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Measuring leg movements during sleep using accelerometry: comparison with EMG and piezo-electric scored events

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Abstract— **Periodic Limb Movements during Sleep (PLMS) can cause significant disturbance to sleep, resulting in daytime sleepiness and reduced quality of life. In conventional clinical practice, PLMS are measured using overnight electromyogram (EMG) of the tibialis anterior muscle, although historically they have also been measured using piezo-electric gauges placed over the muscle. However, PLMS counts (PLM index) do not correlate well with clinical symptomology. In this study, we propose that because EMG and piezo derived signals measure muscle activation rather than actual movement, they may count events with no appreciable movement of the limb and therefore no contribution to sleep disturbance. The aim of this study is thus to determine the percentage of clinically scored limb movements which are not associated with movement of the great toe measured using accelerometry. 9 participants were studied simultaneously with an overnight diagnostic polysomnogram (including EMG and piezo instrumentation of the right leg) and high temporal resolution accelerometry of the right great toe. Limb movements were scored, and peak acceleration during each scored movement was quantified. Across the participant population, 54.9% (range: 26.7-76.3) and 39.0% (range: 4.8-69.6) of limb movements scored using piezo and EMG instrumentation respectively, were not associated with toe movement measured with accelerometry. If sleep disturbance is the consequence of the limb movements, these results may explain why conventional piezo or EMG derived PLMI is poorly correlated with clinical symptomology.**

I. Introduction

Periodic limb movements (PLM) are involuntary repetitive, periodic movements of the lower limb which typically involves the toe, but may include the foot, lower leg, and entire lower limb. When occurring during sleep these are known as periodic limb movements in sleep (PLMS) [1]. PLMS can disturb sleep, resulting in arousals leading to insomnia, and daytime sleepiness [2]. According to current American Association of Sleep Medicine (AASM) guidelines, PLMS should be measured using electromyogram (EMG) of the tibialis anterior [3]. However, historically, muscle contraction of the tibialis anterior has also been measured with piezo-electric gauges. On the basis of such instrumentation as part of an overnight polysomnogram, a PLM is defined by at least 4 consecutive leg movements of at least 8uV in amplitude and 0.5-10 seconds in duration, separated by between 5 and 90 second. PLM events are then summarized as the number of PLM's per hour (PLM index-PLMI), with Periodic Leg movement Disorder (PLMD) diagnosed on the basis of this and clinical history.

However, despite this labor and resource intensive instrumentation, the PLMI does not correlate well with the presence and severity of clinical symptoms [3]. Studies have demonstrated that amplitude thresholds are important in the calculation of PLMI [4], and further, since EMG, and piezo gauges are an indirect, and un-calibrated measure of movement, they are likely to count events which do not correspond to appreciable movements of the limb [5]. It is thus speculated that more accurate assessment of movement intensity may better correlated to the presence and severity of clinical symptoms. Accelerometry based instrumentation may present a robust, cost effective method of measuring such movement intensity.

Literature has described the use of commercial accelerometer based devices such as PAM-RL [6-9] Actiwatch [10, 11], and both [12]. However, these devices record only highly processed accelerometry data, are not able to be directly synchronized with the PSG recording, and as such are unsuitable for analyzing temporal correlations of specific movement events. Furthermore these devices, because of their size, are placed on the ankle rather than the toe where measurement is likely to be most sensitive to limb movement. As such, in this study, we apply a customised, high temporal resolution tri-axial accelerometry measurement to directly measure limb movement. The system is engineered to allow direct accelerometry measurements on the great toe. The aim of this study is thus to evaluate to what extent EMG and piezo based scoring quantify events which are not associated with movement of the lower limb.

II. Methods

A. Subjects and data

Patients attending The Prince Charles Hospital for an overnight diagnostic polysomnogram were invited to participate in this study. Exclusion criteria included patients with a resting, involuntary, tremor (i.e. degenerative neuromuscular disorders such as Parkinson's Disease and Huntington's chorea); Pregnant women; Attendees under the age of 18; and patients with un-interpretable electroencephalogram. Upon consenting to participate in the study, patients were enrolled as participants. In this initial study we analyze data from 9 participants. This study was approved by an institutional human research ethics committee (Ref: HREC10/QPCH/27).

