Mobile Health System for Evaluation of Breast Cancer Patients During Treatment and Recovery Phases

Joaquin Ollero[1], Jose Antonio Moral-Munoz[2], Ignacio Rojas[3], and Oresti Banos[4]

[1] City, University of London, United Kingdom
[2] Dept. Nursing and Physiotherapy, University of Cadiz, Spain
[3] Research Centre for Information and Communication Technologies, University of Granada, Spain
[4] Telemedicine Group, Center for Telematics and Information Technology, University of Twente, Netherlands

Abstract. Breast cancer is the most common tumor in western women and statistically 1 out of 8 women will develop breast cancer over their lifetime. Once overcome it, the stage of rehabilitation that the patient should follow is critical to recover from the suffered disease. In this paper, a system composed of three applications, one for smartwatches, one for smartphones and a web application, is presented. Applications for handheld devices are directed to the patient who is undergoing rehabilitation and allow to monitor parameters of interest, such as the heart rate, energy expenditure and arm mobility, that will indicate whether the rehabilitation process being followed is improving the health of the patient or not. The web application is directed to a medical expert with the objective of tracking rehabilitation conducted by the patients.

Keywords: Mobile health, mHealth system, Android, Android Wear, Smartwatch, Smartphone, Breast cancer, Heart rate sensor, Kinematics sensors, Energy expenditure, Arm mobility, Activity recognition.

1 Introduction

The Foundation for the National Institutes of Health defines mobile health or mHealth as the delivery of healthcare services via mobile communications devices [1]. The term is conceived as a conglomeration of hardware and software components, see mobile devices, a software platform that serves basic funcionality and applications that provide health services to the user [2]. In the recent past, philosophy and traditions were wrong placed: instead of focusing on healthcare, countries and behaviors were centered in sickcare [3]. This is shifting to a more preventive attitude. For example, health insurance in the United States is drifting to a direction in which companies are tending to reward people who exercise more and take care of their well-being [4].

Breast cancer is one of the most common cancers in the world and by far the most frequent cancer among women. It ranks as the fourth leading cause of death from cancer overall as shown in Figure 1 [5]. Complications of breast cancer therapies are common, like cardiovascular disease, which is fairly frequent and leads to morbidity, poor quality of life or premature mortality [6]. There has been an appreciable reduction in the breast cancer mortality rate over the past two decades, especially among women younger than 50 years of age (3.1% per year), attributable to improvements in early detection and treatment [7]. After treatment for breast cancer, follow-up care is important to help maintain good a health, manage any side effects from treatment, watch for signs that the cancer has come back after treatment and screen for other types of cancer. A supervised care plan may include regular physical examinations and other medical tests to monitor the recovery during the coming months and years.

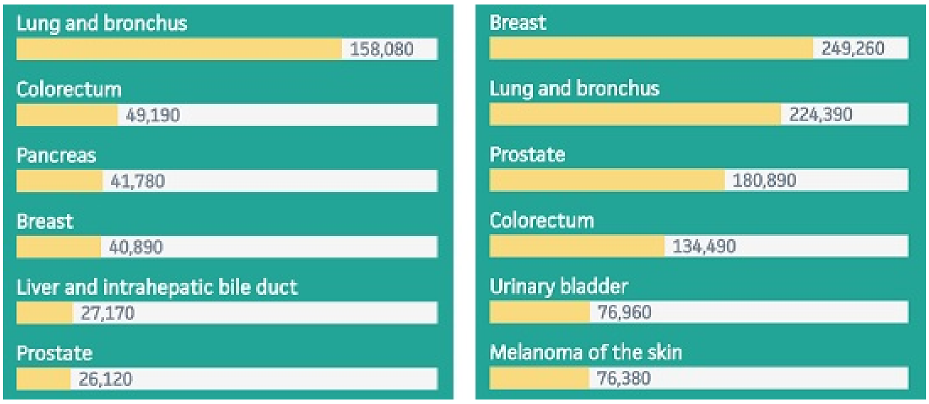

Fig. 1: *(Left)* Estimated deaths and *(right)* new cancer cases in 2016 by cancer type, both sexes combined. American Cancer Society.

