APPROVAL SHEET

Title of Project: PERIODIC LEG MOVEMENTS DETECTION USING WEARABLE ANKLE BANDS

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ABSTRACT

Title: PERIODIC LEG MOVEMENTS DETECTION USING WEARABLE ANKLE BANDS
Prasad Akmar, Master of Science, 2019

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Sleep plays an vital role in one's well-being. Lack of Sleep can result into sleep disorders. Prolonged sleep disorders can result into severe health problems in heart, kidney and other organs [1]. The prevailing approach to study the sleep patterns and analyze the quality of sleep is by visiting sleep clinics and performing a polysomnography [2]. In a Polysomnography, the patient is monitored during the sleep and data is recorded using EMG, EEG and videos. The study analyzes the breathing abnormalities, brain activity, limb movements, sleep positions etc. to summarize the quality of sleep and diagnose a disorder. However, these studies are expensive and uncomfortable for patients due to the number of sensors being attached to them. We propose a in home, mobile and easy to use system, RestEaZe$^{\mathrm{TM}}$, that can predict the sleep quality based on wearable ankle bands. In this project, we have contributed to the system by analyzing the sensor data and identifying periodic leg movements and complex leg movements during sleep.

Periodic Leg Movements Detection Using Wearable Ankle Bands

by

Prasad Akmar

Project submitted to the Faculty of the Graduate School of the University of Maryland, Baltimore County in partial fulfillment of the requirements for the degree of Master of Science
2019

Dedicated to my mentors and friends at MPSS lab

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Chapter 1

INTRODUCTION

Sleep plays a vital role in ones well-being. Getting right amount of sleep at the right time along with good quality sleep is essential for maintaining the physical and mental health of a person as it helps the brain work properly and is also involved in the healing of heart and blood vessels [3]. Table 1.1 shows the amount of sleep a person of in an age group should have, to maintain a healthy lifestyle as recommended by the National Sleep Foundation

1.1 Motivation

Sleep deficiency has different effects on individuals from different age groups, for example, in youngsters and children it may hamper their growth and development while prolonged sleep deficiency in adults may lead to chronic health problems over time.

As per the American Sleep Association,

- 50-70 million US adults have a sleep disorder. 48.0% report snoring. 37.9% reported unintentionally falling asleep during the day.
- 4.7% reported nodding off or falling asleep while driving at least once in the preceding month.

- Drowsy driving during the day is responsible for 1,550 fatalities and 40,000 non-fatal injuries annually in United States.
- Insomnia is a most common sleep disorder. 30% of which have short term problems while 10% have chronic insomnia.
- 25 million U.S. adults have obstructive sleep apnea
- 37% of age group 20 to 39 years and 40% of age group 40 to 59 years report short sleep duration.

