

## Detecting Periodic Limb Movements with Off-the-Shelf Accelerometers: A Feasibility Study

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### Abstract

Periodic limb movements are short movements of the legs that can lead to low sleep quality in the general population. Currently, the gold standard to measure periodic limb movements for diagnostic purposes is polysomnography. This is an expensive technique that requires specially fitted laboratories and specialized personnel. In this paper we explore the use of commercial, off-the-shelf accelerometers to detect periodic limb movements during sleep and compare the results to the gold standard. We recruited two subjects for one night and measured limb movements with polysomnography and Actigraph GT3X accelerometers. We developed an open source Java application for processing the data. A total of 846 events were recorded. We found a very low similarity between polysomnography and GT3X data, indicating that our accelerometer-based method is not yet feasible for medical diagnosis. Several options for further development are: the exploration of different sensor locations, sensors with higher sampling rates, as well as enhancement of data analysis methods.

### Keywords:

Periodic limb movement, accelerometers, sleep disorders.

### Introduction

Limb movements (LMs) are short, leg movements and occur mostly during sleep with a minimum duration of 0.5s and a maximum duration of 10s. A periodic limb movement (PLM) is defined as a sequence of 4 or more LMs separated by intervals of 5 to 90 seconds [1] and with an amplitude  $>8\mu\text{V}$  above the resting electromyography (EMG), according to the American Academy of Sleep Medicine [2]. PLM itself is only a finding, while a PLM disorder (PLMD) is a clinical condition that involves different sleep complaints like insomnia, sleep apnea, snoring or restless legs syndrome (RLS) [1]. PLMs are present in 70-90% of patients with RLS [3,4,5], a condition characterized by limb paresthesia, dysesthesia, and motor restlessness that worsens at rest and in the evening. An important dimension in this context is the PLM index (PLMI), which is the total number of PLMs per hour over a day.

A detailed clinical history is the central component in the diagnosis of RLS, while detection of PLM during sleep and wakefulness is of diagnostic help in unclear cases and may

also indicate the severity of the disease [6] and the effects on sleep quality [7].

The gold standard of recording PLMs is polysomnography (PSG) [5]. PSG is performed in a sleep laboratory, with the subject having to spend at least one night in care. It usually consists of bilateral electromyography (EMG) of the anterior tibialis muscle in addition to an electroencephalogram (EEG), electrooculogram, submental EMG, and respiratory measurements [8]. EMG is used to detect electrical potential generated by muscle cells and is used as a PSG feature to measure PLMs as they initiate most frequently from the tibial anterior muscle [5]. PSG recording requires well-trained sleep experts, a controlled hospital environment, and a relatively long setup time, resulting in high costs. For these reasons, an alternative is desired.

Accelerometers are cheap and easy to use devices with increasing applications in health. If proven as an effective method for PLM detection, they can act as an easy to use and cheap tool. At the same time, this enables the development of products for home, empowering the patients to follow their own disease. It also opens the opportunity for daily life medical assessment of PLM.

Frequent and uncontrolled limb movements can cause frequent awakenings and reduce the quality of sleep [9]. Consequently, those afflicted complain of sleep disorders, insomnia and daytime sleepiness. Research suggests that more than 10% of people who go to their doctor complaining of insomnia have PLM disorder [10].

The detection of PLM plays an important role in the diagnosis and treatment of several medical conditions such as sleep apnea. It has been a focus of research in conditions such as chronic obstructive pulmonary disease, sleep quality, attention deficit in children, hypertension, circadian cycle analysis, and RLS.

There is evidence that patients with restless legs syndrome have a higher prevalence of hypertension and heart problems [10]. Because the majority of patients with restless legs syndrome have PLMs in sleep, transient rises in blood pressure associated with the PLMs in sleep may contribute to heart disease and perhaps stroke when superimposed on an already elevated blood pressure.

The continuous low sleep efficiency caused by numerous sleep disturbances, EEG-Arousals, can lead to daytime fatigue [11],

diabetes [12], headaches [13], and psychiatric disorders [14]. Therefore, it is important to precisely monitor sleep/wake patterns and sleep efficiency. Vegetative-arousals do not lead to sleep interruption, but to increased blood pressure and heart rate. Peripheral arterial tonus reaches more importance considering the development of cardiovascular diseases. PLMs can lead to both EEG-Arousals and to vegetative arousals; therefore the detection of PLMs becomes more meaningful.

Accelerometers have been used to answer a wide range of sleep related questions, namely helping the diagnosis of circadian rhythm sleep disorders. They act as a tool in the detection and classification of sleep-awake cycles or in the diagnosis of RLS. An exhaustive review of the use of accelerometers in sleep medicine can be found in [15].