Technology can greatly help those women who have had breast cancer and have overcome it. For example, Fitbit, an American company known for products like activity trackers, wireless-enabled wearable technology devices that measure data such as the number of steps walked, heart rate, quality of sleep, steps climbed, and other personal metrics, have announced a collaboration by partnering with the Dana-Farber Cancer Institute for breast cancer research [8]. The study will attempt to figure out if exercise helps prevent breast cancer from recurring.

Smartwatches are one of the most popular and powerful devices in wearable technology. These devices are effectively wearable computers, running applications using a mobile operating system, as Android Wear. The smartwatch industry is fast growing, from USD 1.3 billion in 2014 to expected 117 billion in 2020 [9]. New generations of watches feature continuous measurement of physiological parameters, such as heart rate. Smartwatches connect with accompanying smartphones and receive messages and notifications that are potentially very useful for ubiquitous monitoring applications. These devices are equipped with smart sensors, facilitating one of the main trends in big data science-the quantified self (QS). The QS community is engaged in self tracking or group tracking of physiological, behavioral, and environmental information [10]. 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 have created health kit toolsets [11], such as Google Fit or the Apple HealthKit.

The use of wearable sensors has made it possible to have the necessary treatment at home for patients after sudden attacks of diseases such as heart attacks, sleep apnea, Parkinson disease, cancer and so on. Patients after an operation usually go through the recovery process where they follow a strict routine. All the physiological signals as well as physical activities of the patient can be monitored with the help of wearable sensors [12]. During the rehabilitation stage the wearable sensors through media interfaces may provide audio feedback, virtual reality images and other rehabilitative services. The whole activity can be monitored remotely by doctors, nurses or caregivers [13]. Breast cancer rehabilitation can be linked to wearable technology, specifically smartwatches and smartphones, in order to facilitate the recovery from the disease.

In this work, we present a mobile health system for evaluation of breast cancer patients during treatment and recovery phases. The system comprises three different technologies and applications: an application for a smartwatch running on the Android Wear operating system, an application for a smartphone running on the Android operating system and a web server application that can be accessed from any device with an Internet connection. The patient, from the home environment and through the handheld applications, will be able to monitor parameters of importance and send them to the server so the medical expert can visualize them.

The rest of the paper is organized as follows. Section 2 presents the design of the system including the top level view of the system and the description of the theoretical methods used to obtain heart rate, energy expenditure and arm mobility of the patient. Also in this section, a detailed description of the implementation of the system, which consists of by the smartwatch, smartphone and the web applications, is introduced. The global system and the tests conducted to prove its functionality are evaluated in Section 3. Finally, achieved aims and future work are presented in the last section of this paper.

2 System

2.1 Design

The objective of this paper is the design and development of an automatic monitoring system for breast cancer survivors, have overcome it and are undergoing rehabilitation. The system obtains useful data of heart rate, energy expenditure and mobility of the affected arm, through which an expert can reach conclusions based on its knowledge of the rehabilitation that the patient is carrying out.

These data of interest are obtained by heart rate, accelerometer and gyroscope sensors embedded into a smartwatch, the LG G Watch R shown in Figure 2, running on the Android Wear operating system. This information is transmitted to a smartphone running on the Android operating system where data is processed into useful information. Finally, these data are sent to a remote server where they are stored in a database (which also hosts personal patient data available only to the medical expert). Subsequently, the data can be displayed in the form of charts in an accessible web interface to the expert from any mobile device or computer with Internet connection.

Fig. 2: Smartwatch LG G Watch R.

