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HeartHealth: A Cardiovascular Disease Home-Based Rehabilitation System

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Abstract

The increasing pressure on medical institutions around the world requires health care professionals to be prescribing home-based exercise rehabilitation treatments to empower patients to self-monitor their rehabilitation journey. Home-based exercise rehabilitation has shown to be highly effective in treating conditions such as Cardiovascular Disease (CVD). However, adherence to home-based exercise rehabilitation remains low. Possible causes for this are that patients are not monitored, they cannot be confident that they are performing the exercise correctly or accurately and they receive no feedback. This paper proposes HeartHealth, a novel patient-centric gamified exercise rehabilitation platform that can help address the issue of adherence to these programmes. The key functionality is the ability to record the patient movements and compare them against the exercises that have been prescribed in order to return feedback to the patient and to the health care professional, as well. In order to synthesize a compact fully operational system able to work in real life scenarios, tools and services from FI-PPP projects, FIWARE[1] and FI-STAR[2], were exploited and a new FI-STAR component, Motion Evaluation Specific Enabler (SE), was designed and developed. The HeartHealth system brings together real-time cloud-based motion evaluation coupled with accurate low-cost motion capture, a personalised exercise rehabilitation programme and an intuitive and fun serious game interface, designed specifically with a Cardiac Rehabilitation population in mind.

Peer-review under responsibility of the Program Chairs.

Keywords: home-based rehabilitation platform; rehabilitation; CVD patients; CVD exercises, motion capture, serious games;

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1. Introduction

Physical inactivity is the fourth leading risk factor for global mortality[3]. 1.5 billion adults world-wide are insufficiently active and as a result many suffer from Cardiovascular Disease, Coronary Heart Disease (CHD)[4], diabetes[5], obesity and other preventable non-communicable diseases. Exercise is a crucial component to the management and prevention of such conditions and patient adherence to prescribed exercise is absolutely crucial to both disease prevention and rehabilitation.

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The proposed system is an e-Health platform, named HeartHealth, targeting a novel patient-centric, low-cost sensor game-based system, designed to provide a safe and individual exercise environment that could be deployed in any physical exercise-based rehabilitation programme. The main objective of the proposed platform, as the experimental results confirm in Section 5, is that an attractive e-Health software, based on enablers offered by FI-PPP projects, can encourage and motivate patients to use it, since HeartHealth can offer enjoyable rehabilitation at home. The implemented system is specifically targeting this towards CVD patients, for whom we have direct access to through the DCU MedEx programme[6], where the reported experiments (Section 5) took place. However, it should be noted that the proposed Motion Evaluation Specific Enabler has been designed to be applicable to almost any exercise-based rehabilitation programme.

This paper further presents the exploitation of online tools/enablers offered by FI-PPP EU projects, FIWARE and FI-STAR, in e-Heath. In particular, these tools are the basis of our platform that consists of a free online secure registration/authentication system for medical experts and patients, an online database and a web service able to evaluate the physical exercises, named FI-STAR Motion Evaluation SE. Much of our work is the development of this enabler, which is available in FI-STAR catalogue[7]; an online tool able to analyse and compare motion capturing data.

Through the platform, the medical experts are able to set an exercise programme for each patient separately by using off the shelf cheap MoCap devices as MS Kinect[8] and Wireless Inertial Measurement Units (WIMUs) and in correspondence the patients can perform these exercises at home and get feedback from the system. It is worth to be mentioned that HeartHealth offers two different options concerning the motion capturing system, on the one hand, using only one Kinect sensor or, on the other hand, one Kinect sensor and from one to four WIMUs placed on limbs.

Regarding the user environment, the proposed platform is a pure example of applied gamification in medical software. The patients can enjoy themselves by running a video game scenario in a user-friendly 3d environment, while they are performing their cardiac rehabilitation program. During this procedure, the system records, analyses and evaluates the patient physical activity and provides the analytics to the medical professional via cloud.

2. Related Work

Recently it was reported the application of home based exercise programmes in the context of cardiac rehabilitation carried the possibility of providing much higher adherence rates[9] and early stage work has been carried out on self-adaptive home based games in order to adapt to a patient's changing rehabilitation journey[10].

