An Automatic Method for Scoring Leg Movements in Polygraphic Sleep Recordings and Its Validity in Comparison to Visual Scoring

Thomas C. Wetter, MD; Gerhard Dirlich, PhD; Jonathan Streit; Claudia Trenkwalder, MD[1]; Andreas Schuld, MD; Thomas Pollmächer, MD

Max Planck Institute of Psychiatry, Munich, Germany; [1]Present address: Department of Clinical Neurophysiology, University of Göttingen, Germany

Study Objectives: The study presents an automatic method for scoring leg movements in polysomnographic recordings and describes an empirical investigation of its validity.
Design: Leg movements measured by means of the surface electromyogram activation of the right and left tibialis anterior muscle contained in 24 digitally recorded all-night polysomnograms were analyzed visually according to the American Sleep Disorders Association guidelines by 2 experienced raters and automatically scored using a newly developed electromyogram-based analytical method. Two visual scorings and the automatic scoring were compared in pairs using descriptive and confirmative statistical methods.
Setting: N/A.
Participants: All-night polysomnograms of adaptation nights at the sleep laboratory of 10 patients with idiopathic restless legs syndrome (RLS) according to the International RLS Study Group.
Interventions: N/A.
Measurements and Results: Agreement rates between the 2 well-trained scorers and the automatic method were comparable. Based on the first scorer's results (100%) 92.5% of the movements were detected by the second scorer and 94.3% by the automatic method. When the visual scorings were compared, the rate of false-positive and false-negative errors were 7% and 3%, respectively. Comparing both visual scorings with the results of the automatic scoring yielded false-positive and false-negative rates in the range from 3% to 8%.
Conclusions: The degree of accordance between the 2 visual scorings and between the visual and the automatic scorings were comparable. Therefore, this method is valid and may be used for the automatic detection of leg movements in future studies.
Key Words: Periodic leg movements, PLM, sleep, automatic detection
Citation: Wetter TC; Dirlich G; Streit J et al. An automatic method for scoring leg movements in polygraphic sleep recordings and its validity in comparison to visual scoring. *SLEEP* 2004;27(2):324-8.

INTRODUCTION

REGULAR REPETITIVE LEG MOVEMENTS (LMS) DURING SLEEP ARE THE CORE FEATURE OF THE PERIODIC LIMB MOVEMENT IN SLEEP SYNDROME. Periodic leg movements (PLM) are defined as a series of at least 4 consecutive LMs lasting 0.5 to 5 seconds each with an intermovement interval of 4 to 90 seconds.[1] A typical movement consists of a flexion of the ankle, knee, and hip with an extension of the toes, resembling the triple-reflex response of the Babinski sign.[2] The PLM may occur during sleep and relaxed wakefulness[3] and are measured using the surface electromyogram (EMG) of both tibialis anterior muscles.[4] PLM may be associated with a large variety of sleep disorders, including restless legs syndrome (RLS),[5,6] sleep apnea syndrome,[7] narcolepsy,[8] and rapid-eye-movement sleep behavior disorder.[9] However, PLMs may also occur as an isolated cause of insomnia or hypersomnia. The latter condition is regarded as a separate clinical entity and termed periodic limb movement disorder.[1] PLM may be associated with brief arousal reactions such as bursts of alpha activity in the electroencephalogram or full awakenings.[4] In severe cases, hundreds of PLM may be present during 1 night, resulting in poor sleep quality with increased sleep latency, frequent nocturnal awakenings, reduced percentage of slow-wave sleep, and decreased sleep efficiency.[10] However, especially in elderly people, PLM are common even in the absence of complaints of insomnia or excessive daytime sleepiness and, thus, can also occur as a sleep-related phenomenon without known clinical significance.[10,11]

Methods to determine LMs and, in particular, PLM have a wide range of applications in routine diagnostic and clinical studies. The detection of LMs and PLM has been based on visual scoring in almost each study performed to date. Using specific recording procedures and scoring rules for LMs, a high interrater agreement can be achieved.[12] Methods for the automatic detection of LMs have been described in only a very limited number of publications. Tryon et al[13] and Kazenwadl et al[14] have described automatic methods using actigraphy, which measures physical movements of the legs. Kayed and coworkers[15] first described an EMG-based algorithm, but their report lacks important details of the method used and reports no empirical validation. Tauchmann and Pollmächer[16] used the average amplitude of the rectified EMG computed in a moving window as an indicator of LMs. Their algorithm was developed on the basis of very few sleep recordings and, hence, can only be considered to be a preliminary solution.