A diagram of the system comprising the three different applications is shown next:

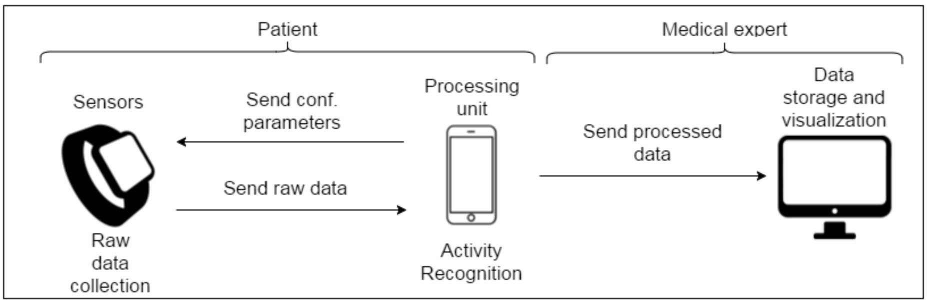

Fig. 3: Top level view of the system.

Each actor of the system has its own set of requirements. Patients need to monitor specific data to provide the doctor with treated information that can easily be interpreted in order to return medical feedback. Due to this reason, information regarding monitoring is displayed to the patient and it is the medical expert the only one who will be able to visualize the performed tests.

Heart rate. Breast cancer therapy alters autonomic function and contributes to cardiovascular disorders. According to the American College of Cardiology and American Heart Association, oncology patients who have received chemotherapy represent a high-risk for heart failure [14].

Heart rate variability (HRV) is an important noninvasive index of vagal-nerve response and a potential stress marker which can be a useful test for autonomic imbalance. It represents the time differences between beat-to-beat intervals, synonymous with RR variability (RR interval in the electrocardiogram). The analysis of the time differences between successive heartbeats can be accomplished with reference to time i.e. time-domain analysis or frequency i.e. frequency-domain analysis. The parasympathetic and sympathetic nervous systems, which are primarily responsible for changes in the inter beat interval, modify the heart rate and can be quantified by using HRV time- and frequency-domain parameters [7].

The initial objective of the system was to calculate heart rate variability due to its crucial importance but it was not possible to attempt because of the technical limitations of current smartwatches, also the device used here. The LG G Watch R smartwatch, equipped with a PPG heart rate sensor but unable to return the raw signal which is needed to calculate HRV. This device running on the Android Wear operating system only returns the heart rate values expressed in beats per second. Instead, the developed system retrieves heart rate values according to a sampling rate and calculates the average of this set of data while at the same time computes the standard deviation, quantifying the amount of variation or dispersion of this set of data values. These results do not replace the calculation of HRV but they quantify how the heart rate varies over time, which supports the initial objective.

Energy expenditure. Accelerometers, as the one included on smartwatches, satisfy many of the requirements for physical activity assessment, such as the possibility of measuring physical activities in free-living conditions with minimal discomfort for the subject and in a representative time frame for the average activity level.

The metabolic equivalent of task (MET) is currently the most used indicator for measuring the energy expenditure (EE) of a physical activity (PA) and has become an important measure for determining and supervising the state of health of an individual.

A physical activity can be measured with accelerometers through calculation of counts. Each count is a value that indicates the strength of a movement and can be used in conjunction with other parameters (height, weight, age, gender) to determine the related METs to a PA and thus the EE. The number of METs can be calculated through the number of counts obtained from information from the accelerometers and the aforementioned physiological parameters.

The system has implemented the algorithm expressed in [15], calculating activity counts of a linear accelerometer reading and transform them into METs. First, raw accelerometer values (x, y, z) are collected for a certain period of time with a sampling rate of 15 Hz. Then the linear acceleration of those values is calculated (with low-pass and high-pass filters) and has to be normalized:

$$\sqrt{(linear\_accel_x)^2 + (linear\_accel_y)^2 + (linear\_accel_z)^2}. \quad (1)$$

