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Mobile tools for home-based cardiac rehabilitation based on heart rate and movement activity analysis

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Abstract—**Cardiac rehabilitation programs are traditionally carried out in hospitals and health centers under the direct personal supervision of mentoring clinicians. Patient barriers, such as time constraints and distance from treatment centers, have lead to poor uptake of programs among eligible patients. To overcome these barriers, home-based care models have been proposed as a viable alternative to hospital-based cardiac rehabilitation programs. We have developed a measurement system and software tools on a mobile phone platform enabling patients to participate in a home-based cardiac rehabilitation exercise program. A mobile application, *TuneWalk*, gives guidance to the patients during home exercises using heart rate and physical activity analysis and also stores long-term information about their progress during the weeks of the rehabilitation program. The measured data are also sent to a server for remote exercise performance analysis and consultation by the patient's personal mentor.**

I. Introduction

Management of acute and chronic Cardiovascular Disease (CVD) incurs annual spending of over $5.5 billion in Australia. Diseases of the heart, blood vessels and stroke are one of the most common causes of death in developed countries and accounted for 34% of all deaths in Australia in 2006 [1]. The burden of CVD is likely to increase because of the aging population, obesity, and diabetes. Hospital and community care center based secondary prevention programs have been shown to reduce cardiovascular risk through comprehensive life style management including exercise training, risk factor modification, education, motivation, and medical evaluation [2]. However, these programs suffer globally from low levels of patient participation. For example, only 10–40% of eligible patients complete a program after myocardial infarction in Australia or USA [3].

Reasons for poor uptake are explained by patients that have work or travel commitments, or just dislike group-based exercise programs [4]. One solution is to offer home-based models for cardiac rehabilitation (CR) where patients can attend and complete a comprehensive program in their home environment without the need to travel to a hospital gym. Such a novel program integrating telephone mentoring via mobile phones, physiological measurements and Internet services [5] is currently undergoing a Randomized Controlled Trial (RCT) within Queensland Health services.

Patients attending either gym- or home-based CR programs are trained to use Borg rating of Relative Perceived Exertion (RPE) [6] to observe and evaluate their exertion levels during exercise sessions. Another measure for attaining adequate exercise intensity is to train at a heart rate (HR) up to 30 beats per minute (BPM) above the resting HR [7]. The "talk test", where the patient is able to talk but not sing during an exercise, is also used as a practical tool to adjust the workout [8]. In traditional programs nurses and physiotherapists continuously observe patients at the gym and coach them to reach optimum exertion levels. HR is also measured before, during, and after the exercises to evaluate patients' physiological response to training.

One of the challenges in home-based exercise programs is providing objective information on the actual exercise levels both to the patient and especially to the supervising mentors. We propose using ambulatory HR and movement activity monitoring device with a mobile phone to measure and transmit the data to mentors. Main objectives are to:

- in conjunction with the RPE scale and "talk test", give real-time feedback to patients during exercise to help them train on a safe but effective intensity level
- motivate the patient to pay attention and follow up his/her exercise levels during the program
- give objective information to the mentor on the patients' exercise levels and HR dynamics to facilitate weekly phone mentoring

Common HR meters have several shortcomings that limit their use in CR programs. Most lack the ability to transfer data to a server, which is necessary for accessing patient data remotely. Even devices with data transfer features don't transmit data automatically; they require a computer with Internet connection and technical skills from the user. Common HR meters also lack feedback and data analysis methods that would take into account the special needs of cardiac patients and their mentors. For example, most of the patients use medication that regulates their HR which is not taken account in the common HR meters.

We have developed a mobile framework to utilize ambulatory HR and movement activity measurement devices to support home-based exercise training of cardiac patients and remote mentoring.

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II. ARCHITECTURE DESCRIPTION

The mobile measurement and analysis framework for home-based cardiac rehabilitation is shown in Fig. 1. An integrated HR/accelerometer sensor and a mobile phone are provided for the rehabilitation patients. The system relies on General Packet Radio Service (GPRS) or third generation (3G) mobile network and the Internet to provide the wireless data transfer infrastructure. Designated mentors can access patient data and analysis results from a remote personal computer (PC). Feedback from the mentor to a patient occurs only through phone or video calls and text messaging.