Here, we describe a method that is similar to Tauchmann and Pollmächer's approach using a refined EMG signal-processing algorithm. The empirical validation is focused on a movement-by-movement analysis based on comparisons of 3 scorings (2 visual scorings as reference and the automatic method as test scoring) and, finally, a micro-analysis of the differences in onset and offset times of LMs between the scorings. The precise determination of the onset and offset of LMs is important for studies investigating the relationships between other biosignals (eg, the electroencephalogram) and leg movements. A database of about 8300 leg movements from 24 all-night sleep recordings was used to investigate the validity of the method by comparing the automatically obtained results with the scoring from 2 visual scorers, which were also compared with each other.

METHODS

Subjects

Thirty nocturnal polysomnograms recorded during the adaptation nights of 10 patients suffering from RLS were selected. All patients were recruited from the outpatient clinic for movement and sleep disorders at the Max Planck Institute of Psychiatry in Munich and took part in a mul-

Disclosure Statement
No significant financial interest/other relationship to disclose.

Submitted for publication July 2002
Accepted for publication October 2003
Address correspondence to: Thomas C. Wetter, MD, Max Planck Institute of Psychiatry, Kraepelinstrasse 10, D-80804 Munich, Germany; Tel: 49-89-30622-1; Fax: 49-89-30622-605; E-mail: wetter@mpipsykl.mpg.de

ticenter trial of the long-term effects of pergolide in the treatment of RLS.[17,18] The protocol was approved by an independent ethics committee, and written informed consent was obtained from all participants. The subjects had a mean ± SD age of 58 ± 12 years and a mean duration of disease of 8 ± 5 years. All patients fulfilled the minimum diagnostic criteria of the International RLS Study Group.[19] Five of the 30 nocturnal recordings were used for the tuning of the automatic method. One recording was excluded from the analysis because of artifacts occurring during the calibration of the LMs. Finally, 24 all-night sleep recordings were included in the test sample.

Recording Technique

The polygraphic recordings included right and left electrooculograms, 2 electroencephalography channels (C3-A2, C4-A1), and 3 EMG channels (chin muscle region and tibialis anterior muscle of the right and left leg, respectively). Two electrodes were used to measure the EMG of the legs: 1 electrode (Ag/AgCl, diameter 10 mm) was placed 8 cm below and 2 cm laterally to the tuberositas tibiae; the second electrode was placed at a distance of 5 cm along a line parallel to the tibia according to standard guidelines.[4] Data were recorded using a digital sleep-recording system (Schwarzer Brainlab 3.30, Munich, Germany) at a sampling frequency of 250 Hz and a sensitivity of 50 μV. The EMG amplitude resolution exceeded 0.01 μV. High-pass and low-pass filters were set at 16 and 300 Hz, respectively.

Scoring Methods

The visual and automatic LM scoring methods described here are in accordance with international scoring rules[4]; the analysis of empirical data is restricted to the data of the 2 EMG channels located at both legs.

Visual Scoring

The EMG data were visually scored independently by 2 trained and experienced scorers blind to each others' results and to that of the automatic scoring. At the beginning of each recording, 5 voluntary calibration movements were recorded for each leg while the patients were lying awake in bed. The patients were instructed to slowly dorsiflex and plantarflex the great toe of each foot to approximately 30º without resistance.[4] Prior to the visual analysis of LMs, 1 of the calibration movements was selected, the beginning and end were marked, and the average amplitude was determined. These amplitude values were used by both visual scorers as amplitude reference criteria. At an amplitude corresponding to 25% of the reference criteria,[4] a horizontal line was displayed together with the 2 EMG channels during the entire scoring procedure. The scorers were advised to use these lines as a reference for evaluating the amplitude of the EMG bursts. Onset and offset of each LM between 0.5 and 5 seconds were marked separately for each leg. Bursts of EMG activity separated by less than 0.5 seconds were joined ('bridged').