In accordance with a standard clinical diagnostic polysomnogram, participants underwent computerised overnight polysomnogram (Compumedics E series, PSG 2

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analysis software) including electro-encephalogram, electro-occulogram, surface electro-myogram, electrocardiogram, respiratory inductance plethysmography, pulse oximetry and thermistor measured oral and nasal airflow. In addition, patients were studied using a customised continuous multisite accelerometry system which recorded tri-axial accelerometry with separate wireless units located on: the central body (sternal notch); the right ankle with an auxiliary sensor on the superior surface of the right great toe; and the right wrist with an auxiliary sensor on the right middle finger. Fig. 1 displays a photograph of the right ankle unit showing the auxiliary accelerometer on the right toe. These units transmit raw tri-axial accelerometry data via a 2.4GHz RF protocol, where it is logged on a PC, with a synchronization channel input to the PSG system. Each accelerometry channel was recorded at 100Hz, with 8bit resolution, and +/-2G dynamic range [13]. In this study we consider only data recorded from the right great toe.

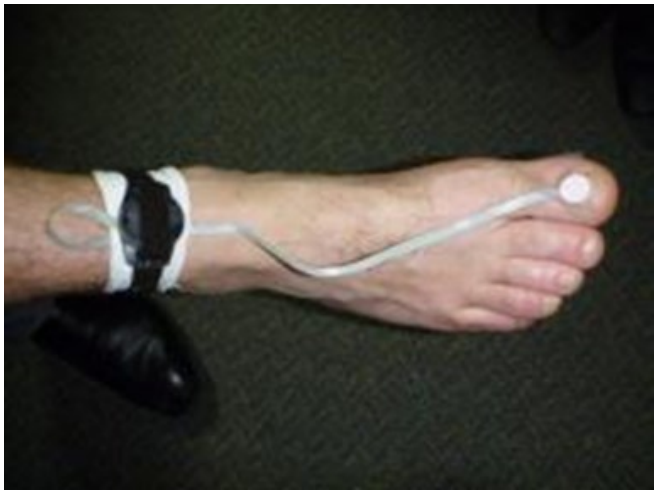

Figure 1. Placement of ankle accelerometer unit showing the auxillary sensor on the superior surface of the great toe.

Sleep stage, respiratory and EEG events were scored by an experienced sleep technologist according to the AASM criteria [14, 15]. Leg movements were scored independently for data recorded using right leg piezo movements, and right leg EMG, in both cases blinded to each other and to accelerometry data. In addition to the scoring of leg movements meeting the criteria for a PLMS, leg movements which met the amplitude, and duration criteria, but did not meet the criteria of "periodic" (i.e. did not meet the requirement of 4 consecutive events) were scored with a "leg movement" coding.

B. Accelerometry Data Pre-Processing

Accelerometry data was manually synchronized with the PSG data, before the toe channel of raw tri-axial accelerometry data was digitally band-pass filtered with an 8-pole Butterworth filter (0.05-5Hz). To address the study aims, it is necessary to detect the presence of movement of the right toe, rather than to characterize the specific nature or direction of such movements. As such, the L_{max} norm was applied to each tri-axial sample to determine the maximum of the x, y and z acceleration axis, at each point in time. The norm accelerometry was heavily filtered with an 8-pole Butterworth low-pass filter (cutoff: 2.5Hz) to remove high frequency components. Finally, a weighted moving average smoothing filter was applied to generate the final processed accelerometry (Acc_p). Fig. 2 displays a sample 10 minute window of Acc_p data, and a plot of the piezo and EMG scored leg events for the same window.

C. Data Analysis

Periods of sleep were segmented from periods of wake, and a histogram of the Acc_p data was generated to determine that the noise floor of the accelerometry data was 0.02G's. Thus periods with Acc_p data greater than 0.02G's were automatically scored as accelerometry movements. The period corresponding to each manually scored EMG right leg movement occurring during sleep was identified, and a 5 second tolerance applied to account for small errors in specific location of manual event markings. For each patient, the percentage of scored EMG movements for which there was no corresponding accelerometry movement was calculated. In addition, the percentage of automatically scored accelerometry movements which were not associated with manually scored EMG movement was calculated. This was repeated for separately for manually scored piezo right leg movements.

III. RESULTS

Table I shows the clinical characteristics of the participants recruited in this study. Table II displays the number of scored right leg movements, and the percentage of these scored movements that were not associated with an automatically scored accelerometry movement. Data is presented for events scored using EMG and piezo leg instrumentation. The event counts for EMG and piezo scored events; accelerometry and EMG scored events; and accelerometry and piezo scored events were correlated (Pearson's correlation=0.76, $p<0.05$; 0.68, $p<0.05$; 0.91, $p<0.05$ respectively), and although the mean number of events was different, this was not statistically significant. The mean percentage of scored events not corresponding to accelerometry movement was greater for piezo scored events (53.5% compared with 40.3%, $p<0.05$).

