Development of an innovative mHealth platform for remote physical activity monitoring and health coaching of cardiac rehabilitation patients

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***Abstract*—This article presents the main features and components of iCardia - an innovative mHealth platform designed to support remote monitoring and health coaching of cardiac rehabilitation (CR) patients, through Fitbit wearable sensor devices, smartphones, and personalized SMS text-messages. The design and development of iCardia were based on an iterative, user-centered design process and an open-service architecture to ensure rapid scalability and adherence to evidence-based guidelines for easier transition into clinical practice. iCardia has the potential to enable a paradigm shift towards a collaborative CR environment that utilizes mHealth technologies to engage patients to more effectively self-manage their cardiovascular disease.**

I. Introduction

Physical activity (PA) is a central component of cardiac rehabilitation (CR) programs [1] and one of the four health behaviors targeted by the American Heart Association's (AHA) 2020 Strategic Impact Goals for improving cardiovascular health [2]. A substantial body of evidence shows that increases in PA are associated with a marked decrease in cardiovascular mortality and significant improvements in many well-known Coronary Heart Disease (CHD) risk factors [3, 4]. The amount of PA currently recommended by the American Association of Cardiovascular and Pulmonary Rehabilitation (AACVPR) for people with CHD is 30 to 60 minutes of moderate-intensity PA per day (e.g. brisk walking) [1]. One of the key aims of outpatient center-based CR is to provide patients with advice, support, and consistent encouragement to achieve these recommended levels. However, prior studies have shown that many patients who attend CR programs fail to reach the target levels, mainly because of lack of PA on non-CR days [5-8]. Non-adherence to this basic lifestyle measure leads to a larger proportion of the CHD population at greater risk for poor health outcomes with substantial economic implications [9]. Innovative, alternative approaches are needed to enhance patient engagement and improve adherence to PA.

Mobile health technologies (mHealth) such as smartphones, mobile applications (apps), and wearable activity tracking devices that permit real-time collection of "big data" have become ubiquitous [10], offering significant and innovative opportunities to researchers and clinicians [11, 12]. New consumer wearable devices such as Fitbits allow users to collect objective measures of their own daily activities and obtain more detailed feedback on their PA performance. In addition to self-monitoring, these devices can support near real-time exchange of information between consumers and health providers via web Application Programming Interfaces (API), enabling remote monitoring and assessment of multiple activity behaviors in various contexts and thus development of more dynamic, responsive, and personalized interventions to support behavior change [13]. However, the potential of these mHealth technologies has not been systematically explored or capitalized in the area of CR. A recent systematic review of mHealth interventions for CR found that despite the large number of commercially available sensor technologies and mobile apps, prior studies have shown little technological innovation [14]. This acknowledgment was also echoed in a recent AHA scientific statement on the use of mHealth technologies for CVD prevention, which identified a critical need for future research studies to include commercially available wearable devices to determine their efficacy in improving PA and decreasing sedentary behavior [11].

This article presents the development of iCardia - an innovative mHealth platform designed to support near real-time remote monitoring and health coaching of cardiac rehabilitation patients through the use of Fitbit wearable devices, smartphones, and personalized SMS text-messages.

II. Methods

We employed a user-centered design philosophy [15] to gather requirements and iteratively design the iCardia platform, leveraging our prior experiences with a base text-messaging system (mytapp) that has been used and tested in other populations [16]. At the concept generation stage, we carried out a scoping review [17] to examine the extent and

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nature of research activities in the area of mHealth for CR, and inform our system design. We also carried out investigations of user needs through interviews and discussions with researchers, clinicians and CR specialists at the University of Illinois at Chicago (UIC). As a next step, we translated the user needs into functional and operational requirements, taking into consideration available guidelines for CR [1], different behavioral change theories and techniques [18], and a host of social and organizational factors associated with the population, environment, and context in which the system will be used. iCardia was developed iteratively by eliciting feedback from end-users on reference and prototype versions and conducting multiple usability tests at the UIC "mHealth Innovation Lab".

III. Results

The iCardia platform is based on an open, service-oriented architecture that utilizes smartphones, commercially available wearable sensor technologies, and web APIs to enable near real-time collection of activity data and communication between patients and CR specialists via SMS text-messages. The core components and overall architecture of the iCardia platform are described in detail below.

A. Platform Components and Architecture

As shown in Figure 1, iCardia currently comprises (a) Fitbit wearable sensor devices supporting heart rate monitoring; (b) smartphones with Android, iOS, or Windows operating system; (c) Fitbit's mobile app and cloud-based server; (d) clinical web-based dashboard; and (e) SMS text-messaging.