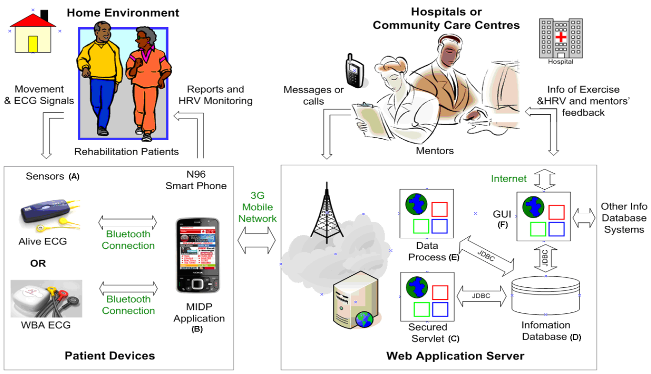

Fig. 1. Framework for mobile measurement and analysis of exercises in home-based CR

The framework is composed of the following major components and software modules:

A. Patient sensors

To acquire HR and movement activity from a patient during an exercise, we currently support Alive Heart Monitor (Alive Technologies, Gold Coast, QLD, Australia; http://www.alivetec.com) and WBA (Wireless Biosignal Amplifier, Mega Electronics, Kuopio, Finland; www.meltd.fi/). Both devices can digitize one-channel electrocardiogram (ECG), three-channel acceleration signal along X, Y and Z axes, and can stream the digital signals to a mobile phone via Bluetooth. WBA also has built-in capability to detect QRS complex waveforms from the ECG signal and transmit R-R interval values to the mobile phone.

B. Mobile exercise application, TuneWalk

An application called *TuneWalk* has been developed for communicating with the sensor devices, guiding the exercises, storing the accumulated data and sending them to a server. For communication with sensor devices, Bluetooth SPP (The Serial Port Profile) server and client modes are supported by the application. Local data storage utilizes file system and data repositories on the phone. GPRS and 3G are utilized to transfer data derived from the sensors to a web server. Necessary DSP functions, such as digital filtering, QRS detection, energy expenditure estimation, heart rate monitoring, etc. are integrated in the application. The application displays device connection states, measurement results, and analysis results to the user. *TuneWalk* is described in more detail in the following chapters.

C. Secure server module

A Java Servlet has been developed to bridge the mobile network and an information database. Data transmission security is achieved with HTTP BASIC authentication protocol protected by secure sockets layer (SSL). In short, the Servlet responds to requests and data transfers initiated by the mobile phones and updates the database accordingly.

D. Information database

MySQL, a relational database, is used to store the raw data from the patient sensors, analysis results from the data analysis module, and mentors feedback and comments.

E. Data analysis module

A data analysis module will be developed to characterize HR, Heart Rate Variability (HRV), and motion activity, to analyze their change trends over the rehabilitation period and furthermore to assess patients' rehabilitation progress. HR, HRV, and step analysis will be implemented in accordance with the work described in [9].

F. Web Graphical User Interface (GUI) module

The web GUI will provide an interface for the mentors to review analysis results, to evaluate patient exercise performance, to print reports, and to make notes of mentoring or from feedback received from the patients. Patient administration and system configuration are also integrated in the web GUI. Additionally, the module will have the potential to exchange information with structured health systems, such as HL-7 (http://www.hl7.org/), or to associate data with other research platforms for further data integration and analysis.

Initial implementation of the framework described above is currently lacking server-side data processing methods and sophisticated web GUIs. The framework will be put into use in a randomized controlled trial with cardiac rehabilitation patients during 2009. Collected data will be analyzed to extract useful features and measures, both from individual exercises and from longitudinal trends. These will then be transformed into report views that the mentors can access.

III. TUNEWALK

The mobile exercise application used in conjunction with a HR and accelerometer sensor is called *TuneWalk*. It was built on Java Platform, Micro Edition (Java ME) (Sun Microsystems, Santa Clara, USA, http://java.sun.com) and uses CLDC 1.0 (Connected Limited Device Configuration), MIDP 2.0 (Mobile Information Device Profile), and JSR 82 (Java Specification Request for Bluetooth; http://jcp.org/en/jsr/detail?id=82) application programming interfaces (APIs). *TuneWalk* is signed with a third-party certificate, allowing blanket permissions to several features otherwise requiring explicit user interaction and acceptance.