After this, an integration process is applied to calculate the area under the curve. Using the trapezoidal rule, the sum of the areas returns the total number of counts:

$$\int_a^b f(x)\,\mathrm{d}x = (b-a) \cdot \frac{f(a)+f(b)}{2}. \quad (2)$$

Once obtained the counts, METs are calculated through the following mathematical formula (for all age-groups combined) with the physiological information (height, weight and age) of the patient:

$$METs = 2.7406 + 0.00056 \cdot ACs - 0.008542 \cdot age - 0.01380 \cdot bodymass. \quad (3)$$

where ACs are the activity counts measured in $counts \cdot min - 1$, age measured in years and the body mass index computed as it follows:

$$BMI = \frac{mass(kg)}{height^2(m)}. \quad (4)$$

Arm mobility. After breast cancer surgery, some women experience numbness, swelling, weakness, or tingling in the arm and shoulder area on the same side of the body on which surgery was conducted. Wearable sensor technology has enabled unobtrusive monitoring of arm movements of different diseases survivors, like stroke survivors, in the home environment, with accelerometry representing the most established approach [16].

Following the method proposed by [17], the system qualitatively assesses functional arm use in the home environment, relying on only a single wrist-worn sensor module, like a smartwatch equipped with both accelerometer and gyroscope sensors. In order to achieve this, first, raw accelerometer and gyroscope values (x, y, z) are obtained for a certain period of time with a sampling rate of 50 Hz. Then, the forearm orientation relative to the earth referential frame is calculated using the gradient descent orientation filter proposed by Madgwick [18], which fuses sensor measurements of gravity and angular rate into an optimal orientation estimate. The filter outputs orientation in a quaternion representation, $q = [q_0, q_1, q_2, q_3]$, which has to be transformed into a 3 x 3 direction cosine matrix R. To calculate the forearm elevation, the forearm vector expressed in the earth fixed referential is needed:

$$a_e = R^T[1,0,0]^T. \quad (5)$$

The elevation Θ of the forearm vector $a_e = [a_{ex}, a_{ey}, a_{ez}]$ can be computed as:

$$\Theta = arctan(\frac{a_{ez}}{\sqrt{a_{ex}^2 + a_{ey}^2}}). \quad (6)$$

and then described in a polar representation. The system calculates the elevation Θ of the forearm activity measuring between -90 and 90 degrees on the vertical axis.

2.2 Implementation

The standalone system comprises different devices and technologies. Its design involves three different applications that are connected and synchronized to offer the desired functionality. Through the use of these applications, the patient will be able to monitor automatically valuable information about the rehabilitation that is in current progress and the medical expert will have an adaptive environment to check the data generated by the patient.

Smartwatch application. Android Wear is a version of the Android operating system of Google designed for smartwatches and other wearables. By pairing with mobile phones running Android version 4.3 or newer (by the accompanying Android Wear app that should be downloaded and configured on the phone), Android Wear integrates mobile notifications and other features. Also, it adds the ability to download applications from the Google Play Store. A differentiating factor over other devices is the large number of sensors included in such devices. For example, a heart rate monitor is a usually included working sensor that can only be found in specific devices prepared to calculate this information. The intrinsic design of smartwatches makes the use of such sensor in these devices ideal.

First, the smartwatch application must receive, from the mobile phone application, the configuration parameters, monitoring time and frequency time, of the desired reading or readings to be performed. Then, it should monitor the desired physiological information (heart rate, as shown in Figure 4 , energy expenditure or arm mobility) of the patient through the integrated sensors of the device and send this data to the mobile phone application. It is essential that it shows a friendly and intuitive user interface (UI), since the potential user of this application may not be experienced with the use of a smartwatch. The UI is divided into three different screens dedicated to display heart rate, energy expenditure and arm mobility respectively.

Smartphone application. Android is a key technology in the system since the Android Wear version is used on the smartwatch and the mobile operating system acts as a gateway between the wrist device and the web server application. The mobile phone application is represented as the processing unit. A compatible Android device that runs Android 2.3 or higher will run the system because it will be able to use the Google Play services APIs to access the Wearable API [19], the Activity Recognition API [20] and the HTTP library Volley [21] which is used to transmit data to the web server application.