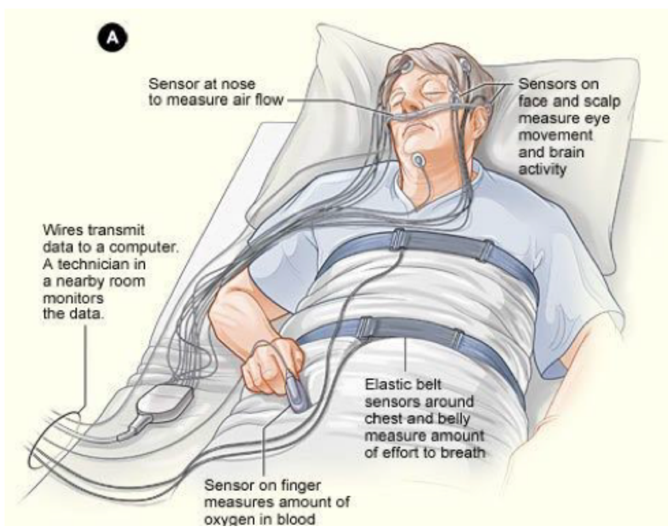

Fig. 1.1. Polysomnography

The primary method doctors use to diagnose some sleep disorders is by asking questions to patients about the sleep schedules. In cases where this is insufficient, doctors might advise the patient to go under sleep studies in sleep centers. These studies are painless non-intrusive tests that measure various parameters of the patient during a full night sleep. Some of the parameters that are monitored during the night include the brain activity, breathing, limb movements etc. The recorded results are then studied by a sleep expert and a treatment plan is decided. The currently prevailing approach for sleep studies is visiting the sleep centers , called Polysomnography. The technicians then visually score the videos which include characteristics like limb movements, body position, leg position, brain activity etc. These sleep centers are often very expensive and uncomfortable for the patients (include figure) . We are trying to build a comfortable, affordable and easy to use approach using wearable ankle band system (RestEaZe^{TM} described later), which records the position of the body through the night.

Chapter 2

RELATED WORK

2.1 Wearable sensors

The field of wearable sensors has been growing recently. Wearable technology to monitor older adults or people with chronic conditions have been some of the rising applications [4]. The commercial market now has a variety of choices of smart watches and health bands which track a persons daily routine and provide them with a feedback [5]. This feedback includes the amount of time they spent sitting down, walking, running, bicycling and sleeping. This is achieved by the various sensors that are embedded in the wearable products. These sensors include accelerometers, gyroscopes, magnetometers etc. Some of higher end medicine grade devices also provide heart rate monitoring. These monitored values are aggregated to create a history of their activities. One of their approaches was to measure the acceleration during movement and then find the displacement by taking the second integral of the measured acceleration. The approach is dependent on the user's body specifics and tracks position based on displacement. Our application involves minimum displacement. However, we considered their approach of calculating angles between axes. In another research [5], the authors are tracking activity of the patient by wrist and ankle mounted accelerometers. They have used the Single Magnitude Vector, SMV, given by: $SMV = \sqrt{AccX^2 + AccY^2 + AccZ^2}$ to detect motion.

2.1.1 Sleep Monitoring Devices

- Phone Apps: Mobile applications on both Android and Iphones make use of IMU sensor inside to determine the position of the subject and determine the movement accordingly. They work fairly accurately giving out total sleep time, light sleep and deep sleep.
  However they fall short in determining details like periodic leg movements, or complex leg movements. Subject can also feel uncomfortable keeping a phone inside the pocket all night long.

- Fitbit: One of the most popular health monitoring wrist bands. Along with heart rate monitor, step counts, it can also keep track of user's sleep patterns. They make use of the accelerometer and gyroscope sensors to measure user's hand movements during the sleep time, and calculate the sleep index along with user's respiration.
  These trackers are lightweight and user can easily get used to wearing them 24/7. However, it can not determine leg movements.

- Withings Sleep: It is a sleep tracking mat which the user has to keep on the bed. It tracks all the user movements during the night. It claims to auto-detect the events. It can measure deep sleep and shallow sleep ans well as REMs. All the data is transmitted to mobile based application via WiFi.

As per many user reviews, the readings are not always accurate. It misses some events. It can not determine leg movements.

- ResMed S+: This device is one of a kind non-touch sleep tracking device. It measures light, noise and temperature conditions in user's room. It syncs with user's smartphone to provide tailored feedback and suggestions on how to improve sleep routine and sleep conditions in the bedroom.

  Like all other devices, this also works with a smartphone app which it communicates with and sends data to. But is it is a non-touch device, it cannot measure body movements.

- PAM-RL: It is a wearable ankle band which the user has to wear on one of the legs. It uses IMU sensor to detect leg movements and keep track of PLMs.

  It falls short in determining complex leg movements, and hence cannot determine arousals. Another potential problem with this device may be that there is only one band and can go on either of the legs, cannot be on both the legs.