Automatic Scoring Method

The automatic method for the detection of LMs described here is a heuristic pattern-recognition algorithm imitating the visual-scoring procedure. It aims to detect EMG bursts consisting of high-amplitude spikes recurring at a high rate of repetition during a time interval between 0.5 and 5 seconds. The algorithm is based on 3 features of EMG activity bursts: (a) the rate of repetition of the spikes (labeled 'burst density' in the following), (b) their average amplitude, and (c) the duration of the burst. The algorithm performs the following 3 subtasks: (1) EMG amplitudes exceeding 30 μV are truncated. (2) Large and rapid changes of the EMG amplitude are detected and marked as indicators of EMG bursts in the following way: in a moving window of 16 milliseconds' duration (containing 4 sampling points), the SD of the amplitude values is computed. If the SD is greater than 0.6 μV, a large and rapid amplitude change is recorded. (3) Burst density is defined using a moving window of 0.5 seconds' duration (containing 125 sampling points). If the number of large and rapid amplitude changes contained in the moving window continuously exceeds 100 (ie, 80% of the sampling points) during a time interval between 0.5 and 5 seconds, an LM is indicated. Interruptions between LMs of less than 0.5 seconds' duration are bridged.

Data Analysis

The LMs scored by the 2 visual scorers (labeled *V1* and *V2*, respectively) and the automatic method (labeled *A*) in both legs of the 24 sleep recordings formed the database of the validation study. The LMs of the right and left leg were scored separately.

First, an analysis of the number and the mean duration of the LM in each scoring of the 24 recordings is reported. Pearson correlation coefficients and linear regression coefficients were computed in order to describe the relationships between pairs of scorings, ie, between V1 and V2, V1 and A, and V2 and A. Group mean differences between the scorings in the numbers and mean durations of LMs were studied by analysis of variance (ANOVA) using a general linear model for repeated measurements with the intraindividual factors 'leg' (left, right) and 'scoring' (V1, V2, A) and simple contrasts.

Second, a movement-by-movement analysis of the validity of the automatic method is presented. It is based on the different types of possible LM patterns encountered when 2 different scorings of a recording are compared movement by movement. Pattern type '1-to-1' was assigned when an LM in the test scoring co-occurred with an LM in the reference scoring (Figure 1). An LM in the test scoring co-occurring with 2 or more LMs in the reference scoring formed a '1-to-x' pattern. Similarly, 'x-to-1' and 'x-to-x' patterns were formed. The last 3 patterns are referred to as 'multiple' in the following. The 'false-positive' pattern type was assigned to LMs in the test scoring when a corresponding event was missing in the reference scoring. The 'false-negative' pattern type was assigned to LMs in the reference scoring without a corresponding event present in the test scoring. The LMs contained in 'multiple' pat-