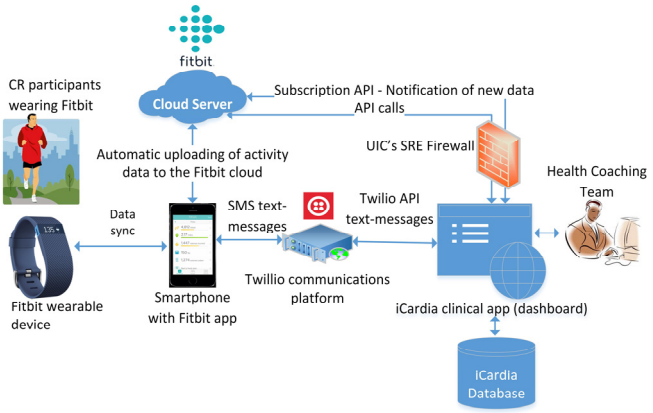

Figure 1. iCardia platform components and architecture

Fitbit was selected because of the popularity, validity, affordability, and user-friendliness of its wearable activity tracking devices. Fitbit currently holds the largest market share in the United States and has established itself as a global leader in the connected health and fitness market. Fitbit's activity trackers have been tested in various validity studies and shown to be accurate in measuring PA, exercise (Ex), sedentary time, sleep, and heart rate (HR) [19]. Furthermore, their feasibility, usefulness, ease-of-use, and acceptability have been demonstrated in many interventional studies involving diverse populations and age groups, including CHD patients attending CR programs [20].

Smartphones were considered to be the optimal communication platform as near ubiquitous mobile broadband availability allows remote monitoring of physical activity/exercise and health coaching via text-messages to take place in almost any location.

Fitbit Charge HR, Charge 2, Surge, and Blazer are all wrist-based wearable devices that use a three dimensional accelerometer and an optical HR sensor to monitor intensity-specific minutes of PA, Ex, sedentary time, HR, sleep, and caloric expenditure, among other measures. While iCardia is compatible with and can also receive activity data from other Fitbit activity tracker models, the capability to monitor continuous HR and hence caloric expenditure more accurately, in addition to other activity parameters, is considered advantageous for monitoring CHD patients. As shown in Figure 1, Fitbit devices pair with a Fitbit mobile app via Bluetooth Low Energy (BLE) network technology, wirelessly uploading activity data to the app to provide users with easy to understand visualizations of their daily activity parameters. The Fitbit mobile app incorporates a host of behavior change techniques and tools, including goal setting, self-monitoring of activity behavior and goals (e.g. PA, exercise, and sedentary time), feedback on performance, prompts/cues, social support, gamification in the form of "challenges", rewards (e.g. badges), and general encouragement among others.

Synced data are automatically relayed from the Fitbit mobile app to the Fitbit cloud server, every 10-15 minutes or any time a participant accesses the app. When CR participants upload data from their Fitbit devices to the cloud, the iCardia server is automatically notified through Fitbit's Subscription API. This allows iCardia to retrieve participants' latest data without having to implement a polling or scheduling system. Following receipt of notifications, iCardia initiates a number of API calls to retrieve the actual data from the Fitbit cloud server (e.g. steps, active minutes, exercises, heart rate, and sleep), and store them securely in its database.

iCardia's clinical app (dashboard) is a password and firewall protected web application that is currently hosted in a HIPAA-compliant virtual server located in UIC's Secure Research Environment (SRE). The iCardia dashboard, described below in more detail, provides a user-friendly environment that allows CR specialists to view each participant's activity data in the form of graphs and send personalized, motivational text-messages to their mobile phone via SMS to improve PA and decrease sedentary behavior. The text-messaging app is integrated with the clinical dashboard and utilizes Twilio's API to send text-messages to registered CR patients. Twilio is a cloud based communications platform that allows software developers to programmatically send and receive text-messages using its web service APIs. Text-messages can be sent from iCardia immediately, recurrently (e.g. daily) or at a scheduled date/time to one or more participants at a time.

B. Remote monitoring of Physical Activity and Exercise

Physical activity and exercise are core components of CR programs that must be measured objectively on a regular basis, as other major risk factors. Fitbit's newest activity trackers are capable of capturing the frequency, duration, and intensity of physical movement and HR in a time-stamped manner. They are also capable of automatically detecting and recording continuous, high-movement activities and aerobic exercises, such as walking, running, and cycling, through an innovative

feature called "SmartTrack". iCardia collects in near real-time from the Fitbit cloud server, intraday time-series data pertaining to PA and HR, and graphically displays this information in meaningful and informative ways using data analytics and visualization tools to effectively support remote monitoring and health coaching of CR patients at any time and in any place. As shown in Figure 2, CR specialists can select a specific date using the calendar feature, and then view each patient's minute-level step count and HR data, including total number of steps, PA minutes classified by intensity (light, moderate, and vigorous), and calories burned.

Figure 2. Intraday physical activity and heart rate

In addition to intraday data, iCardia supports analysis and visualization of PA/Ex data over longer periods of time (Figure 3). CR specialists can select a date range to view each patient's activity progress and trends over time in terms of steps, light or moderate-to-vigorous physical activity minutes (MVPA), and exercise. These measures are also supplemented with charts indicating actual Fitbit wear-time. iCardia implements a novel algorithm that leverages Fitbit's HR sensor to accurately calculate the total number of minutes each patient has worn his/her Fitbit activity tracker on any given day. This wear-time measure serves three purposes: 1) it is used by the system for sending automated text-messages to patients who are not adherent to wearing their Fitbit device (e.g. <10 hours/day), 2) it allows CR specialists to determine whether decreases in activity are due to real changes in PA behavior or non-adherence to wearing Fitbit, and 3) it can be used in data analysis for filtering out days that do not contain sufficient data.