System	Location	Leg Activity	PLM	Arousal
Phone Apps	Pocket	No	No	No
Fitbit	Wrist	No	No	No
Withings Sleep	Mat	No	No	No
PAM-RL	Ankle	Yes	Yes	No
RestEaZe	Ankle	Yes	Yes	Yes

Table 2.1. Advantages of RestEaZe™ over existing sleep monitoring systems

Table 2.1 shows the existing sleep monitoring devices and how they compare with RestEaZe

2.2 Relevance of Leg Movements During Sleep

Leg movement in sleep can provide a lot of information about a one's health and well-being. A person suffering from a sleep disorder has certain type of periodic, or complex leg movement. These movements can be classified into following types:

2.2.1 Periodic Leg Movements of Sleep (PLMS):

The classic periodic dorsiflexion of the foot at the ankle produced by activation of the anterior tibialis muscle. As the name suggests, a particular type of leg movement is repeated within a certain interval of time. PLMS reveal possible medical conditions such as restless legs syndrome (RLS), sleep apnea, and REM behavior disorder.

2.2.2 Complex Leg Movements during Sleep (CLMS):

CLMS is detection of more complex, slightest of the sudden movements of leg during sleep. CLMS patterns reveal texture and severity for sleep-behavioral intervention.

Chapter 3

SYSTEM DESIGN

3.1 RestEaZe^{TM} System

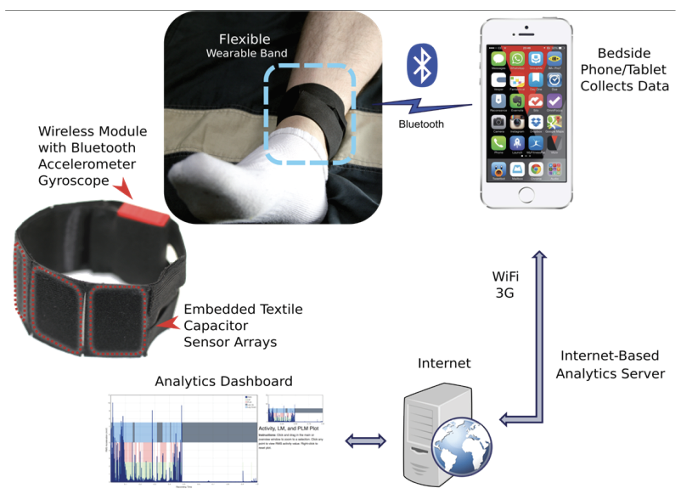

FIG. 3.1. RestEaZe^{TM} System

RestEaZe^{TM} is a sleep monitoring system designed with the goal to overcome the cost and convenience issues faced in a sleep lab study. It is an affordable product and service that patients can take home and use in their natural sleep setting. The system tracks the leg movements made by the patient during the night and translates them to a sleep quality measure based on specific types of movements identified by sleep science laboratories.

RestEaZe^{TM} is made of three pillars as seen in Fig.3.1.

1. Wearable Ankle Bands
2. Mobile Application
3. Back End System

3.1.1 Wearable Ankle Bands

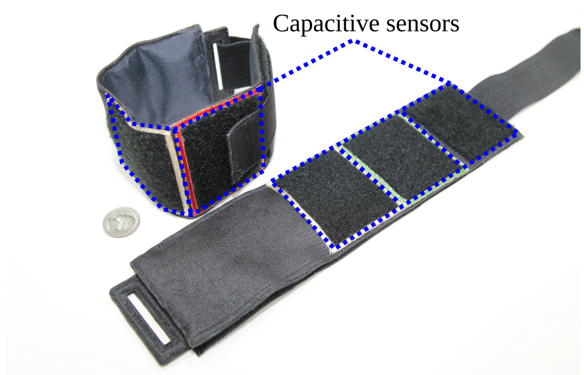

FIG. 3.2. RestEaZe^{TM} Wearable Ankle Band

Every system has two wearable ankle bands, each of which is equipped with a sensor array of three capacitive plates, a three-axis accelerometer and a gyroscope. It also consists of a low power Bluetooth sensor to communicate with the smartphone, and a small 400mAH battery to power them. Capative sensor used primarily to detect the periodic leg movements (PLMS). It also measures the capacitance change to wake the up the IMU sensor which detects complex leg movements (CLMS) with help of the accelerometer along with the gyroscope, hence making the system run much longer with the available small battery.