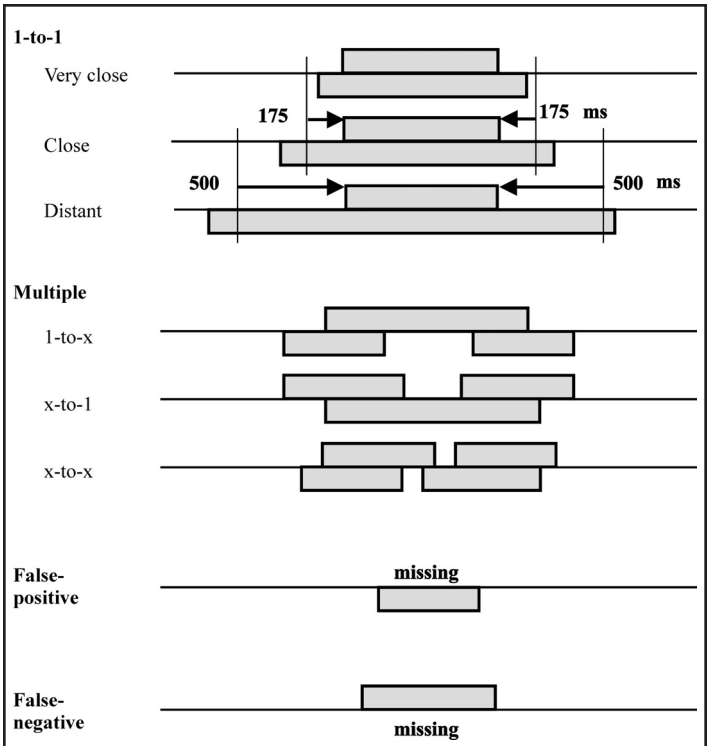

Figure 1—Patterns of corresponding events. The horizontal axes represent time. The events marked by the first scorer (test scorer) are represented as rectangles above the time axes. The events marked by the second scorer (reference scorer) are below the axes. From top to bottom: the first 3 patterns consist of 2 corresponding events. Each scorer marked 1 event. The events are partially overlapping (type '1-to-1'). The next 3 patterns contain more than 1 event at least for 1 scorer (type 'multiple'). The last 2 patterns show 1 event marked by either the first (test) scorer or the second (reference) scorer while no corresponding event was marked by the other scorer (types 'false-positive' and 'false-negative', respectively).

terns are interpreted as an accordance of test and reference scorings. The frequencies of these types of LM patterns were determined for the 3 pair of scorings (test references: V2-V1, A-V1, A-V2). Then, the rates of correct detections and false-positive and false-negative errors were computed to obtain information on the interrater reliability and the validity of the automatic method on a movement-by-movement description level.

In addition, a semiquantitative analysis was performed using the onset and offset times of 1-to-1 LM patterns (Figure 1): if onset and offset times of corresponding LMs in the 2 scorings differed by not more than 175 milliseconds, the 1-to-1 pattern was classified as 'very close' (this time interval corresponds to 5 pixels on the computer screen used for the visual scoring and is near the limit of precision when measuring onset and offset of an LM by cursor markings) (Figure 1). If onset and offset times of the corresponding LM differed by 175 milliseconds to 500 milliseconds, the pattern was classified as 'close.' If onset and offset differences exceeded 500 milliseconds, the pattern was classified as 'distant.'

RESULTS

Number and Duration of LMs

Large interindividual variability of the number of LMs in the sample of 24 recordings was seen in both the 2 visual scorings and the automatic scoring (range: 41 to 849 LMs per recording, Table 1).

All correlation coefficients between the numbers of LMs in 2 scorings, ie, V1-V2, V1-A, V2-A, were very high (exceeding 0.99) and significant at the 1% level (Table 2). Pronounced linear relationships between the numbers of LMs in different scorings exist (Figure 2). Group means of the number of LMs in the 3 scorings varied between 152.1 and 181.5 (Table 1). With the number of LMs (average of the left and right legs) detected by the first visual scorer (V1) as reference (100%), the number of LMs detected by the second visual scorer (V2) was 92.5% and that of the automatic scoring (A) was 94.3%. Some differences in the numbers of LMs between the scorings were found to be statistically significant: ANOVA with the intraindividual factors 'leg' (left, right) and 'scorer' (V1, V2, A) with simple contrasts against V1 yielded a significant effect of 'scorer' $F_{2,46} = 9.91$, $P < .0001$. The differences between V1 and V2 ($F_{1,23} = 14.00$, $P = .001$) and between V1 and A_($F_{1,23} = 10.80$, $P = .003$) were significant. No significant differences were found between V2 and A.

