Preliminary Analysis of the Use of Smartwatches for Longitudinal Health Monitoring

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***Abstract*—New generations of smartwatches feature continuous measurement of physiological parameters, such as heart rate, galvanic skin resistance (GSR), and temperature. In this paper we present the results of preliminary analysis of the use of Basis Peak smartwatch for longitudinal health monitoring during a 4 month period. Physiological measurements during sleep are validated using Zephyr Bioharness 3 monitor and SOMNOscreen+ polysomnographic monitoring system from SOMNOmedics. Average duration of sequences with no missed data was 49.9 minutes, with maximum length of 17 hours, and they represent 88.88% of recording time. Average duration of the charging event was 221.9 min, and average time between charges was 54 hours, with maximum duration of the charging event of 16.3 hours. Preliminary results indicate that the physiological monitoring performance of existing smartwatches provides sufficient performance for longitudinal monitoring of health status and analysis of health and wellness trends.**

I. Introduction

The smartwatch industry is fast growing, from USD 1.3 billion in 2014 to expected 117 billion in 2020 [1]. New generations of watches, such as Basis Peak [2], feature continuous measurement of physiological parameters, such as heart rate, galvanic skin resistance (GSR), and temperature. Basis Peak receives messages and notifications that are potentially very useful for ubiquitous monitoring applications. Basis watch wirelessly syncs with an iPhone or Android phone app. The trend is expected to accelerate with the introduction of Apple Watch [3].

Smart sensors, such as pedometers, sleep monitors, and smartwatches, facilitate one of the main trends in big data science – the quantified self (QS) [7][8]. QS community is engaged in self tracking or group tracking of physiological, behavioral, or environmental information. The community shares insights, approaches, and algorithms. New sensors and systems enable seamless collection of records and integration in databases that can facilitate data mining and new insights. Several companies created health kit toolsets, such as Google Fit, Apple HealthBook, Samsung S.A.M.I, and Microsoft Healthvault.

The smartwatch is worn more than any other wearable sensor or device. Due to the constant contact with the skin it may collect biological, environmental, and behavioral information about user's activity, and even identify the user.

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Reliability of measurements and lack of context of collected information is often cited as a major obstacle for wider use of ubiquitous wearable health monitoring. Applications of interests include analysis of physiological rhythms, such as circadian rhythms, and long term monitoring of trends of wellness indicators. In this paper we present analysis of use and reliability of continuous physiological measurements of Basis watch and comparison with the standard polysomnographic monitoring systems.

II. Methods

Preliminary analysis of the use and reliability of physiological measurements on the smartwatch includes a single male subject, age 54. In this paper we present analysis of continuous monitoring using Basis smartwatch during 122 days, or 173,410 measurements. The system stores measurement on the server at a rate of one measurement per minute [2].

Physiological measurements are validated with two standard monitors Zephyr Bioharness 3 and polysomnographic monitor SOMNOscreen+ during sleep. The watch is waterproof to 5 ATM, which means that it can be used in the water like a regular water-resistant sports watch. However, capacitive screen commands and heart rate monitoring are usually disturbed during washing or shower. Therefore, during this experiment watch was removed during showers, which introduces a missed sequence of records.

We define three classes of missed data events:

- *Smartwatch charging* is defined as interruption of more than 60 minutes,
- *Short breaks* represented by continuous missing records 10-60 minutes
- *Missed data events* are represented as continuous missing records of up to 10 minutes.

Typical example of a display representing daily activity can be seen in Fig. 1. A 3-hour charging event can be clearly depicted starting from 10 am, followed by the physical exercise around 1 pm. All measurements were downloaded in CSV format using iPhone Basis application.

Zephyr Bioharness 3 sensor [4] was used for recordings during sleep to compare measurements with recordings on Basis Peak. Bioharness 3 is a chest belt that monitors body position, activity, heart rate (RR intervals), breathing rate, and temperature. Bioharness was used consecutively for 44 days during sleep only.

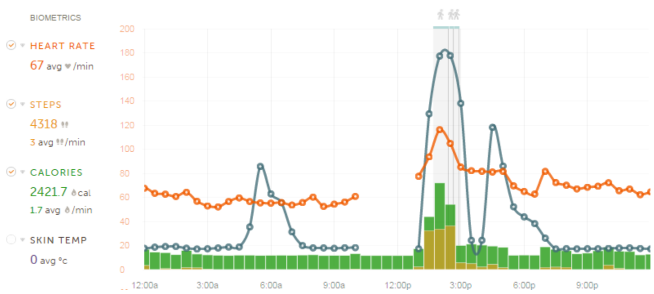

Fig. 1. Typical representation of daily activities on Basis portal.