First attempts to explore accelerometers for the detection of PLM happened in the nineties and were performed with prototype devices (MOVOPORT; Rimkus, Germany and Swiss-type; Gaehwiler Electronics, Switzerland). Those studies reported a significant correlation between accelerometers and PSG, but with significant underestimations of PLM [16,17]. More recent devices have been evaluated as well [4,18]. One study using a device with a watch form, developed for sleep studies, but worn at the ankle and toe, found good validity of the results when compared to PSG [19]. The same device was found to have insufficient accuracy for medical detection of PLM in a newer study [20]. There is no established consensus of the viability of PLM detection through accelerometers.

In this paper we explore the use of off-the-shelf, commercially available accelerometers, namely the Actigraph GT3X accelerometer, to detect PLMs and compare it with the current gold standard PSG.

## Materials and Methods

### Subjects

We asked all the subjects that were referred, during a two weeks period, to Clinic Bad Reichenhall for the study of possible sleep disturbances to participate in our study. The inclusion criteria was the suspected diagnosis of sleep apnea. One of our exclusion criteria was suspected or diagnosed RLS. This is because in these cases, limb movement can be caused by dysaesthesia and not only by PLMs. Our other exclusion criteria were any conditions, such as skin irritation, that could prevent accelerometer measurement. The ones accepting to participate spent one night in the sleep laboratory of the clinic while undergoing standard PSG analysis, under medical supervision. At the same time, they wore two GT3X accelerometers on both their right and left ankles.

Two subjects accepted the invitation. The study had been approved by the relevant local ethics committee and was carried out according to the Helsinki declaration.

### Sensors

We used the Philips Respironics Alice 5 Diagnostic Sleep System (Philips Healthcare, Best, The Netherlands) as PSG equipment. It is a complete PSG system with up to 55 channels, comprising a wide range of physiological measurements, including electrocardiogram, electromyogram, temperature, breathing rate, nasal flow, and sound. For our study, the most important parameter from PSG was the muscle tension that was acquired through electromyograms for measuring the activity of skeletal muscles on the legs.

As a motion sensor we used the GT3X (Actigraph LLC, Pensacola Florida, USA), a tri-axial acceleration device. It uses a MEMS technology and has a sampling rate of 30Hz, although the configuration allows recording of epochs of 1 second to 1 minute, or raw data, before or after filtering. The filter, implemented in the firmware, is, according to the manufacturer, a bandpass between 0.25 to 2.5 Hz. The battery is built-in, with capacity of up to 30 days of recording, with safe duration of 21 days. They are small and lightweight (3.8 x 3.7 x 1.8 cm, 27g). We used a revision of the GT3X sensor with 4MB of total memory.

The GT3X sensor was configured for collecting data in the highest sampling the sensor can handle (30HZ, raw data, pre-filtered mode, and 3-axis). The subjects wore sensors at both legs at ankle level. The sensors were securely attached by custom made elastic belts with Velcro fastening for ease of use and comfort. We chose this location for two reasons: 1. usability is high; 2. movements are expected to have maximal amplitude.

### Software

The data from the GT3X sensors was first downloaded and visually checked for sensor failures using Actilife Software version 4. The PSG data was managed in the bundled Alice 5 Software. The medical team inspected all the channels for any sign of failure and after that we exported the right and left leg EMG channels into raw output files and the event log into a text file. The log file provides a method to check the accuracy of our own analysis methods on the detection of PLMs.

We developed a simple Java application, named *Movyzer*, for the analysis of the data of this study and for future studies. The application is open source, available at <http://code.google.com/p/movyzer/> and we want to invite researchers to contribute to its further development.

The *Movyzer* application is able to process the output files of GT3X sensors and plot the results. It is also capable of processing the event log of the Alice PSG equipment and showing the PLM events recorded for the period. The parameters provide the possibility to set the PLM thresholds as required by medical specialists, both for the PSG and accelerometer data.

The 3 axial data produced by the GT3X sensor is combined into a single magnitude value, Vector Magnitude Units (VMU), before any other calculations and display, according to formula (1)

$$|VMU| = \sqrt{x^2 + y^2 + z^2} \quad (1)$$

Figure 1 shows a screenshot of the application, with the main interface areas identified.

In Figure 2, we show a zoom in of the PSG plotting area, where one can see the visual identification of PLM events. We use blue frames as an overlay for the accelerometer and PSG data to visualize the events classified as PLM according to the parameters. In the data presented in figure 2, there were no PLM events detected on the GT3X data. This provides an immediate visual indication of the accuracy of both methods.