TABLE I. CLINICAL CHARACTERISTICS OF STUDY PARTICIPANTS

Participant	Age	Gender	AHI	PLMI (EMG)	PLMI (Piezo)
1	40	M	81.4	0	0
2	49	F	16	34	34
3	81	F	18.8	10.2	22.2
4	24	M	5	0	0
5	57	M	48.2	0	0
6	32	M	1.6	0	0
7	33	M	11.6	1.1	1.4
8	56	F	16.1	0	0
9	54	F	5.2	43.8	45.9

Age; Gender; Apnoea-Hypopnoea Index (AHI); Periodic Leg Movement Index (PLMI) for EMG and Piezo scored events for each study participant.

TABLE II. NUMBER OF SCORED LEG MOVEMENTS AND % SCORED EVENTS ASSOCIATED WITH MOVEMENT ON ACCELEROMETRY

Participant	Manual Piezo Leg Movement Scoring		Manual EMG Leg Movement Scoring		Automatic Accelerometry Leg Movement Scoring		
	Number of Scored Events	% Events Not Associated with Movement on Accelerometry	Number of Scored Events	% Events Not Associated with Movement on Accelerometry	Number of Scored Events	% Events Not Associated with Scored Piezo Event	% Events Not Associated with Scored EMG Event
1	33	39.4	16	25.0	49	67.3	79.6
2	84	72.6	33	39.4	25	20.0	40.0
3	112	50.0	141	54.6	159	69.2	64.8
4	59	76.3	22	36.4	30	56.7	60.0
5	64	26.6	21	4.8	61	34.4	73.8
6	26	50.0	33	48.5	13	15.4	0.0
7	25	60.0	18	55.6	32	65.6	68.8
8	57	73.7	46	69.6	49	71.4	79.6
9	167	45.5	97	17.5	96	13.5	20.8
Mean	**69.7**	**54.9**	**47.4**	**39.0**	**57.1**	**46.0**	**54.1**
Range	**25-167**	**26.7-76.3**	**16-141**	**4.8-69.6**	**13-159**	**13.5-71.4**	**0-79.6**

IV. DISCUSSION

The primary objective of this study was to determine whether tibialis anterior EMG and piezo based scoring of leg movements may be quantifying neurological events which are not associated with actual movement of the lower limb. Results indicate that 39.0% and 54.9% of events, scored with EMG and piezo instrumentation respectively, are not associated with movement detected with high temporal resolution tri-axial accelerometry of the great toe. Furthermore, 54.1% and 46.0% of automatically scored accelerometry movements are not associated with a scored EMG or piezo event. If sleep disturbance associated with PLMD manifests as a result of limb movements disturbing sleep, these results may explain why the conventional PLMI correlates poorly with clinical symptomology. It is also important to note that there was also a large variation across the study population (27.1-78.9% for piezo and 4.8-68.6% for EMG events). This suggests that in some individuals the neurological stimulation of the tibialis-anterior is more often associated with a measurable movement than in other individuals. This may suggest that PLMD is a complex disorder, whereby there may be different pathological traits, or "phenotypes" leading to disorder.

It is necessary to consider the limitations of this study in the interpretation of these results. The first, and perhaps the most important, is that the patients in this study are drawn from a general population of patients attending the sleep lab for a diagnostic polysomnogram. The consequence of this is that all patients considered in this analysis were primarily attending for suspected obstructive sleep apnea – rather than for suspected PLMD. Given the nature of this population, and therefore the relatively small number of events meeting the criteria for a PLM, we considered an alternative event – limb movements whereby individual EMG and piezo events meeting the amplitude and duration criteria for individual elements of a PLM; but not meeting the separation and repetition criteria for a PLM. Such events may be of different neuro-muscular physiology, and as such, care must be taken in generalizing conclusion to actual PLMS. This is also a small pilot study (N=9) of a non-homogenous clinical population, limiting the generalisability to a broader population.

