorder where periodic limb movements occur involuntary during sleep. Although often the patient is completely unaware, the occurrence of these leg movements (LMs) is accompanied by fragmentation in the sleep process with possible consequences over the patient's health. About 4% of the adult population is suspected to suffer from PLMD [3].

The work of Coleman et al. in 1980 [4] was the first to establish criteria for the detection and scoring of PLMs, and in 1993 the American Sleep Disorders Association (ASDA) provided a manual aimed at the standardization of the recording conditions, the terminology, and the scoring rules [5]. Later on, in 2006 the World Association of Sleep Medicine (WASM) published a review of the scoring rules responding to the new requirements of computerized sleep recording, and the new understanding of pathologies related to the presence of PLMs [6]. Almost concurrently, the American Association of Sleep Medicine (AASM, formerly ASDA) published in 2007 its own updated version of the 1993 manual [7]. The AASM manual has been further updated over the time, and nowadays the last version of this manual dates back to July 2015 [8]. Both WASM and AASM criteria for the definition and scoring of LMs and PLMs are similar, and both standards co-exist today as the two major references for the scoring of these events. Both guidelines agree in the basic definitions of LMs and PLMs (see [6,8]). There are some differences though, for example, regarding the rules for the time association of LMs with respiratory events, thus while the WASM states that an interval of ±0.5 s around the end of the respiratory event has to be considered, the AASM takes as reference 0.5 s before the start to 0.5 s after the end of the event. Also the AASM manual includes

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http://dx.doi.org/10.1016/j.bspc.2016.01.008
1746-8094/

Respiratory Effort Related Arousals (RERAs) as respiratory events to be taken into account, while WASM does not explicitly mention this possibility. Criteria for the combination of both leg derivations for the computation of bilateral movements do also differ. While the WASM considers a bilateral movement if the difference between the offset and the onset of two LMs scored in different channels is less than 0.5 s, the AASM considers that the difference should be less than 5 s from onset to onset. Another difference is that the WASM does explicitly mention that a PLM series can go on during wake and sleep (although for the PLM index in sleep one counts only those during sleep).

Both the AASM and the WASM standards consider electromyographic (EMG) activation of the anterior tibialis muscles as the principal source for the definition and the detection of LMs. Recording of this activity is recommended as part of the default clinical polysomnographic (PSG) montage [8]. Manual scoring of these events by the sleep technicians, however, is a very time-consuming task, and is prone to errors. The development of automatic detection methods is therefore of clear interest, with the objective of saving costs and reliably speeding up the tedious manual revision process.

Some examples of such approaches are already available in the literature that have focused on this topic. The first paper that we know of describing results on the automatic detection of leg movements is the work of Kayed et al. [9] in 1990. They used a database of 10 PLM patients for testing, however in this work the authors did not present any description of the underlying developed algorithm. It was not until 1996 that Tauchmann and Pollmächer [10] formally described the first algorithm for the detection of PLMs. Validation of the algorithm was carried out in a database containing 10 recordings from 5 different PLM patients. A few years later, in 1998, Roessen et al. [11] described a semi-automatic detection program for the scoring of LMs, including also a validation on a set of 30 ambulatory recordings. Later on, in 2004, Wetter et al. [12] refined the algorithm of Tauchmann and Pollmächter with a method based on the analysis of 3 parameters: rate of repetition of spikes, average amplitude of spikes, and burst duration. A dataset of 24 recordings was used to test their approach. Their tests included only evaluations of LMs and not of PLMs. Subsequently Ferri et al. [13] published a paper that optimized two detection thresholds using receiver-operator characteristic (ROC) plots. A dataset containing 15 patients with PLM symptoms and 15 control subjects (narcoleptic) was used in their validations. More recently, and probably the most complete work up to today describing a computer algorithm for the detection of PLMs, was reported by Moore et al. [14] in 2014. In this work a comparability analysis of their algorithm's performance is done using two different databases containing a total of 78 recordings from subjects with different conditions. In their analyses they also included their own implementation of the previously mentioned methods described in the works of Tauchmann and Pollmächer [10], Wetter et al. [12], and Ferri et al. [13]. Finally, Huang et al. have just reported on the preliminary validation of a WASM-compatible MATLAB script for scoring PLMs. A dataset of 15 RLS and 9 controls subjects was used on which a two-level validation process, namely micro- and macro-analysis was carried out [15].