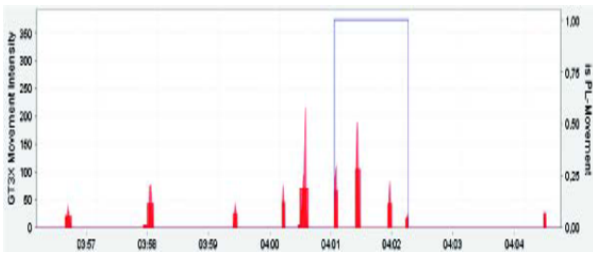


Figure 2 - Zoom in of the PLM identification interface. The red line shows intensity, the red transparent bars show the LMs, the blue line borders the PLMs

### Similarity function

Besides the visual plot of both the PSG and GT3X data, we implemented a similarity function. Such a function is very useful, as PSG and GT3X have independent clocks that are very hard to synchronize on the start of the study. It also provides us with the essential tool to compare GT3X data to PSG,

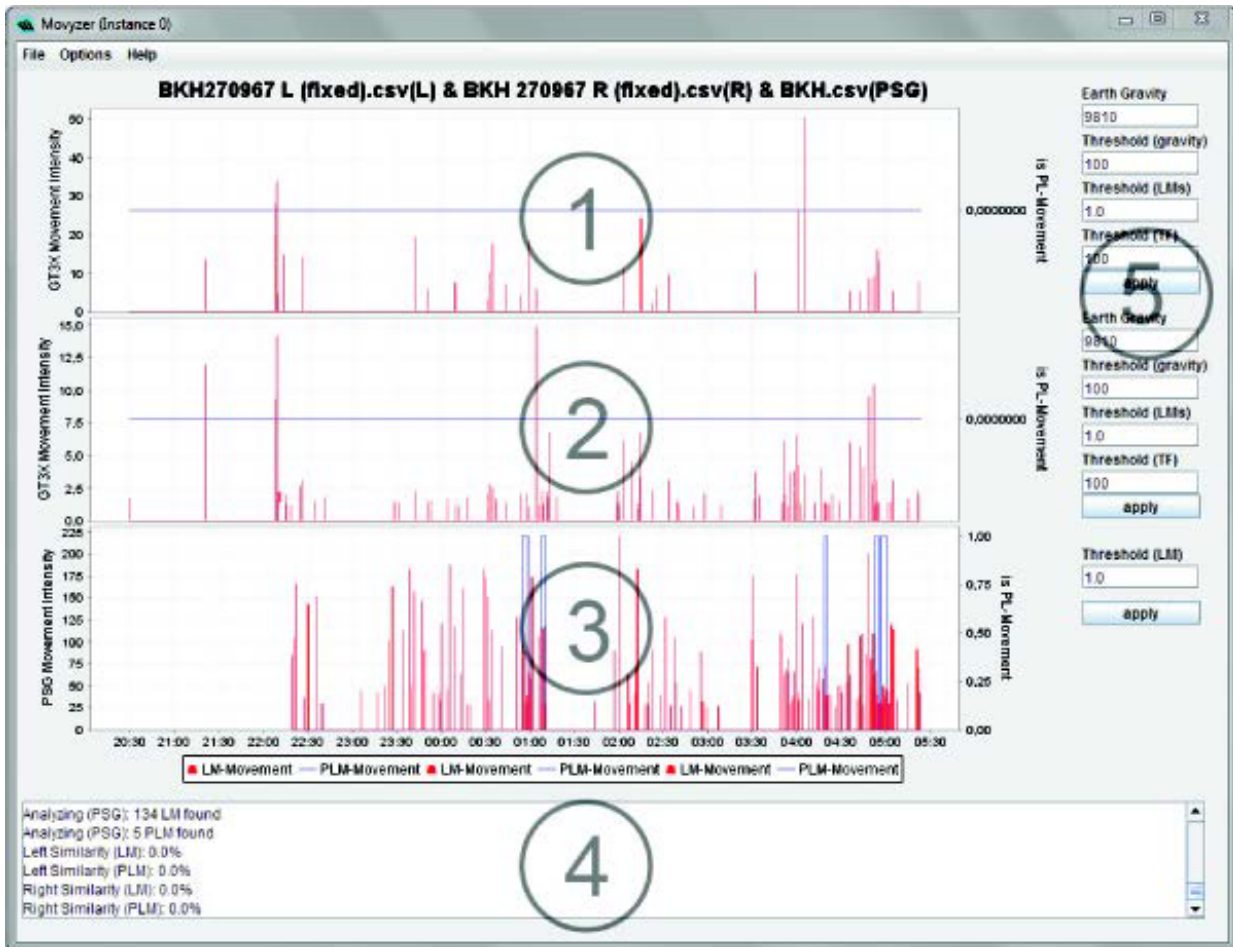


Figure 1 - Main window of the Movyzer application: (1) GT3X Graph (left leg), (2) GT3X Graph (right leg), (3) PSG Graph, (4) Log field, (5) Parameters

in a first phase, before exploring the statistical associations. To address this problem, we implemented a routine that can take a lower and upper bound for the possible time difference and plot the similarity of both time series across that range of shifts.