This application presents a home screen with a formulary to be filled in with personal information that is needed to calculate and contextualize heart rate,

Fig. 4: Smartwatch application ready to monitor heart rate data.

energy expenditure and arm mobility. Then, it is required to send to the smartwatch application the configuration parameters (monitoring time and frequency time) of the heart rate, energy expenditure and arm mobility desired readings. Consequently, the handheld application must receive, from the smartwatch application, all the data generated by the sensors of this device. Then, it processes all the information received from the watch according to each methodology and to build valuable objects containing results of those processings of heart rate, energy expenditure and arm mobility. Additionaly, it uses the Activity Recognition API to detect the activity that patients are performing at the same time they are calculating their heart rate, energy expenditure or arm mobility in order to contextualize this information and make it more valuable. The resulting objects of this process are sent to the web server application so the medical expert can graphically visualize this information related to each patient. It presents a configurable and easy-to-use user interface, where the patient can select the configuration parameters and check information about the readings that are in progress. The UI is divided between a home screen with a formulary and three different screens contained in tabs dedicated to both heart rate, energy expenditure and arm mobility respectively.

Web server application. A web server application has been implemented in order to give access to the medical expert in a comfortable way so it is possible to check out all the information about its related patients and the tests they have performed from their handheld applications. The web server application has been implemented in Python and Flask programming languages for the back-end. MongoDB has been used to build the databases and the front-end has being built in HTML5, Bootstrap, nvd3 (for charts) and JavaScript.

The main goals of the web server application are to provide a server that can be hosted anywhere (local or cloud) prepared to receive data from the mobile phone application. It must hold a database system to manage the personal information of patients and their related tests performed on the smartwatch and mobile phone applications and show in an easy-to-understand manner the charts of the performed tests in order to obtain conclusions about the rehabilition that patients are following. In general terms, it presents a front-end application where the medical expert can log in and manage all the information that is stored in the databases. It shows menus, tabs, formularies, tables and charts to ease the use of the platform.

3 Evaluation

In this section some initial tests are presented to prove the functionality of the system. The tests were performed on healthy patients in a supervised environment while performing daily activities such as being still or walking. The devices used to attempt these tests are the LG G Watch R smartwatch, the Samsung Galaxy A5 smartphone and any device (computer, mobile phone or tablet) with Internet connection. The graphical representation of these tests shows the functionality of the system. The displayed data began being monitored on the smartwatch, passing through the smartphone application for proper processing and ending in the web server application to be stored and represented in charts.

Heart rate tests were performed with a monitoring time of three minutes and a frequency time in intervals of 30 seconds. Three different charts result from this monitorization: a chart for the average of heart rate as shown in Figure 5, another one for the standard deviation of the heart rate data and the activity recognition detected while performing the experiment. Tests show that the heart rate relates according to activities carried because it increased when the user was not still (from second 30).

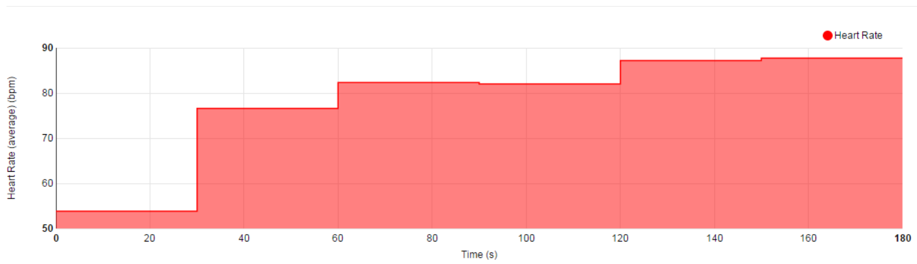

Fig. 5: Heart rate (average) chart.

Energy expenditure tests were performed under the same parameters for the monitoring and frequency times, resulting in a chart for the average of activity counts observed as shown in Figure 6, another one for the METs that are calculated from the activity counts and finally the activity recognition while performing the readings. The activity counts relate to the activities recognized by the smartphone because first more intense activities were performed, then more relaxed ones.