Comparison of the scorings with respect to the individual mean duration of LM values varied between 1.45 seconds and 2.84 seconds, with

Table 1—Number and duration of leg movements

Leg	V1		V2		A	
Movements	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
No.						
Mean	165.7	181.5	152.1	168.8	154.3	172.7
SD	153.4	207.0	142.7	195.9	140.8	195.9
Minimum	48.0	58.0	41.0	43.0	42.0	50.0
Maximum	640.0	849.0	559.0	763.0	573.0	771.0
Mean duration, sec						
Mean	1.96	1.94	1.99	1.96	2.01	1.98
SD	0.28	0.30	0.26	0.29	0.31	0.33
Minimum	1.45	1.51	1.48	1.50	1.45	1.54
Maximum	2.49	2.55	2.51	2.75	2.61	2.84

V1 refers to visual scoring 1; V2, visual scoring 2; A, automatic scoring.

Table 2—Correlation coefficients of leg movements in 24 all-night polysomnograms

Leg	V1-V2		V1-A		V2-A	
Movements	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
No.	0.995	0.997	0.997	0.997	0.994	0.997
Mean duration, sec	0.881	0.895	0.948	0.934	0.849	0.901

V1 refers to visual scoring 1; V2, visual scoring 2; A, automatic scoring.

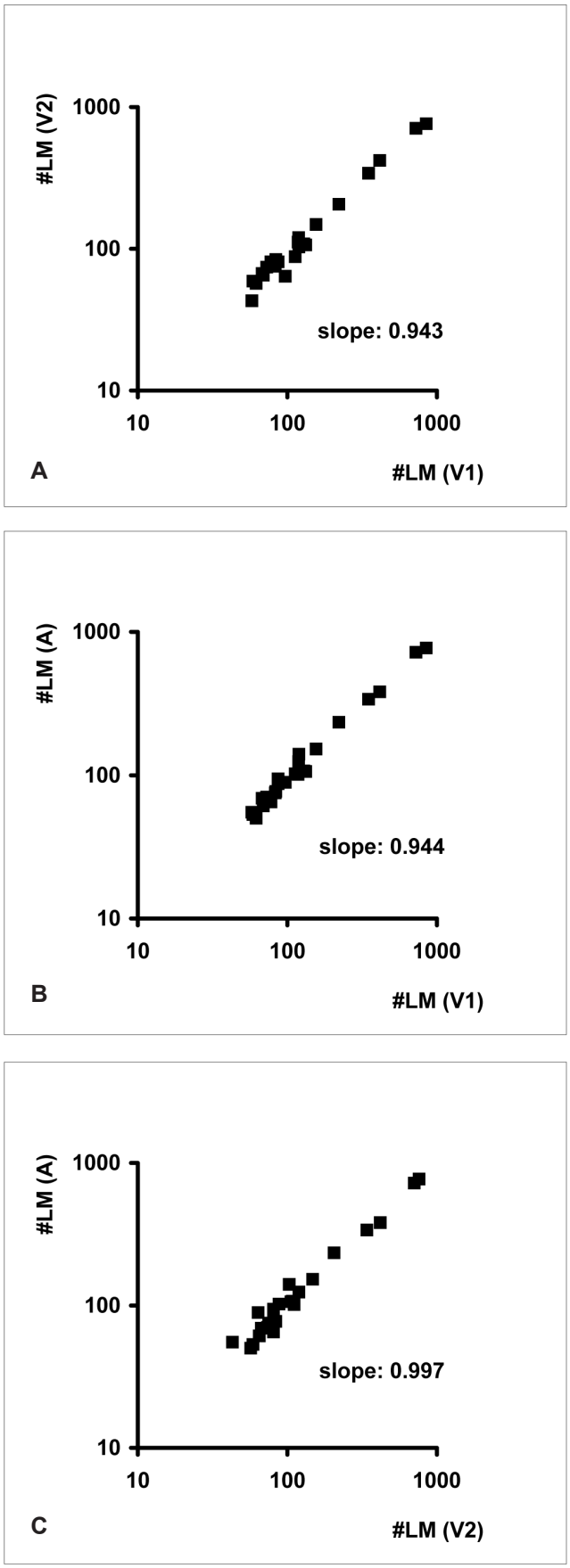

Figure 2—Scatter plots of the numbers of leg movements (LM) of the right leg demonstrating the correlation and the linear relationship (a) between the 2 visual scorers V1 and V2, (b) between V1 and the automatic scoring method A, and (c) between V2 and the automatic scoring method A. Axes with logarithmic scaling. Slopes of the linear regression line. V1 refers to visual scoring 1; V2, visual scoring 2; A, automatic scoring.