The sensor readings are then recorded and stored on chip memory or streamed back to the smartphone to store, based on the operating mode of the band. Fig3.2 shows how the sensors are put together on the ankle band.

3.1.2 Mobile Application

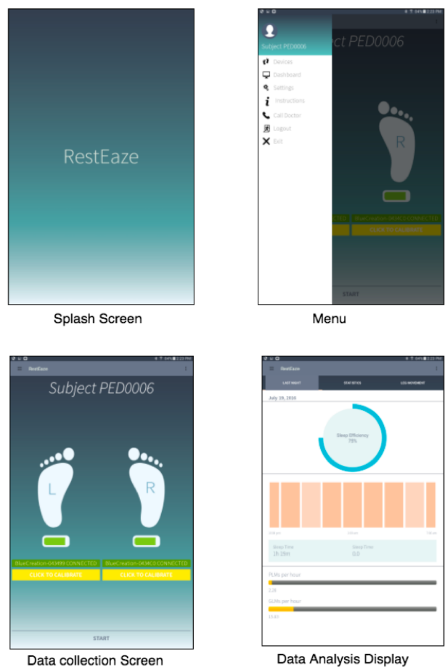

FIG. 3.3. Mobile Application

The mobile application connects two ankle bands simultaneously over Bluetooth. The application offers a basic user login which helps maintain user profiles. It also offers one time configuration of the bands and then is responsible for automatically connecting to bands once started. The applications user interface has been designed targeting maximum population and minimum complication. The user can calibrate the bands, Start and Stop the data collection, configure the system to work in streaming mode or caching mode and configure whether the data received should be uploaded to the server or written to files locally by the settings provided in the app. The calibration offset values for all the sensors, the start time of data collection and the stop time of data collection is stored by the application in the form of sessions, to a metadata file. Each time a user hits Start, a new session is generated. That session is active until the user hits Stop. The data received over Bluetooth is saved to a database and gets either uploaded from the database to a server or written to files locally. In Fig 3.3, we can see the user interface of the mobile application.

3.1.3 Back End System

FIG. 3.4. Back End System

The mobile application communicates with the back end system via Bluetooth to store the data collected from the sensors. The data is then analyzed using a custom made software to detect number of periodic movements, number of complex leg movements, number of arousals during the time, wake after sleep onset duration, and sleep efficiency. We will have a brief look at the analysis in the next section. Fig3.4 shows visual representation of a user's sleep data analysis.

3.2 Sleep Data Analysis

The data stored from the mobile application is in form of a CSV file format. The python program accepts the data for both left and right legs. Following are the parameters which are stored for each leg band over the period of a subject's sleep time.

Sr. No	**Features**
1	Accelerator X-axis
2	Accelerator Y-axis
3	Accelerator Z-axis
4	up2Down1
5	Timestamp
6	Gyroscope X-axis
7	Gyroscope Y-axis
8	Gyroscope Z-axis

Table 3.1. Caption

The flow of calculating leg movements, complex leg movements, sleep index, wake-after-sleep-onset goes like follows:

1. Synchronize both leg bands data

    - The data for both left and right leg is fed to the program. And due to certain reasons like sensor inactivity, malfunction or battery, time for both bands data needs to be synchronized. In this function, we set the start time of the tracking as same to synchronize.

2. Calculate RMS

   - We calculate root-mean-square value of the accelerometer data for both legs, which we will use in future steps.

3. Computer LM movements

   - The function accepts predefined parameters related such as threshold values, minimum and maximum threshold durations of periodic movements, etc and the RMS values, up2down1 value - indicating whether the patient is awake or asleep and returns matrix of leg movements having minimum duration of 0.5 seconds and no max duration.