TuneWalk has been built as a customizable and modular mobile exercise application platform. It consists of several core classes implementing basic functionality and offers utility classes for use with specialized exercise program implementations. An exercise program can be built on the *TuneWalk* platform by implementing three modules and their corresponding views; settings, exercise, and reporting. We have implemented these modules for the cardiac rehabilitation case supporting either the WBA or Alive device. An architectural overview of the *TuneWalk* platform and its specialization for CR are depicted in Fig. 2. From here on all implementation details describing *TuneWalk* are conveyed as they are implemented for the home-based CR trial.

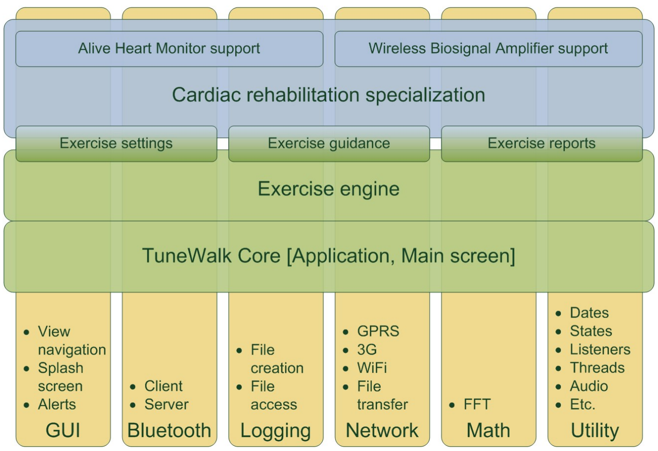

Fig. 2. Architecture of the TuneWalk Java ME application. Core classes are shaded green, supporting libraries are shaded brown, and cardiac rehabilitation implementation classes are shaded blue.

During a CR exercise, the following values are computed in real time by *TuneWalk*:

A. Heart Rate

In normal operating mode, the WBA device sends a data packet every 10 seconds, containing R-R intervals detected during this period. *TuneWalk* averages these values to obtain current HR. The delay induced is acceptable but real time updates in HR would be preferred.

Alive Heart Monitor doesn't have internal processing of ECG, it transmits the raw ECG signal. Due to this difference, when using the Alive Heart Monitor with *TuneWalk*, the ECG signal processing and QRS complex detection are performed by *TuneWalk* using the U3 algorithm [10]. After QRS detection, heart rate computation is done similarly than with the WBA device.

B. Metabolic Equivalents (MET) energy expenditure

We estimate energy expenditure from the raw activity signal. The three axis accelerometer data are converted into a one-dimensional activity signal by computing acceleration vector's magnitude at each sample. In anticipation of calibration problems, the acceleration component caused by earth's gravity is nullified by calculating the average activity magnitude over a period of time and subtracting it from each individual activity magnitude. Integral of the subtracted signal gives us a total activity value from the period, which is then offset and scaled to derive the final MET energy expenditure value during this time.

C. Step rate

Step rate denotes the number of steps taken per minute. It is derived from one dimensional activity magnitude signal by taking Fast Fourier Transform (FFT) of a window of 1024 samples (~41 seconds of data) and finding the dominant frequency. This is obtained with a peak detection algorithm that locates the maximum value from the FFT.

IV. TuneWalk Usage Walkthrough

Home-based cardiac rehabilitation patients in the trial will use *TuneWalk* as follows:

A. Launching Tunewalk

TuneWalk can be launched from the mobile phone's menu. It immediately attempts to create a connection with a HR device via Bluetooth. If a connection is established, the user can start exercising immediately. If no devices are found, the user must first initialize the connection before being able to start an exercise. In addition to manual startup, *TuneWalk* is configured to listen to Bluetooth connections initiated by a WBA device and it will launch automatically by using the MIDP 2.0 Push Registry. This allows starting an exercise with a convenient one-click operation, pressing only the connect button on a WBA device once. This feature is not available with Alive Heart Monitor, because it acts as a Bluetooth server and doesn't initiate connections.

Options in the *TuneWalk* main screen, besides initialization or starting the exercise, include changing the settings and viewing previous reports (Fig. 3, left view). The user may also exit the application if he/she so wishes.