SOMNOscreen+ is a clinical level polysomnographic monitoring system used in sleep studies. The system records data overnight and stores records on a flashcard or transmits wirelessly to a workstation. SOMNOscreen+ system was used for three nights as a standard for validation of measurements.

III. Results

We collected total of 173,410 records (120.42 days). We used iPhone Basis application to download all records in the experiment. Individual measurements missed because of the lack of proper contact, or because the watch was not used, are represented as empty fields in the downloaded CSV file. Analysis of the data sequences is represented in Table I.

TABLE I. Analysis of the Data Sequences

Error sequence [min]	Number of seq	Total duration [min]	Mean duration [min]	Total percent [%]
No missed data	3,090	154,126	49.88	88.88%
1-10	2,965	5,904	1.99	3.40%
11-60	73	1,621	22.21	0.93%
> 60	53	11,759	221.87	6.78%
Total	**6,181**	**173,410**		**100.00%**

Overall, 11.12% of records were missing. Length of correct sequences is important for some applications, such as assessment of physiological rhythms. Distribution of missed sequences of different length is provided in Table II. Missed sequences of up to 10 minutes can be attributed to missed data due to the poor contact or motion artifacts. It is clear that 3.4% measurements have missed data sequences of less than 10 minutes, and half of them are sequences of 1-2 lost samples that can be corrected by interpolation between known samples without significant influence on signal processing and analysis. Relative contribution of data sequences is represented in Fig. 2. Typical records and monthly averages are presented in Fig 3 (skin temperature) and Fig. 4 (heart rate). SOMNOscreen+ record had significantly smaller sequences of lost data. Total ratio of lost data for the whole night recording (7 hours and 52 minutes) is 1.43%. Fig. 5 represents a segment of recordings from SOMNOscreen+ and Basis Peak.

Zephyr Bioharness 3 has been used for monitoring during sleep for 44 consecutive nights. Average length of the lost data records was 417.28 seconds, or 1.74% with standard deviation of 1.4 % and maximum of 5.87% of the record.

TABLE II. Distribution of the Missed Data Sequences on the Smartwatch

Sequence length [min]	Number of seq	Total duration [min]	Total percent
1	1,598	1,598	0.92%
2	675	1,350	0.78%
3	296	888	0.51%
4	178	712	0.41%
5	92	460	0.27%
6	49	294	0.17%
7	39	273	0.16%
8	19	152	0.09%
9	13	117	0.07%
10	6	60	0.03%
Total	**2,965**	**5,904**	**3.40%**

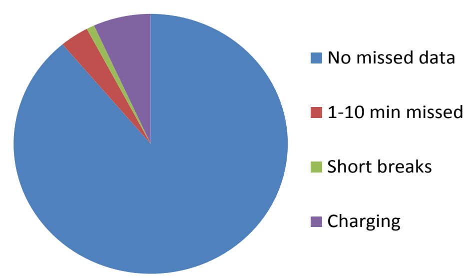

Fig. 2. Distribution of data sequences

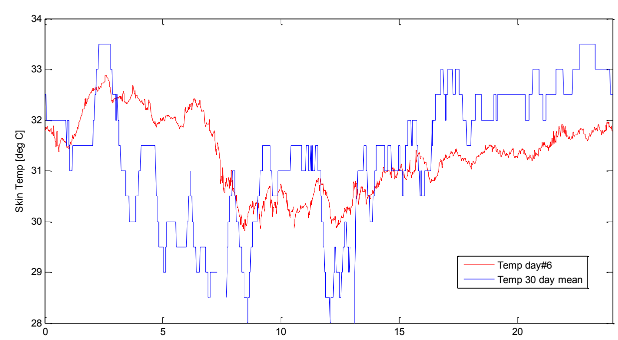

Fig. 3. An example of the daily change of skin temperature measured on the Basis Peak smartwatch and a 30 day average for the same period.