The similarity is calculated as a percentage of the time overlap of all events classified as a limb movement according to the medical parameters. This is a visual tool for comparing the accuracy of GT3X to the PSG gold standard. The time coordinate with maximum value of similarity is an estimation of the correct time correction for the two time series. The code for the similarity function is shown in Figure 3.

```
function plot_similarity(lowerTime, upperTime)
  for timeShift = lowerTime to upperTime
    graph(i) = similarity(PSG, GT3X, timeShift)
  endfor
  plot(graph)
end
```

```
function similarity(PSG, GT3X, timeShift)
  for i = 0 to PSG.LMCount
    PSGTime = PSG.getNextLM.getTime
    GT3XTime = GT3X.getNextLM.getTime
    totalOverlap += PSGTime.timeOverlap(GT3XTime)
  endfor
  similarity = totalOverlap / PSG.TotalDuration
end
```

Figure 3 - Algorithm for the similarity function

## Results

The two recruited subjects registered a total of 846 limb movement events during the measurement period, as recorded by the PSG.

Table 1 shows the age and gender of the two recruited subjects, the number of PLM events recorded, and the similarity of the GT3X accelerometer data to the PSG data. We can see a very low similarity value for both subjects. This indicates that the GT3X sensor is unable to detect the PLM.

Figure 4 shows the output plot of the similarity function for the subject S1. It shows that the clocks of GT3X and PSG system had a shift of 300 ms, as we were expecting. The similarity of both time series at the maximum point is 8%. The point where the maximum occurs indicates the time shift between the clocks.

Table 1 – Subjects characteristics, PLM events and similarity results

Subject	Age	Gender	Number of LM events	Maximal similarity
S1	51	M	655	8%
S2	63	F	181	5%

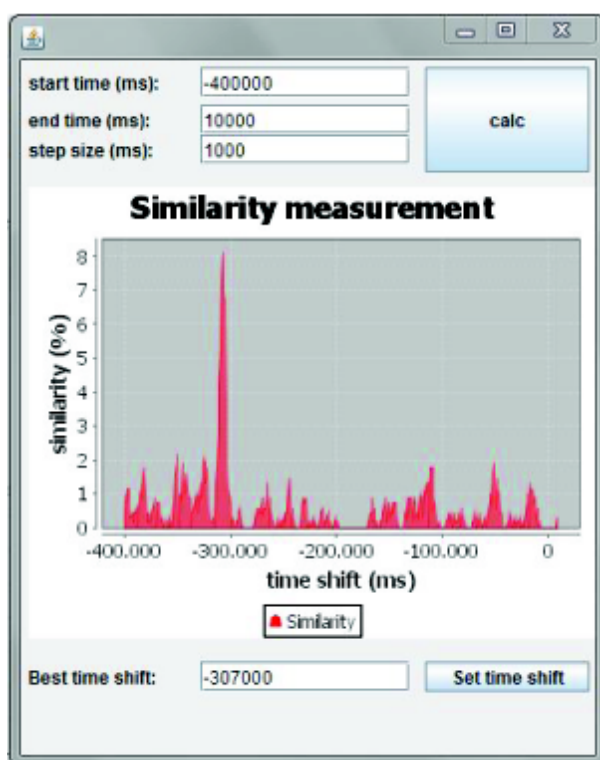


Figure 4 - Similarity measurement for subject S1

## Discussion

We have recruited two subjects and we recorded 246 PLM events in the measurement period. We also implemented a simple Java application to analyze the data of both GT3X and PSG. After correction for possible time shifts in both clocks, we found a very low similarity measurement between both sensors. The highest similarity value of 8% we achieved is far

from relevant for medical applications. This indicates that the GT3X is not capable of detecting small movements as the ones present in the PLM or that there is a strong technical limitation to the accuracy of the setup. Our results are also in direct contrast with previous published results for studies assessing the use of accelerometers for detecting PLMs. Although other authors reported an underestimation of PLMs events of the accelerometers when compared to PSG, we found very little information in the accelerometer data.

We need to explore new versions of the GT3X sensor with larger memory capacity and higher sampling rate that would allow us to record raw data at 100hz for the whole study period. We will have to consider other placements of the sensor, namely the toe, although we expect very low acceptance due to comfort concerns. Although the plots show very low match of PSG and GT3X we must also explore other similarity measurements to understand the details of the accelerometer signal and get clues as to why it is not recording the movements.

The current study uses data from only two patients. The lack of a significant number of episodes and the number of patients is a limitation to the significance of the results. To achieve robust conclusions we need to recruit more patients in future studies.

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