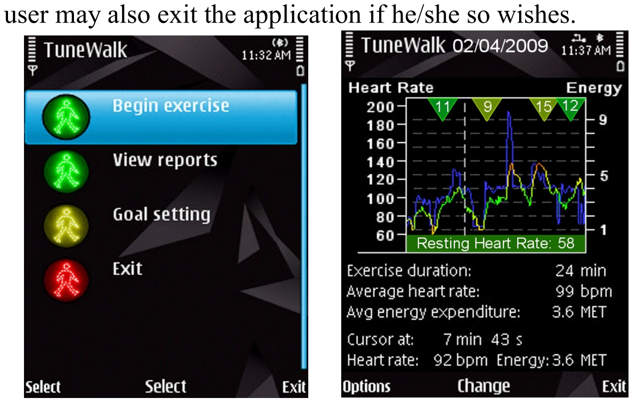

Fig. 3. Main screen and a report screen of the *TuneWalk* CR application. Blue line is MET energy expenditure, green-yellow-red line is heart rate, triangles denote perceived exertion levels during the exercise.

B. Exercise settings

At any time between exercises, user can go into the settings dialog to modify available configuration options. These include the resting heart rate and a heart rate level for a "talk test" reminder.

C. *Exercising with TuneWalk*

During an exercise the user is always shown current heart rate, an estimate of their energy expenditure, elapsed exercise time, and guidance text driven by the resting heart rate and "talk test" reminder level. Verbal feedback is also provided so that the user may keep the mobile phone in his/her pocket and not carry it by hand all the time. The application will advice the user to do the "talk test" if the heart rate and activity levels remain high and will give an encouraging note with information about the current exercise levels when the exercise has continued for a period of time.

TuneWalk will not give explicit instructions in regards to whether the user should be going faster or slow down. Instead, the user is advised to exercise at all times at the correct perceived exertion level (using RPE they are familiar with). The user is also instructed to keep track of his/her exertion feelings during an exercise. To do this, he may at any time enter an RPE value which will be stored in the corresponding instant of exercise time. After finishing the physically straining part of an exercise, a short cool down period is encouraged to be registered before the exercise is finally ended by pressing a command button on the phone.

D. *Exercise report*

When the user has ended a training session he/she is asked for a total RPE value for the exercise after which a report is presented (Fig. 3, right view) and data are sent over to the server in the background. The report view shows total exercise time, heart rate, energy expenditure, and RPE levels entered during the exercise. A cursor can be moved over the graph to view values in detail at each instant of time. The user may change the view to a previous report and compare how his heart rate, energy expenditure, and exertion levels have changed over the course of the rehabilitation program.

V. Technical Evaluation

Objective of the technical evaluation was to validate heart rate and movement activity measures that *TuneWalk* uses internally and shows to the user during exercise, namely heart rate, MET values, and step rate. From the supported heart rate monitor implementations in *TuneWalk*, only WBA was validated as it has been selected for use in the trial. The technical evaluation was performed by two of the authors, a 32-year-old male and a 29-year-old female.

Heart rate was validated against a commercial training computer, the FRWD W600 (FRWD Technologies, Oulu, Finland; www.frwd.fi), consisting of a recorder unit, which records GPS signal and heart rate from a heart rate belt, and a wrist unit for real-time feedback. During validation, the subjects wore two textile heart rate belts simultaneously, one with WBA and one with a Polar heart rate transmitter (Polar Electro, Kempele, Finland; www.polar.fi). Heart rate variability and activity data measured by WBA were recorded by *TuneWalk* and the heart rate data from Polar heart rate transmitter were recorded by FRWD recorder unit.

A. *Heart Rate validation*

Heart rates used and displayed in *TuneWalk* application were validated in a 25-minute protocol consisting of 5-minute periods of walking and running at increasing speeds. The target speeds were selected as walking at 2, 3 and 4 miles per hour and running at 5 and 6 miles per hour to use the same data for MET validation. The subject tried to walk and run as naturally as possible and used the GPS-enabled FRWD wrist display to help achieve the target speeds.

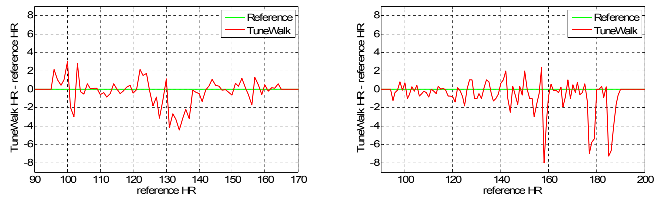

Fig. 4. Heart rate difference between *TuneWalk* and reference device.