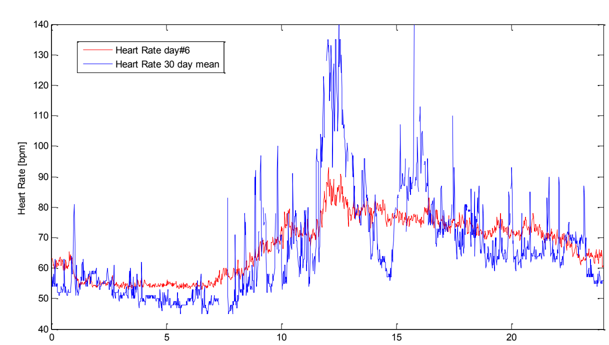

Fig. 4. An example of the daily change of heart rate measured on the Bais Peak smartwatch and a 30 day average for the same period.

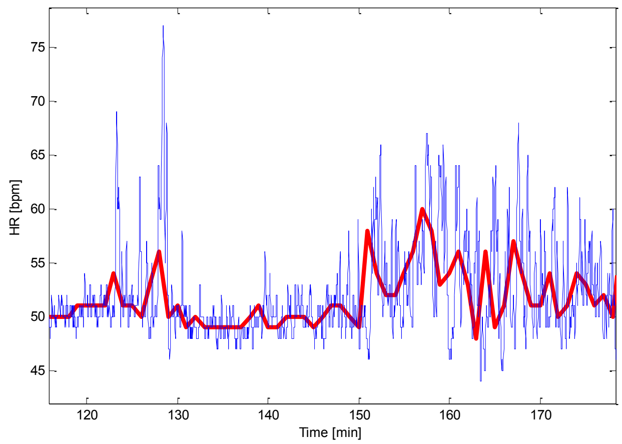

Fig. 5. Heart rate from the PPG sensor of SOMNOscreen+ (blue line, Fs=4Hz) and Basis Peak (red line, Fs=1/60 Hz);

We analyzed the difference between average heart rate measured by Basis Peak smartwatch and Zephyr Bioharness 3 belt measured at 4 am for 5 minutes, for 30 days. The average difference was 0.89 bpm with standard deviation of 1.03 bpm, and maximum difference was 3.13 bpm.

IV. Discussion and Conclusion

Introduction of continuous physiological monitoring on smartwatches may revolutionize the field of mHealth and longitudinal monitoring. Smartwatches provide unprecedented opportunity for collection of large data sets that can be used for individual monitoring as guidance and monitoring of specific patient populations. In this paper we presented preliminary results of analysis of the use and reliability of physiological records collected with the smartwatch. We conclude that the current state of the smartwatch technology provides sufficient performance for longitudinal monitoring of health status and analysis of health and wellness trends.

In this paper we analyzed the performance and use of the Basis Peak, as the first smartwatch featuring continuous monitoring of heart rate. Apple Watch is expected to provide similar functionality, but it was not commercially available at the time of writing.

Continuous monitoring and analysis of different conditions require different features and sensor performance.

The most important features of the smartwatch based physiological monitoring systems include:

- *Wearability*. Several factors influence wearability of sensors: size, weight, skin irritation, and tightness/pressure.
  - *Size and weight* of the smartwatch significantly influence the frequency of use of the smartwatch. This is particularly critical for fragile population, such as elderly. Early smartwatch products were relatively heavy and bulky, although new generations feature much more acceptable size and weight of the smartwatch. This is certainly the case with Basis Peak.
  - *Skin irritation.* The main causes of skin irritation are the belt and elevated part of the light sensor. Belt width and softness are extremely important for the prolonged use. Optical sensor features an elevated, dome like, structure to allow better contact with the skin. However, the sensor creates more pressure at the contact with the skin. Moreover, reliable monitoring requires tight contact with the skin, much tighter than the regular watch. We experienced limited irritation after 12-24 hours of the use of Basis Peak, depending on the tightness of the belt. Most manufacturers advise users to make breaks and change watch location to the opposite hand periodically. This could be an important issue for the elderly population, which is an important long term monitoring application. A softer and more flexible belt would improve user comfort. A variety of alternative belts have been introduced at the time of writing.
- *Immunity to artifacts*. Wrists are not very convenient for physiological sensors, mostly because of the motion artifacts, access to the skin (e.g. hairy skin), or skin complexion (darker skin provides less reliable measurements). However, embedding sensors in objects that are regularly used, such as watch, is a great idea. There are several ways to improve precision of the watch sensors:
  - *Additional sensors* can provide more robust measurements at less noisy locations. Typical example would be the use of Bioharness belt around the chest. The belt would provide more reliable measurements in most cases; however, certain body positions, such as laying on the side during sleep, may cause poor electrode contact with the belt and lost measurements. Therefore, robust monitoring might integrate several sensing modalities. Measurements can be integrated on the phone or the smartwatch.
- *Sampling frequency.* Required sampling frequency is application dependent. Basis Peak saves by default average heart rate every minute (1440 measurements per day). However, new monitors allow “near real-time” monitoring of heart rate, that is of interest for most exercise monitoring applications. It is important to emphasize that exercise increases motion artifacts and reduces reliability of heart rate monitoring; however, at least one or two good measurements every 3-5 seconds provide sufficient information about the intensity of measurement. Basis Peak automatically switches display to “exercise monitoring” if walking or running is detected. By default the watch still saves heart rate only every minute, even in the case of exercise.

