Smartwatch: Performance Evaluation for Long-Term Heart Rate Monitoring

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***Abstract*—Recent advancement in wearable technologies, particularly smart watches embedded with powerful processors, memory subsystems with various built-in sensors such as accelerometer, gyroscope and optical sensor in one single package has opened a whole new application space. One of the main applications of interest is the monitoring of movement patterns, heart rate, ECG and PPG particularly for longer duration's in natural environments. In this study, we conducted a performance evaluation on the optical heart rate sensor of the smartwatch with respect to the commonly used ECG and PPG devices. Results have shown that the heart rate acquired from the smartwatch is reasonably accurate with a high degree of correlation. Further, we conducted a preliminary exerise to evaluate sleep quality using the heart rate readings and accelerometer readings captured from the smartwatch and compared with a commercially available and clinically used non-contact sleep sensor, RESMED S+.**

I. INTRODUCTION

Monitoring heart rate continuously in natural settings can have significant impact on treatment plans on patients with heart conditions as number of studies have highlighted heart rate as a physiological parameter of importance for condition such as coronary heart diseases [1]. Heart rate provide some information regarding the efficiency and the functionality of the cardiovascular system [2]. Heart rate variability (HRV) is a measure commonly used to estimate the cardiac autonomic modulation (temporal variation between sequences of consecutive heart beat [3]) as well as a prediction and monitoring tool for disease progression in congestive heart failure[4]. Further, it is also proven to be essential and apparent in post cardiac transplantation patients where HRV is markedly reduced [4], [5].

Conventionally, there are a number of methods used for heart rate recording which includes electrocardiogram (ECG) and photoplethysmogram (PPG), i.e. pulse oximeter. In typical clinical environments and or in organized clinical trials, heart rate measurements are performed using ECG [6]. The use of ECG machine is limited due to complexities in setting up and generally unaffordable cost involved particularly for home-based and long-term monitoring applications. Since we are specifically looking monitoring in home based setting and longer term use, PPG (i.e. pulse oximeter) is not well suited either for the targeted applications due to the discomfort caused from the fingertip probe and the additional connector although it meets the expectation in most applications in terms of size and cost.

(a) LG smartwatch [9] (b) RESMED S+ [10]

Fig. 1: Example of devices used in the Experiment Trials

The advancement of technologies has made the sensing of certain human physiological signs and movements possible with integrated systems where accelerometers, gyroscopes, magnetometer and heart rate monitors are combined into a single device. One example of such devices is the smartwatch. Since then, wearable watch is gaining popularity and used for various activities ranging from normal activity tracking [7] to medical use of analysis and diagnosis of tremor [8]. The key questions is can we extend the use of smartwatch in various home-based applications with necessary reliability.

In this study, we investigated the performance of the heart rate sensor of the smartwatch and compared with the ECG measurement system and the pulse oximeter. Further, we conducted preliminary studies on monitoring movements during sleep utilizing the accelerometers in the smartwatch and a commercially available sleep monitoring sensor. This paper is organized as follows. Section II briefly describes the experimental mechanism. Evaluation and data analysis is given in section III. The conclusions and further discussions on this study is given in section IV.

II. EXPERIMENTAL MECHANISM

Two different types of experiments were carried out in this study to evaluate the accuracy of heart rate sensor in the smartwatch and its feasibility in providing some meaningful information for sleep monitoring applications.

The first experiment was aimed at evaluating the accuracy of the smartwatch (LG G Watch R) heart rate sensor in comparison to the Pulse Oximeter (CMS-60D) and Electrocardiography (ECG- PowerLab & ADInstruments) [11] measurements. Both the pulse oximeter and the ADInstruments ECG are commercially available and widely used in heart rate monitoring [12], [13], [14], [15] applications. Some of the devices used in the experiment are shown in Fig.1. Four volunteer subjects were wearing the smartwatch with the pulse oximeter attached to the index finger and the 3-lead ECG to the body. Each data acquisition session lasted for approximately 10 minutes. The readings from both pulse oximeter and the ECG served as the ground truth in evaluating the accuracy of the smartwatch with heart rate measurements.