Corazza *et al.* propose REHAL[11], a platform that manages home-based cardiac rehabilitation programs based on the awareness that safe home rehabilitation is possible in the post-hospital phase. The platform consists of a web-based database and client software, enabling health staff to manage the sessions without real-time connection and legal liability. The client software permits the complete management of a bike (web transmission, training session settings, and data recording) via a PC connection. Patients' data can be accessed by health personnel to evaluate the results and introduce longitudinal ambulatory information together with updated physical activity protocols. The client software acquires and records heart-rate, loads, pedalling speed and other parameters of interest (i.e., arterial pressure) and forwards data to a web-based database. Health personnel is able to modify the scheduled exercise settings, analyse the results of each session and compare sessions. In any case, although REHAL is used in real life and is a quite satisfying tool for CVD patients and medical experts, it has the limitation of monitoring specific physical exercise activity (biking) with cumbersome equipment.

Sarela *et al.*[12] propose a home-based service model for cardiac rehabilitation based on mobile technologies. The primary focus of this platform is on physical exercise, especially walking, and to keep a wellness diary that supports entry of a plethora of parameters such as weight, eating, stress level, sleeping hours, blood pressure, fat percentage, blood sugar and tobacco and alcohol consumption. Although the platform is portable and easy to use, it remains a rough approach of monitoring since only the physical activity is detected automatically using smart phone sensors to measure the number of steps and the rest information is manually inserted from the patient.

A serious game can be thought of as any game based interface that has been designed for any purpose other than pure entertainment[13]. Inspired by the success of video games and through the inherent ability that games have to keep a person's attention, serious games have grown into a significant research area[14]. The design of computer games can offer valuable contributions to develop effective games in the area of rehabilitation. A survey of relevant work and applications on serious games for rehabilitation was published by Rego *et al.*. Serious games in rehabilitation have been used for successful balance re-training[15], rheumatoid arthritis rehabilitation[16], but most of the recent work reported relates to rehabilitation following stroke which often necessitates upper limb rehabilitation[17], and the performing of large repetitions of motions. Home based rehabilitation games have been investigated to help improve the motivation of stroke patients in performing their daily exercise regime[18]. The effective management of the large quantities of data involved in multimodal rehabilitation has been investigated by Notelaers *et al.*[19], in which the authors highlight the necessity to group the data in a sensible manner in order not to overwhelm the therapists with too much detailed information.

Within the HeartHealth project we have built on the currently existing state-of-art in serious game application to rehabilitation whilst adding our extensive expertise in human based bio-mechanical analysis to produce a truly personalized home based Rehabilitation System that incorporates real-time multi-modal patient monitoring. The HeartHealth system employs a sensor fusion approach that combines body worn WIMUs with the Kinect V2 to allow for highly accurate biomechanical movements to be incorporated in to the rehabilitation programme. These sensor modalities are fused together to produce an accurate skeleton of the user that is then incorporated into a serious game. We have focused on developing a story driven game-based exercise programme that will keep the patient's attention, interest and encourage them to complete the game while going through their exercise programme. One of the key novelties of the HeartHealth system, that to the best of our knowledge does not currently appear in the literature, is that with the HeartHealth system clinicians can record patients performing any exercise they have selected for them based on their individual physical limitations. These recordings then form the ground-truths for that specific patient, therefore truly personalising the motion capture and providing a unique and individual Cardiac rehabilitation experience.

3. The Rehabilitation System

The HeartHealth system allows a 'Medical Professional' who wished to prescribe any exercise-based rehabilitation to record any required exercise motion that can be performed by their patients. These exercises are stored securely online in the patients account and are utilised during the course of rehabilitation game. During the game the patients motions are recorded, via a fusion of data from the Microsoft Kinect V2 and body worn WIMUs, and sent to the Motion Evaluation Specific Enabler (SE) for comparison, see Section 3.1. The results are then used to assess the patients progress through their rehabilitation journey and are securely stored in their exercise diary for them to review later or for a doctor to remotely analyse. The detailed architecture of HeartHealth system and the interaction between the components are presented in Figure 1.