- *Streaming of RR intervals* is very important for some applications, such as biofeedback applications. Basis Peak allows streaming of heart rate in near real-time. Accuracy of optical sensors is currently not sufficient for the heart rate variability analysis, but real-time monitoring of heart rate could be useful in a number of applications.
- Current performance of smartwatches is sufficient for monitoring of some long term parameters, such as resting heart rate, or early morning resting heart rate.

- *Personalization* of monitoring and presentation of information is very important for most users. The system should provide option for configuration and presentation of information.
- *Seamless data integration* is crucial for future analysis, personalization, and data mining applications. Repositories, such as Apple Health, allow automatic storage of records from the smartwatch, according to user's preferences. Currently, both Basis Peak and Apple Watch are directly supported. After enabling access, selected information is automatically stored and seamlessly integrated into the personal record. Android Wear and Google Fit also support seamless integration.
- *User identification* is currently limited to password protected access to data and configuration. Several groups experimented with the use of data stream for user identification, mostly in laboratory settings.

Advisable features include:

- *Connectivity*. Range of Bluetooth, commonly used for communication between smartwatch and a smartphone, could be a limiting factor for some applications. An alternative wireless interface, such as WiFi, or alternative gateway, such as home router, can significantly improve the performance for some applications.
- *Multisensory integration* may include other physiological sensors or integration with ambient sensors, particularly with emerging Internet of Things (IofT) systems.
- *Ambient temperature/barometric pressure* can provide very important context of measurements, such as detection of step climbing, or environmental conditions. Some smartwatches already provide additional sensors.
- *Context awareness* could be very important for data analysis. For example, sudden change of heart rate might be discarded if the motion artifact is detected using accelerometer on the smartwatch; also, stable increase of heart rate can be attributed to the increase of ambient temperature if the user goes outside. Other sources of information, such as calendar, can also provide valuable insights about the context of collected measurements.

Continuous monitoring and unstructured data collection create significant challenges for long term monitoring applications. Open research issues include:

- *Signal processing*. Typical problems include removal of artifacts, filtering, and processing of incomplete records caused by missed samples. Acceptable data loss is application dependent.
- *Sampling frequency* or *minimum set of signals* is very important for the overall performance of the application. Lower sampling frequency can significantly reduce power consumption and extend battery life, allowing longer uninterrupted montirong and improved wearability of the system.
- *User input/notes and annotations*. Many applications depend on user input, specialized questionnaires, or simple notes that can help with the annotation of the records. Typical example is reporting "chest pain" or "cold sweat" with time stamp that should be seamlessly integrated with physiological record in the database and used during analysis. Currently, this is responsibility of individual applications.

With the mass production of smartwatches with physiological sensors we expect a variety of models, features, and configuration options with decreasing price and extended battery life. Availability of technology and widespread use will facilitate collection of massive databases at the scale not possible even several years ago. New sensors inspire new startups that dramatically change diagnostic procedures and facilitate personalized and preventive healthcare [9]. However, it is very important to understand limitations of sensors and measured data sets.

This paper provides early insights into tradeoffs between user's convenience and reliability of measurements, and their applicability for the long term monitoring. This paper demonstrates that the current generation of smartwatches with physiological sensors already provides sufficient performance for some long term monitoring applications.

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