PLMD is a common disorder which is frequently undiagnosed, and misdiagnosed, and at least in part, this is likely to be related the poor correlation between the PLMI and clinical symptomology [3]. To the individual, it may have significant impact on quantity of life, and more broadly, it may contribute a considerable burden of disease to society [2]. Given that effective treatment is available it is highly desirable to develop improved diagnostic criteria, such that patients may be efficiently diagnosed, and appropriately treated. EMG used to generate the PLMI is carried out as part of a full overnight polysomnography which is an expensive test, requiring significant physical and human resources. Consequently, diagnostic methods which may be performed outside this dedicated environment (i.e. remote screening) are highly desirable. And indeed, commercially available accelerometer based devices have been trialed in such applications [6-12]. These systems however, suffer from some limitations – in particular, their size limiting application to the ankle rather than toe, and the difficulty distinguishing true PLMS from leg movements which are the result of gross body movements. This is a particular problem in people who also have respiratory related sleep disorders such as obstructive sleep apnea, where respiratory events result in arousals and gross body movements, which are then falsely detected as PLM [16, 17]. The customised accelerometry system used in this study – allowing for simultaneous accelerometry of the great toe, ankle, central body, wrist, and middle finger - may have the ability overcome the limitations of these commercial devices.

At present, only toe accelerometry data has been analyzed within this study. As such, further work includes analysis of all accelerometry channels to differentiate gross body from leg movements; and to examine the significance of movements observed on the ankle accelerometer relative to those observed on the toe accelerometer. Quantification of accelerometer movements has also been limited to a simple, time-series threshold based quantifications. However, there

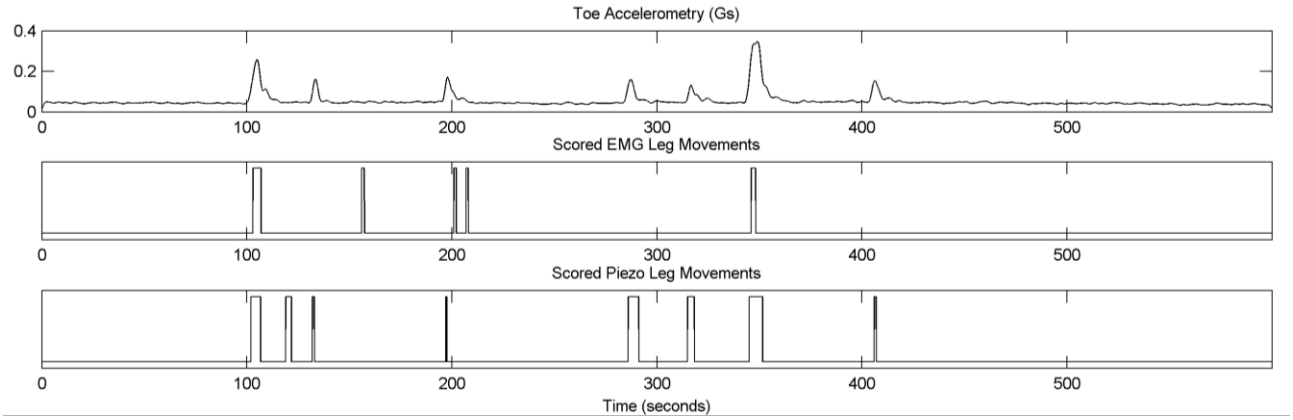

Figure 2. Processed right toe accelerometry and manaually scored right leg movement events based on piezo and EMG instrumentation of the right tibialis-anterior.

are a number of other methods of quantifying such data that may provide more physiologically relevant information about the nature and significance of such movements [18]. As these analyses become more refined, and larger clinical studies can be conducted, novel indices of PLMD disease severity may be developed which better correlate with clinical symptomology.

V. Conclusion

Leg movements scored on the basis of EMG or piezo instrumentation of the tibialis anterior muscle are often not associated with movement observed in toe accelerometry. If arousals following limb movements are the cause of sleep disturbance in PLMD, this observation may explain why the PLMI is poorly correlated with clinical symptoms. Future work to develop new indices of disease severity on the basis of accelerometry and existing data may lead to improved understanding of PLMD, and more effective diagnosis and management of patients with the disease.

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References

[1] K. Staisny, W. H. Oertel, and C. Trenkwalder, "Clinical symptomology and treatment of restless legs syndrime and periodic limb movement disorder," *Sleep Medicine Reviews,* vol. 6, pp. 253-265, 2002.

[2] M. Karatas, "Restless legs syndrome and periodic leg movements during sleep: diagnosis and treatment," *The Neurologist,* vol. 13, pp. 294-301, 2007.