4. Calculate CLM

   - Once leg movements for both legs are identified, we try to find out complex leg movements (CLMS). we use the leg movements identified by the previous function as an input, along with fixed threshold value parameters and return identified CLMs.
   - Using some threshold value parameters, we identify bilateral movements which are consisting of multiple monolateral movements longer than a fixed time interval, those are flagged as CLMs.

5. Indentify Arousals

   - The CLMs are output of the previous function is used here along with the original input data to identify possible arousals.

- Based on the CLM data for the exact time in band data, based on the user is awake or asleep, the accelerometer, gyroscope sensors are used to calculate MaxActivity, and AUC activity of the legs. These values will further be used to identify patterns in the leg movements.

6. Calculate Periodic Leg Movements based on Arousals and CLMs

   - The CLMs we identified earlier are primarily used here along with a few predetermined values with some medical studies to identify periodic leg movement patterns in some type of leg movements over time. There are threshold values for time and movement lengths considered which are identified by medical standards.
   - To have clarity on a periodic movement, the intermediate leg movements occurring between two periods are accompanied with a break-point. The CLMs are then checked for re-occurring movements and identified accordingly.

7. Additionally, Calculate patient Sleep Score Index, Wake-After-Sleep-Onset (WASO).

   - Sleep index is identified with help of PLMs, CLMs and RMS value. We identify number of PLMs and CLMs per 10 epoch. Similarly the amount of time the patient was awake is used to identify the time of deep sleep, compared to the ideal sleep standards and a numeric result is generated.
   - The Wake-After-Sleep-Onset contains parameters like sleep start time, number of times the patient woke up after sleep, the duration of the sleep and the average duration of each waking period. Threshold values for minimum sleep time, up2down1 and sampling rate are considered.

Chapter 4

EXPERIMENTS & RESULTS

We feed the program the leg movements data and it results with providing various sleep related parameters. The MATLAB counterpart of the program is considered as the standard to which the current program output is compared with.

4.1 Input & Output parameters

Input	**Output**
Left Leg datafile Right Leg datafile Patient ID	Patient ID Record Start Record Stop Total Sleep Time PLMS/hour Arousals/hour Sleep Efficiency Sleep Quality WASO

Table 4.1. Result Parameters

Similar to its MATLAB counterpart, the program accepts files in the leg movement data files in pairs. Each pair consists of data files for left and right leg data respectively. The patient ID is also provided along with the file names.

The program is expected to output a text file with parameters described in table 4.1.

1. Patient ID: Patient identification number
2. Record Start: Clock time of start of the recording
3. Record Stop: Clock time of stop of recording
4. Total Sleep Time: Total time the patient was asleep
5. PLMS/hr: Avg. Periodic Leg Movements observed per hour
6. Arousals/hr: Avg. number of arousals observed per hour
7. Sleep Efficiency: Efficiency of a whole night sleep session
8. WASO: Wake-After-Sleep-Onset value

For this experiment, We executed the Python program and the MATLAB program on same input files and compare their outputs.

4.2 Experimental Results

We have used annotated data from 6 different sleep studies for the implementation of this project.
The patients are regular patients who are being treated at the hospital. We cannot share additional information about the patients.

4.2.1 Results Comparison:

Following is the the output of the program compared with the MATLAB code.

Experiment 1 01_15_2019_Rightsleep1

	MATLAB	Python
Record Start	18:59	18:59
Record Stop	06:38	06:38
Sleep Efficiency	0.84	0.84
Total Sleep Time	589.02	589.02
PLMS/hr	0.00	0.00
Arousals/hr	0.00	0.00
Sleep Quality	0.00	0.00
WASO	110.0	110.0