The second experiment was aimed at investigating the feasibility of using the smartwatch in sleep monitoring applications. For this purpose, the heart rate and the accelerometer readings from the smartwatch were recorded. Ensuring the subject sleep is not interfered in anyway, a commercially available non-contact sleep sensor (RESMED S+)[10] was used in this trial. S+ is a non-contact Doppler based device that can track the breathing and movements accurately. Other studies reported using Doppler radar to capture accurate respiration patterns and functions were demonstrated in [16]. S+ operates based on listening to the echo of a transmitted pulse at 10.5 GHz. The use of S+ is to obtain a better understanding of the sleep patterns in relation to the heart rate as well as the movement (i.e. jerks of hand or motion of body) captured by the smartwatch (Accelerometer & PPG (Heart rate monitor)). For this experiment, all the respective data were acquired for a duration of 4-6 hours of sleeping.

III. Results and Analysis

A. *Preprocessing*

Smartwatch not only provided the heart rate information but also the accuracy level of the measurements in terms of five categories: high, medium, low, unreliable and non-detected. The accuracy level was low, unreliable or even not detected for a small duration due to certain body movements during sleep. We performed a smoothing and fitting operation around missing data points to compensate the missing information. Nevertheless, these instances are not very common as long as the smartwatch is attached properly to the subject's wrist. Subsequently, all the readings from all three devices were re-sampled and synchronized prior to further analysis. The Fig. 2 shows the a typical heart rate signal recorded for a duration of approximately 10 minutes from the three distinct devices from a single subject.

B. *Statistical analysis of the device accuracy*

When evaluating the accuracy of the device, we analyzed the deviations of the smartwatch readings from the reference signals; the ECG Powerlab and Pulse Oximeter. The comparisons were made by calculating the root mean square error (RMSE) and the standard error (SE) between data from smartwatch (X) compared to the reference data (Y) from ECG Powerlab/Pulse Oximeter,[17], [18]. The two term of errors were calculated based on equation (1) and (2).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}(X_i - Y_i)^2}, \qquad (1)$$

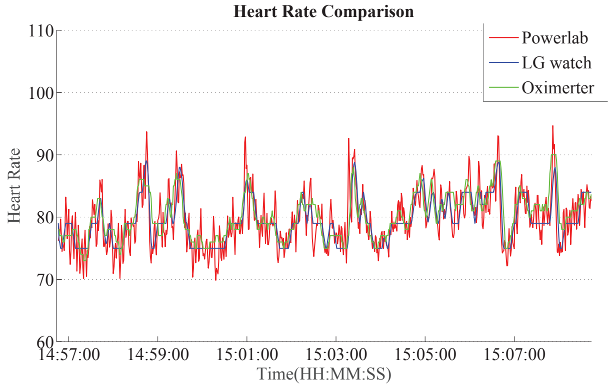


Fig. 2: Heart rate comparison between the three devices

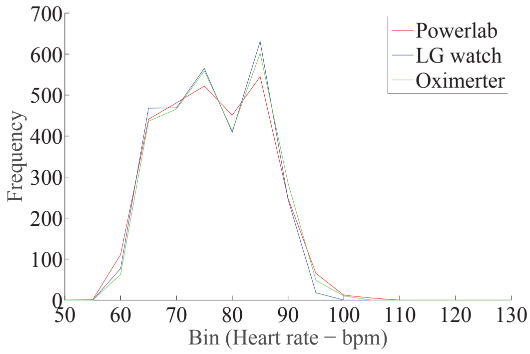


Fig. 3: Heart rate distribution of the four subjects

where X is the heart rate data from smartwatch, Y is heart rate data from the reference device, and n is the number of recorded data of X and Y.

$$SE = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(E_i - \mu)^2}, \qquad (2)$$

where $\mu = \frac{1}{n}\sum_{i=1}^{n} E_i$ is the mean of the error $E = (X - Y)$. Correlation is often used to measure the similarity of two signals which is calculated using equation (3).

$$corr(X,Y) = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2(Y_i - \bar{Y})^2}}, \qquad (3)$$

where $\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$ and $\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Yi$.