group means between 1.94 and 2.01 seconds for the sample of 24 recordings (Table 1). All correlation coefficients of the mean duration of LMs between 2 scorings, ie, V1-V2, V1-A, and V2-A were high, exceeding 0.80, and statistically significant at the 1% level (Table 2). An analysis of the group mean differences between the 3 scorings in the duration of LMs (ANOVA with the intraindividual factors 'leg' [left, right] and 'scorer' [V1, V2, A] with simple contrasts against V1) yielded significant differences between V1 and V2 and between V1 and A (contrast V1-V2: $F_{1,23}$ =.48, P = .012; contrast V2-A: $F_{1,23}$ = 9.90, P = .005). No significant differences were found between V2 and A.

Movement-by-Movement Analysis

High accordance in comparing the numbers or durations of LMs marked in different scorings is a necessary, however, not sufficient precondition for a high validity of a scoring method. Even with equal numbers of LMs or equal duration, there could be a smaller or larger portion of false-positive or false-negative events. This weakness of the analysis can only be overcome by adding a movement-by-movement analysis.

The movement-by-movement comparison was based on the different types of LM patterns (Figure 1) for the 2 visual scorings (Table 3, V2: test scoring, V1: reference scoring) showed that 84% and 82% of the LM patterns in the left and right leg, respectively, were of the 1-to-1 type. About 3% false-negative errors (LMs detected by the reference scorer but not by the test scorer) and about 7% false-positive errors (LMs detected by the test scorer but not by the reference scorer) occurred. A comparison of the automatic scoring (as test scoring) with both visual scorings (as reference scorings) showed that more than 80% of the LM patterns in both legs were of the 1-to-1 type. When comparing the automatic scoring with visual scoring 1, the false-negative and false-positive error rates were both about 5%. In visual scoring 2, the respective rates were about 8% and 4% (Table 3).

Additional information on the reliability of the visual scorings and the validity of the automatic scoring was obtained from an analysis of the differences in onset and offset times of the '1-to-1' patterns, distinguishing the subtypes by 'very close,' 'close,' and 'distant' differences (Table 4).

Table 3—Relative frequencies of 1-to-1 patterns and errors

Pattern	V2-V1		A-V1		A-V2	
Type	Left	Right	Left	Right	Left	Right
1-to-1	84.2	82.1	85.0	83.3	83.2	81.0
Multiple	6.4	7.7	4.3	6.0	5.6	7.5
False-negative	2.9	2.8	5.4	5.1	7.5	7.7
False-positive	6.5	7.4	5.3	5.6	3.7	3.8

V1 refers to visual scoring 1; V2, visual scoring 2; A, automatic scoring.

Table 4—Relative frequencies of very close, close, and distant differences in onset and offset times

Pattern	V1-V2		V1-A		V2-A	
Type	Left	Right	Left	Right	Left	Right
Very close						
Mean	57.0	55.5	55.0	53.5	44.5	43.0
SD	14.2	10.5	13.8	8.1	14.8	10.0
Minimum	29.4	34.9	29.5	35.6	13.0	24.7
Maximum	77.6	74.6	81.6	66.1	67.8	61.9
Close						
Mean	17.6	17.4	21.9	22.3	29.8	29.8
SD	6.5	4.8	7.8	5.8	7.9	5.9
Minimum	10.4	12.0	8.8	8.8	17.4	19.1
Maximum	34.9	33.5	40.0	32.8	46.1	39.7
Distant						
Mean	9.6	9.2	8.1	7.5	8.9	8.2
SD	4.8	3.9	5.0	3.3	4.7	4.4
Minimum	3.4	1.7	1.4	1.7	2.2	1.3
Maximum	19.6	16.1	20.5	13.7	21.0	18.3

V1 refers to visual scoring 1; V2, visual scoring 2; A, automatic scoring.