HR levels shown in TuneWalk were compared to the heart rate signal recorded with FRWD, see Fig. 4. Spikes showing larger differences are mostly due to few samples at particular HR levels. Correlations between the heart rates reported by *TuneWalk* and FRWD were 0.996 and 0.991 ($p < 0.01$); root mean squared errors (RMSE) were 3.03 and 3.53.

B. *Energy expenditure validation*

MET values calculated by *TuneWalk* from the activity signal were validated by comparing them to the Compendium of Physical Activities table of MET values of walking and running at different speeds [11], converted here to metric units from the original manuscript.

TABLE I
MET Energy Expenditure Evaluation Results

Subject, exercise type	Target speed (km/h)	Measured speed (km/h)	Target MET	Measured MET
S1, walking	3,2	3,1	2,5	2,2
S2, walking	3,2	3,3	2,5	2,6
S1, walking	4,8	4,6	3,3	3,1
S2, walking	4,8	5,0	3,3	3,4
S1, walking	6,4	6,8	5,0	5,3
S2, walking	6,4	6,0	5,0	4,8
S1, running	8,0	8,2	8,0	8,3
S2, running	8,0	8,6	8,0	10,1
S1, running	9,7	9,7	10,0	7,7
S2, running	9,7	10,4	10,0	10,2

As can be seen in Table 1, *TuneWalk*'s MET estimation with the test subjects is fairly accurate at walking speeds. When running, the results become unreliable. In our case this should not present a major problem, since in the home-based CR program exercises are walking at relatively slow speeds. Including heart rate in MET computation should increase the accuracy and is being investigated, despite high variance in patients' resting HR and HR dynamics.

C. Step rate validation

Step rate was validated by walking 1-minute periods on constant step rates. The target step rates were 90, 120, and 150 steps per minute and running at 130, 150, and 180 steps per minute. The subjects used a mobile phone metronome (Metronome, http://www.garret.ru/En_Timer.htm) to set and keep the pace.

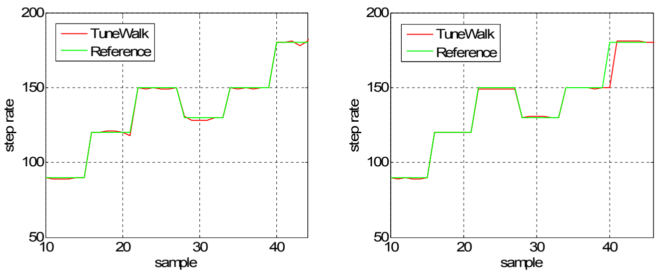

Fig. 5. Step rate difference between *TuneWalk* and target rate, corrected by the delay in dominant frequency detection due to large frequency changes.

From Fig. 5 it can be seen that step rate detection is very accurate at step rates of 90 steps per minute or more.

VI. Discussion

Mobile CR exercise tools presented in this paper, *TuneWalk* and the supporting framework, will be used in a randomized controlled trial of a home-based cardiac rehabilitation program [5] during 2009. Patient recruitment for the trial has commenced. Future work includes development a proper portal GUI for the mentors, and designing more user-friendly interfaces for all aspects of the system. Analysis and display of clinically relevant measures such as Heart Rate Recovery [12], HRV, walking pace, activity measures, and combinations of these [9] will be analyzed as real patient data starts flowing in. Meaningful analysis views for individual exercises and long-term trends will be developed to motivate the patient, and to help the patient and mentor adjust the exercise program.

For *TuneWalk* application we plan to study novel exercise guidance methods, such as using music together with pace or vibrations to provide information about an ongoing exercise. Safe methods for encouraging patient exertion levels to correct range during an exercise will also be investigated. In regards of reporting, trends found over the course of the rehabilitation program can be visualized for the patient in the *TuneWalk* application itself.

Modular structure of *TuneWalk* makes it easy to add support for more advanced Bluetooth devices that acquire more information from the patients. The modularity also allows us to extend *TuneWalk* and the framework to other application fields, such as occupational health, wellness applications, and fitness applications.

VII. Conclusion

We have developed mobile exercise tools for home-based CR that is comparable in accuracy to a commercial heart rate monitor currently used in hospital-based cardiac rehabilitation. They will be used in a randomized controlled trial and refined further as data from CR patients are collected. Further development of the framework is possible on several fronts, including novel exercise guidance methods, longitudinal trend analyses, and integration with other data sources.

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