Detailed analysis of the data from the four subjects are shown in TABLE I and TABLE II. The average error shows an acceptable values between the smartwatch and the reference signals where RMSE is 3.48 bpm for Pulse Oximeter and 3.54 bpm for ECG Powerlab and SE is 2.29 bpm for both devices. Computed correlation coefficients is around 0.89 - 0.9 where value '1' correspond to the perfect correlation. Furthermore, the heart rate distribution frequency from all devices for all the subjects are plotted in Fig. 3.

The results indicated a significant correlation and a non-significant error between the evaluated heart rate and reference

TABLE I: ERROR EVALUATION BETWEEN SMARTWATCH AND REFERENCES

Subject	Pulse Oximeter		ECG Powerlab	
	RMSE(bpm)	SE(bpm)	RMSE(bpm)	SE(bpm
1	5.16	3.59	5.88	3.99
2	2	1.26	2.58	1.64
3	4.06	2.45	3.02	1.8
4	2.68	1.85	2.69	1.71
Average	**3.48**	**2.29**	**3.54**	**2.29**

TABLE II: MEAN AND STANDARD DEVIATION OF HEART RATE FOR FOUR SUBJECTS

Subject	Mean (bpm)			STD (bpm)		
	Powerlab	Oximeter	Smartwatch	Powerlab	Oximeter	Smartwatch
1	87.04	87.51	85.64	4.23	3.07	3.95
2	79.53	80.19	79.51	4.35	3.53	3.74
3	72.69	73.44	72.77	3.98	3.21	3.20
4	65.62	65.62	65.40	3.33	2.66	2.72

heart rate. In this first part of experiment, the evaluation was conducted with four normal subjects without any external activities. In the future, more subject will be trialed with other possible deciding factors, i.e. during exercise to further improve the robustness and the reliability of the smartwatch.

C. *Smartwatch in sleep monitoring application?*

A large number of studies from different perspectives have been carried out to quantify the quality of sleep using professional medical devices which are expensive and typically only available in hospital setup or in sleep clinics. With the advancement of technology, researchers have turned into smartphone type devices to monitor sleep by observing body movements, sound during sleep utilizing built-in sensors such as accelerometer, gyroscope, etc. This is predominately due to the lack of data when sleeping in natural environments and hence the possibility that more subtle information can be captured with longer term monitoring [19], [20]. With satisfactory results and raised confidence with the measurements from the first experiment, we further investigate the use of smartwatch in sleep monitoring. The idea is to combined the acquired heart rate readings and the accelerometer readings simultaneously during sleep. The use of accelerometer in detecting the movement of arm and body can directly be interpreted from the more obvious and change in the acceleration readings, typically, any movement causes an increased value in the readings.

In Fig. 4, we illustrated an example on the variability in acceleration for three different movement intensities, namely; static, slow, and fast motion. It was observed that the acceleration increased as the repeated movements were becoming more intense. Using this characteristics, it could potentially be used to detect sudden movements or jerking during sleep based on the magnitude of the acceleration. In order to capture more information to understand sleep patterns and to verify