When comparing the 2 visual scorings, about 50% of the LMs had 'very-close' onset and offset times, differing less than 175 milliseconds. More than 15% of the patterns had 'close' onset and offset times, with differences between 175 and 500 milliseconds, while only less than 10% of the patterns had 'distant' onset and offset times, ie, the differences failed the 500-millisecond limit. Similar relative frequencies were found when comparing the visual scoring V1 and the automatic scoring, whereas the portions of LM patterns with 'very close' onset and offset times were found to be lower for the visual scoring V2 in relation to the automatic scoring.

DISCUSSION

It was the aim of the present study to develop a refined method for the automatic scoring of LMs and to validate it empirically. The method is based on a refined EMG signal-processing algorithm modifying the method described by Tauchmann and Pollmächer.[16] Summarizing the results, it can be stated that the degree of accordance between the visual scorings and the automatic scoring was very similar.

The movement-by-movement analysis yielded results such that the visual scorer V2 detected 97% of the LMs marked correctly by the visual scorer V1 (computed from Table 3: [sum of relative frequencies '1-to-1' and 'multiple'] divided by [sum of relative frequencies '1-to-1', 'multiple' and 'false negative'] times 100); the respective rates for the automatic scoring in relation to V1 and V2 were 95% and 92%, whereas Tauchmann and Pollmächer[16] reported 93%. The rate of LMs marked by visual scorer 2 that corresponded correctly with LMs contained in the visual scoring 1 was 93%. A comparison of the automatic scoring with either of the visual scorings yielded rates of 95% and 96% of automatically detected LMs correctly corresponding to visually marked LMs. They were quantitatively similar to the results of the respective measurements obtained for the interrater reliability of the 2 visual scorers. Even on the refined level used for analyzing the differences in onset and offset times, the results obtained for the comparison of 1 visual scoring with the automatic scoring were quantitatively similar to the results obtained for the comparison of the 2 visual scorings with more than 50% of the 1-to-1 LM patterns differing less than 175 milliseconds in onset and offset times. However, the respective portion was reduced to about 40% when comparing the automatic scoring with the second visual scoring.

In contrast to previous studies, the method described here is based on a physiologically reasonable algorithm of the EMG activity: it detects high-amplitude EMG bursts of high density persisting for a time interval of 0.5 to 5 seconds. However, in contrast to the algorithm described by Tauchmann and Pollmächer,[16] we have used a larger data set for the empirical validation. The method described here was implemented as a JAVA program. The data are compatible with the commercial sleep-recording and analysis system used in our laboratory (Schwarzer Brainlab 3.30, Munich, Germany). Moreover, it can be implemented on any kind of computer. However, applications in connection with other recording systems using different data formats may require modifications of parts of the program that can be performed by an experienced programmer.

The neurobiologic process underlying PLMs is unknown. A suprasegmental disinhibition at the brain stem or spinal-cord level has been suggested and supported by neurophysiologic data, functional magnetic resonance imaging studies, and the observation of PLMs in patients with structural and functional lesions of inhibitory spinal pathways.[20-22] These and future research paradigms require reliable and validated techniques for scoring LMs, which has been proven by our method. Using the same definitions for LMs, high interrater reliabilities for the number of movements during sleep were shown by visual scoring.[12] However, this procedure is time consuming, and a regular training for achieving high interrater reliability is necessary.[12] In addition, intrarater reliability may be a critical issue, although this has not been investigated formally for LMs.

This report is limited because no data on LM-associated physiologic events such as electroencephalographic arousals are reported. These changes of the microarchitecture of sleep are relevant for clinical and scientific issues[23]; however, an arousal detection and quantification of LMs during wakefulness and different sleep stages were not the purpose of the present study and will be performed in a second step. To conclude, the high degree of accordance between the visual and the automatic scorings will allow future studies to apply our method for automatic LM detection.

ACKNOWLEDGEMENTS

We would like to thank Irene Gunst and Susanne Gudewill for scoring the leg movements in the polysomnographic recordings.

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