[3] A. S. Walters, G. Lavigne, W. Hening, D. L. Picchietti, R. P. Allen, S. Chokroverty, C. A. Kushinda, D. L. Bliwise, M. W. Mahowald, C. H. Schenck, and S. Ancoli-Israel, "The scoring of movements in sleep," *Journal of Clinical Sleep Medicine,* vol. 3, pp. 155-167, 2007.

[4] V. Gschliesser, E. Brandauer, H. Ulmer, W. Poewe, and B. Hogl, "Periodic limb movement counting in polysomnography: effects of amplitude," *Sleep Medicine,* vol. 7, pp. 249-254, 2006.

[5] W. Hening, "The clinical neurophysiology of the restless legs syndrome and periodic limb movements. Part I: Diagnosis, assessment, and characterization," *Clinical Neurophysiology,* vol. 115, pp. 1965-1974, 2004.

[6] E. Sforza, M. Johannes, and B. Claudio, "The PAM-RL ambulatory device for detection of periodic leg movements: a validation study," *Sleep Medicine,* vol. 6, pp. 407-413, 2005.

[7] K. Tuisku, M. M. Holi, K. Wahlbeck, A. J. Ahlgren, and H. Lauerma, "Quantitative rest activity in ambulatory monitoring as a physiological marker of restless legs syndrome: a controlled study," *Movement Disorders,* vol. 18, pp. 442-448, 2002.

[8] K. Tuisku, M. M. Holi, K. Wahlbeck, A. J. Ahlgren, and H. Lauerma, "Actometry in measuring the symptom severity of restless legs syndrome," *European Journal of Neurology,* vol. 12, pp. 385-387, 2005.

[9] L. M. Trotti, D. L. Bliwise, S. A. Greer, A. P. Sigurdsson, G. B. Gudmindsdottir, T. Wessel, L. M. Organisak, T. Sigthorsson, K. Kristjansson, T. Sigmundsson, and D. B. Rye, "Correlates of PLM's over multiple nights and impact upon RLS diagnosis," *Sleep Medicine,* vol. 10, pp. 668-671, 2009.

[10] H. E. Montgomery-downs, V. M. Crabtree, and D. Gozal, "Actigraphic recordings in quantification of periodic leg movements during sleep in children," *Sleep Medicine,* vol. 6, pp. 325-332, 2005.

[11] M. K. King, M. Jaffre, E. Morrish, J. M. Shneerson, and I. E. Smith, "The validation of a new actigraphy system for the measurment of periodic leg movements in sleep," *Sleep Medicine,* vol. 6, pp. 507-513, 2005.

[12] V. Gschliesser, B. Frauscher, E. Brandauer, R. Kohnen, H. Ulmer, W. Poewe, and B. Hogl, "PLM detection by actigraphy compared to polysomnogram: A validation and comparison of two actigraphs," *Sleep Medicine,* vol. 10, pp. 306-311, 2009.

[13] P. I. Terrill, D. G. Mason, and S. J. Wilson, "Development of a continuous multisite accelerometry system for studying movements during sleep," *Conference Proceedings of the 32nd Annual Conference of the IEEE Engineering in Medicine and Biology Society,* pp. 6150-6153, 2010.

[14] M. H. Silber, S. Ancoli-Israel, M. H. Bonnet, S. Chokroverty, M. M. Grigg-Damberger, M. Hirshkowitz, S. Kapen, S. A. Keenan, M. H. Kryger, T. Penzel, M. R. Pressman, and C. Iber, "The visual scoring of sleep in adults," *Journal of Clinical Sleep Medicine,* vol. 3, pp. 121-31, 2007.

[15] C. Iber, S. Ancoli-Israel, A. Chesson, and S. F. Quan, *The AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specification*: American Academy of Sleep Medicine, 2007.

[16] R. P. Allen, "The resurrection of periodic limb movements (PLM): Leg activity monitoring and the restless legs syndrome," *Sleep Medicine,* vol. 6, pp. 385-387, 2005.

[17] R. P. Allen, "Improving RLS diagnosis and severity assesment: Polysomnography, actigraphy and RLS-sleep log," *Sleep Medicine,* vol. 8, pp. S13-S18, 2007.

[18] S. J. Preece, J. Y. Goulermas, L. P. J. Kenney, and D. Howard, "A Comparison of Feature Extraction Methods for the Classification of Dynamic Activities From Accelerometer Data," *IEEE Transactions on Biomedical Engineering* vol. 56, pp. 871-879, 2009.