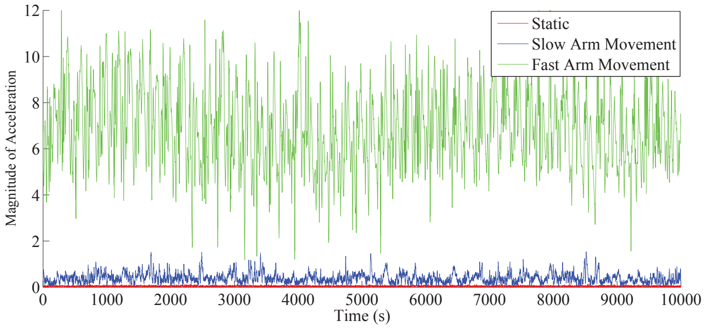


Fig. 4: Acceleration patterns for various Movements

TABLE III: DETAILED ANALYSIS OF SLEEP MONITORING FROM THE SMARTWATCH AND THE s+

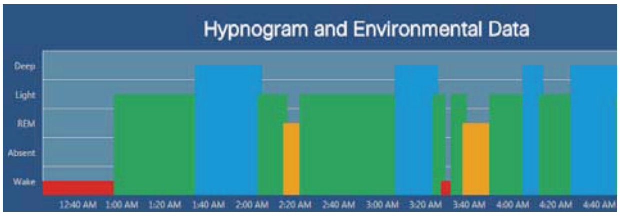
Start Time	End Time	Sleep Stage	No. Movements
0:23:00	1:00:59	Wake	5430
1:01:00	1:35:59	Light	607
1:36:00	2:04:59	Deep	0
2:05:00	2:15:59	Light	242
2:16:00	2:22:59	REM	0
2:23:00	3:06:59	Light	982
3:07:00	3:24:59	Deep	0
3:25:00	3:27:59	Light	0
3:28:00	3:32:59	Wake	315
3:33:00	3:38:59	Light	0
3:39:00	3:50:59	REM	434
3:51:00	4:05:59	Light	223
4:06:00	4:12:59	Deep	0
4:13:00	4:27:59	Light	289
4:28:00	4:48:59	Deep	0

the feasibility of smartwatch in sleep monitoring applications, the commercial S+ device is used at the same time in this preliminary assessment to verify the assertions made by the proposed system.

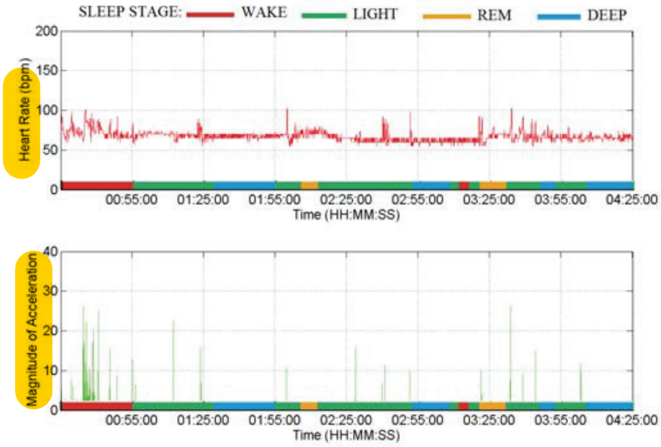
Fig. 5 displays the heart rate and acceleration recordings during the sleep (4 hours) along with the sleep pattern results from S+. Based on the result of S+, we calculated the number of movements during each sleep stage. A single movement can be considered as a peak of the acceleration magnitude from the accelerometer readings. A detailed result is shown TABLE III. Number of movements are highest during the wake stage as expected and higher during light and REM stage compared to the deep sleep stage. Indeed the changes in the heart rate does correlate to body movements enabling us to monitor heart rate to acquire an understanding of the movements during sleep. For sleep studies involving a large number of subjects possibly with various physiological conditions, it will be particularly useful to use a single easily wearable device where data can be captured for an extended duration.

IV. Conclusion

In this study, we evaluated the feasibility and the potential to use a smartwatch equipped with specific sensor types such as heart rate monitors and accelerometers for monitoring of certain parameters of interest in sleep studies. A higher corre-



(a) Sleep stages from RESMED S+



(b) Heart Rate and Acceleration Monitoring from smartwatch

Fig. 5: Sleep Monitoring from Smartwatch and RESMED S+

lation as high as 90% was observed using the optical heart rate sensor of smartwatch against the two commonly used devices, ECG Powerlab and Pulse Oximeter. We have also conducted a preliminary assessment on sleep monitoring utilizing the heart rate sensor as well as the acceleration readings from the smartwatch. The results demonstrated confirmed the existence of a relationship between the sleep stage, heart rate variability and movements during sleep. However, the number of subjects involved are small and more experimental analysis need to be carried out with a larger number of subjects in order to confirm the assertions made in this preliminary analysis.

The use of smartwatch for health-monitoring can open up multitude of applications particularly in health care service as some work has already been conducted in reviewing various heart rate monitoring system for different purposes, e.g. stress test, sleep tracking, physical activity analysis, etc. [21], [22], [18], [17]. Thus, more rigorous research in extending the use of smartwatch in various applications, i.e. in sleep monitoring (sleep stage and occurrence of sudden movement) and assessment of activities of daily life(ADL). Indeed information based on longer term monitoring of subjects in their natural environment has the potential provide deeper understanding of numerous disorder, behaviours that has not been possible in the past.

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