The arm mobility tests were performed during 1 minute of monitorization time, handling all the data generated by the sensors. This results in an arm

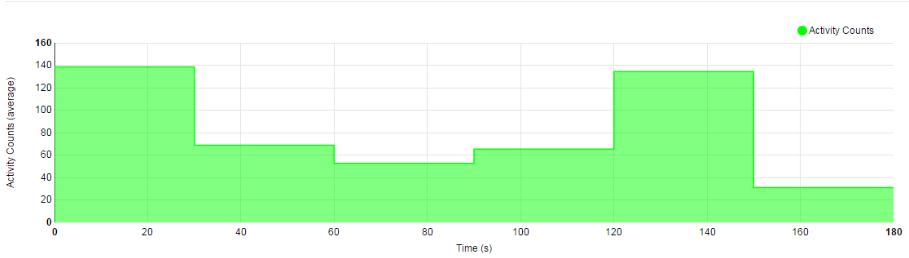

Fig. 6: Activity counts (average) chart.

mobility chart, as shown in Figure 7 that relates to the real movements of the arm, because it the arm was still at the beginning and then it was moving up and down continuously.

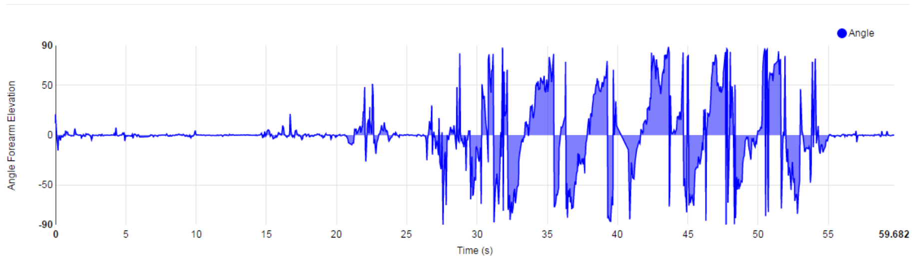

Fig. 7: Arm mobility chart.

4 Conclusion

This work has presented a self contained system to monitor breast cancer survivors. Comprising three different devices and applications, patients are able to monitor crucial parameters such as heart rate, energy expenditure and arm mobility from a smartwatch device running on the Android Wear operating system, send the sensor generated data to a mobile phone application running on the Android operating system so the data is processed and finally send this information to a web server application. A medical expert in charge of these patients is able to access to a multiplatform web server application, to manage patients, visualize performed readings and tests that the patients have performed comfortably in their home environments, without the need of visiting to a medical center.

The basic functionality of the system and all its applications have been achieved by developing a standalone system that allows monitoring of crucial parameters from sensors, such as heart rate, energy expenditure and arm mobility, to supervise patients recovery from breast cancer. Efficient communication has been implemented between the developed applications on different devices and as well as storage mechanisms to save physiological information of patients and tests performed on a remote web server application. All this is presented on user-friendly interfaces to make the use of the applications as easy and comfortable as possible through accessible and interactive elements such as tabs and charts.

Given the huge importance of the wearable technology applied to the health environment, more specifically to the breast cancer and other diseases monitoring, this functional, compact and flexible system could be improved with new functionalities. Some of them are highlighted as it follows. First, it would be important to calculate HRV due to its importance for functional status assessment and to implement the activity recognition on the smartwatch instead of the mobile phone application because it is the smartwatch that generates the sensor data, so the totality of information would come from the same source (available when Android Wear 2.0 is released). Regarding the UIs of the smartwatch and smartphone applications, in order to make the monitoring process completely automatic e.g. handled by the medical expert, they would dissappear, so the user does not have to input any parameter making the use of these applications easier and free of obligations. Finally, it has been proposed to conduct experiments with patients in real life to validate the real functionality of the system. This study should be performed with a number of breast cancer survivors and it would thrown interesting and decisive conclusions about the functioning of the system in order to improve it and make it more accesible to the users that use it.

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