All the previous approaches used limb electromyographic (EMG) derivations from both legs as the source for LM detections, which is the recommended standard in the clinical practice [6,8]. Nonetheless in the literature we can also found some works describing automatic detectors using actigraphic devices [16,17]. These approaches, however, present several inconveniences such as lack of sleep and respiratory event correlation, or the difficulty to integrate data from both legs [18].

The method that we are presenting in this work uses standard limb electromyographic (EMG) derivations, and has been inspired by the previous method of Roessen et al., [11] which has been successfully used in our department for several years to help the clinicians in the scoring of LMs. This method has been re-implemented, providing it with new and more robust detection capabilities, and adapting it to the most recent WASM and AASM scoring standards. At this respect, however, it is worth to mention that whenever a difference in a scoring rule between the two manuals exists, we have chosen to follow the WASM recommendations [6]. The resulting algorithm is robust in the presence of artefacts, and it does also include the option to dynamically adjust the detection thresholds to adapt to changing signal conditions. An extensive validation of the method has been done using a database of 70 PSG recordings obtained in both ambulatory and in-hospital conditions. Validation has been carried out separately on each case, and for all the 70 recordings at once. To our knowledge this is the very first work to provide such a comparison. In addition, to expand our comparability analysis, the experimental procedures have been repeated including the results from two additional automatic approaches of reference: the already mentioned methods described in Moore et al. [14] and in Roessen et al. [11].

2. Methods

2.1. Patients and recording protocol

For the validation of our algorithm a set of 70 recordings has been randomly selected from a retrospective inspection of our patient database at the Sleep Centre, Medisch Centrum Haaglanden and Bronovo-Nebo, The Hague, The Netherlands. All data were gathered exclusively in the context of common-practice, and did not subject people to any other treatment nor prescribed any additional behaviour. Under these circumstances Section "b" of Article 1, paragraph 1, of the Dutch law about "Medical-scientific research on people" (law about Ethics requirements) [19] clearly states that Ethics approval requirement does not apply. All patient data were anonymised and can in no way be related to individuals. Patient data were made not publicly available nor were shared with third parties. According to Article 467 of Civil Law Book 7, Title 7, Section 5 (the section about medical treatment of patients) the way we retrospectively used patient data is considered fully legal, and just in The Netherlands [20].

The selection was done purely random using PSG recordings from patients visiting our centre between January and June in 2015. Random selection was aimed at resembling the normal patient workflow in our centre, including a mixture of healthy subjects and patients suffering from different types of sleep disorders. The 70 recordings were organized in two groups: group A contains 35 recordings obtained in ambulatory conditions (APSG), whereas group B is composed of 35 recordings obtained during attended in-hospital conditions (HPSG). Table 1 summarizes general data from the recordings included into our dataset. In both cases (APSG and HPSG) the montage used for sleep analysis was in accordance with the standard recording guidelines [6,8]. Specifically for the

Table 1
Demographic and diagnostic descriptors of the PSG database categorized per groups.

	Total ($n = 70$)	APSG ($n = 35$)	HPSG ($n = 35$)
Age	49.11 ± 18.99	51.23 ± 15.51	47.00 ± 21.97
Gender (F/M)	19/51	9/26	10/25
AHI	10.58 ± 11.46	10.53 ± 11.74	10.63 ± 11.35
PLMS/h	22.26 ± 35.68	24.41 ± 29.94	20.11 ± 40.97
TST (h)	6.19 ± 1.42	6.67 ± 1.10	5.72 ± 1.57
TST/TIB	0.81 ± 0.16	0.88 ± 0.13	0.76 ± 0.16

Data is shown as mean ± std; n = number of recordings; F = Female; M = Male; AHI = Apnoea–Hypopnoea Index; PLMS/h = Periodic Legs Movements during Sleep per hour of recording; TST = Total Sleep Time; TIB = Time In Bed.