Table 4.2. Experiment 1

Experiment 2 01_18_2019_Leftsleep1

	MATLAB	Python
Record Start	19:00	19:00
Record Stop	03:35	03:35
Sleep Efficiency	0.84	0.84
Total Sleep Time	435.00	435.00
PLMS/hr	0.00	0.00
Arousals/hr	0.00	0.00
Sleep Quality	0.00	0.00
WASO	80.42	80.42

Table 4.3. Experiment 2

Experiment 3 01_17_2019_Leftsleep1

	MATLAB	Python
Record Start	18:59	18:59
Record Stop	03:13	03:13
Sleep Efficiency	0.87	0.87
Total Sleep Time	430.79	430.79
PLMS/hr	0.00	0.00
Arousals/hr	0.00	0.00
Sleep Quality	0.00	0.00
WASO	64.00	64.00

Table 4.4. Experiment 3

Experiment 4 01_16_2019_Leftsleep1

	MATLAB	Python
Record Start	18:59	18:59
Record Stop	01:02	01:02
Sleep Efficiency	0.70	0.69
Total Sleep Time	253.51	251.00
PLMS/hr	0.00	0.00
Arousals/hr	0.00	0.00
Sleep Quality	0.00	0.00
WASO	110.00	112.51

Table 4.5. Experiment 4

Experiment 5 01_17_2019_Rightsleep1

	MATLAB	Python
Record Start	19:00	19:00
Record Stop	03:12	03:12
Sleep Efficiency	0.87	0.87
Total Sleep Time	428.26	428.26
PLMS/hr	0.00	0.00
Arousals/hr	0.00	0.00
Sleep Quality	0.00	0.00
WASO	65.00	65.00

Table 4.6. Experiment 5

Experiment 6 01_16_2019_Rightsleep1

	MATLAB	Python
Record Start	18:59	18:59
Record Stop	23:22	23:22
Sleep Efficiency	0.83	0.83
Total Sleep Time	218.03	218.03
PLMS/hr	0.00	0.00
Arousals/hr	0.00	0.00
Sleep Quality	0.00	0.00
WASO	45.00	45.00

Table 4.7. Experiment 6

Chapter 5

CONCLUSION

In our study, I used data collected from six patients with help of the leg bands, overnight to calculate the Periodic Leg Movements, Complex Leg Movements during sleep, Sleep efficiency and Sleep Score indicating the quality of the sleep. While working on the I observed that we have to take in consideration the external factors like the reliability, accuracy of the sensor data, and battery of the sensor. The data collected overnight from both the leg bands (left and right) needed to be synchronized to first to be able to consider it for further identifying leg movements and patterns. The results of the a sleep monitoring system that uses leg movements as a marker for arousals, restless sleep, and as an aid for diagnostics of sleep-related disorders such as RLS and ADHD.

Appendix A

APPENDIX

A.1 Sleep Disorders

Sleep disorders represent some of the most challenging medical conditions and effect 1 in 3 people at some stage of their lives. Here are some major sleep disorders which have severe health risks:

- Restless Legs Syndrome: RLS is a condition that causes an uncontrollable urge to move your legs, usually because of an uncomfortable sensation [6].

- Attention Deficit Hyper Activity Disorder: ADHD is a disorder that makes it difficult for a person to pay attention and control impulsive behaviors. He or she may also be restless and almost constantly active

- Sleep Apnea: It is a serious sleep disorder that occurs when a person's breathing is interrupted during sleep [6].

- Insomnia: Insomnia refers to trouble falling or staying asleep. In rare cases, it can be fatal.

- Narcolepsy: It is a sleep disorder characterized by excessive sleepiness, sleep paralysis, hallucinations, and in some cases episodes of cataplexy [7].

- Circadian Rhythm Disorder: Your circadian rhythm can get out of sync for a variety of reasons. For example, the demands of a job, newborn baby or travel can disrupt your body clock. When your internal rhythm is off, it can affect your sleep [6].

- Snoring: Snoring is the sound of turbulence and soft tissue vibration in the back of the throat. The sound of snoring generally does not come from the nose. Rather, snoring sound occurs in the back of the airway.

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