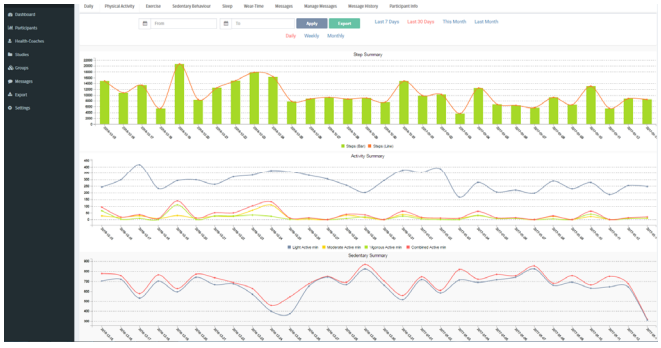

Figure 3. Physical activity trends analysis over time

C. *Remote monitoring of sedentary time and behavior*

Evidence from multiple epidemiological studies and meta-analyses shows that sedentary behavior is associated with increased cardiovascular specific and overall mortality [21]. Sedentary behavior refers to any waking behavior characterized by an energy expenditure ≤1.5 metabolic equivalents while in a sitting or reclining posture. Walking for a few minutes every hour has been shown to reduce the negative impacts of sitting. iCardia implements tools to (a) capture and visualize each patient's sedentary time as well as episodes of prolonged inactivity (defined as <250 steps/hour), using Fitbit's intraday time-series data, and (b) send automatic, individualized text-message reminders when a period of inactivity has occurred to encourage patients to decrease their sedentary behavior.

D. *Behavior Change Text-Messages*

Mobile phone text-messaging is a potentially powerful tool for behavior change, because it is widely available, inexpensive, and easy to use [22]. A substantial body of evidence spanning several years of research demonstrates that text-messaging interventions have positive effects on health outcomes and behaviors [23]. Text-messages can be used at any time and in any place to encourage PA, Ex, and other healthy behaviors in patients with CHD by delivering educational, prevention and self-management components based on behavioral theory models and strategies [14]. iCardia is built to support the development, tagging, classification storing, and delivery of both individual and group text-messages. CR specialists can use iCardia to create theory-based text-messages and store them in meaningful ways, using the classification and tagging tools that are implemented in the system for quick access and retrieval. The tone and nature of SMS messages can be adapted based on the incoming Fitbit data and progress of each participant. Messages can be sent right away, recurrently (e.g. daily, weekly, on weekends or weekdays) or at a scheduled date and time. iCardia also supports receiving text-messages from CR participants to enable two-way communication between patients and clinicians.

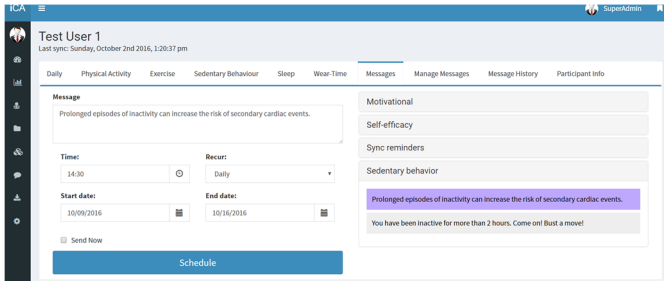

Figure 4. Text-messaging interface

IV. DISCUSSION

This article outlines the main components and features of iCardia – an innovative mHealth platform that supports remote activity monitoring and health coaching of CR patients through smartphone and Fitbit technology. CR is a multidisciplinary lifestyle intervention that has a robust evidence base demonstrating improvements in a host of clinical outcomes[24]. However, participation in traditional, center-based CR programs remains dismally low in the United States, particularly in older adults, women, and minorities [25, 26]. Advanced wearable sensor technologies and smartphones can help broaden the reach of traditional CR programs as well as overcome common accessibility barriers that limit patient participation. In this line of thought, iCardia has been designed with the intent of serving a dual purpose: (a) complement

traditional center-based CR programs by increasing patient engagement and compliance on non-CR days, and (b) provide an alternative delivery model that can be used to reach and empower CHD patients who are unable or unwilling to attend center-based CR programs. One of iCardia's limitations is that it does not currently include all CR components recommended by international guidelines [27]. However, it is designed based on an open-service architecture that allows modular expansion and integration of multiple other technologies to support additional CR components in future iterations (e.g. nutrition, medication, and hypertension management). As a next step, we plan to evaluate the feasibility and efficacy of iCardia in a randomized controlled trial of adult patients with CHD. iCardia has the potential to enable a paradigm shift by providing a collaborative care environment that efficiently integrates advanced wearable sensors with smartphone technology, all in a cost-effective manner to facilitate real-time remote monitoring, personalized feedback, patient empowerment, and improved self-management of CHD. The overall concept of the iCardia platform is transferrable to other chronic diseases and conditions such as diabetes, asthma, and chronic obstructive pulmonary disease.

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