HeartHealth consists of two front-end interfaces, a user-friendly physiotherapeutic Unity3D game and an Android application. The game interface offers all the operations of the platform, both for patients and medical experts, and supports the usage of the motion capturing sensors. First, the system gives the option to the patients to train themselves based on their rehabilitation programme, in a friendly game environment. Afterwards, the patient can select to enter the core game scenario where is able to play by performing the appropriate exercises, while in parallel, the Motion Evaluation SE evaluates the attempts and returns the feedback and the rest analytics in the cloud. Additionally, the medical professionals can use the game interface to record new exercises and use them as reference for the rehabilitation programme of each patient. Finally, the patients and the medical professionals have the opportunity to watch the history of the performances and adherence.

The Android application is a native android app developed only for medical experts in order to offer a more portable and flexible option to monitor their patient's history and adherence through their Android devices.

The back-end of the platform is based on the Motion Evaluation SE, described in 3.1, and two existing Generic Enablers (GEs) from FIWARE platform, Identity Management KeyRock (IdM) and Orion Context Broker (CB). IdM acts as the main tool for the user registration, the administrator panel and the user authentication, as it depicted in the architecture. CB represents the database where the motion data and the analytics are stored. Each of these GEs is a significant part of the platform and they are described in detail in the sections 3.3.1 and 3.3.2 respectively.

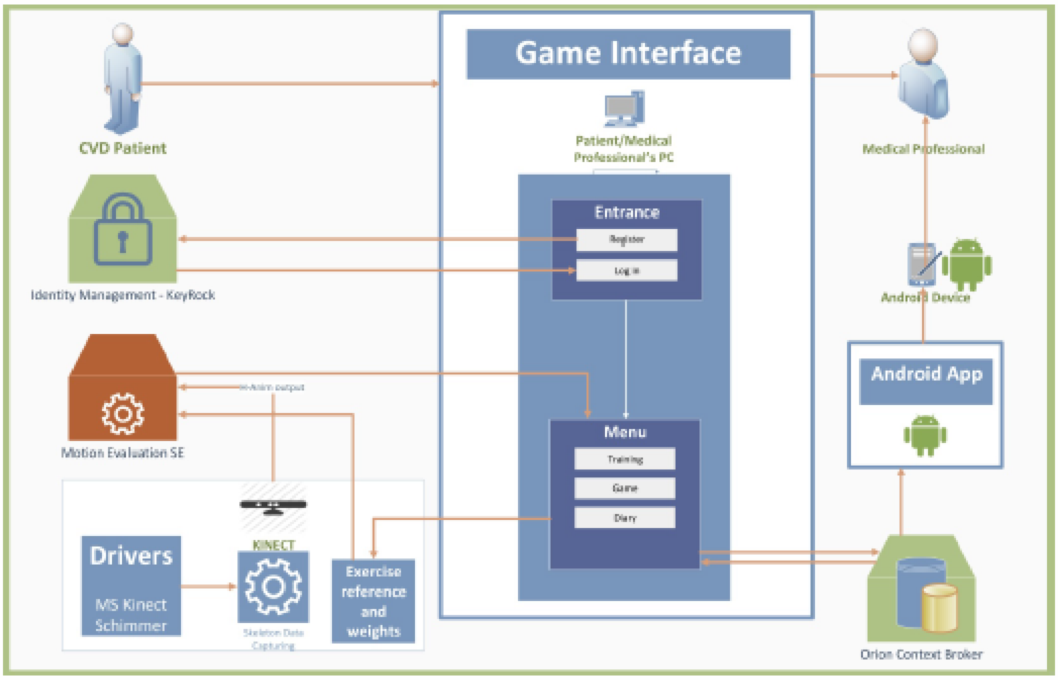

Fig. 1. System architecture.

3.1. *Motion Evaluation Specific Enabler*

The Motion Evaluation enabler performs an evaluation of a captured human motion in comparison with a reference one. Received human motion data (in H-Anim format[20]) either are used as recorded or reference motion. In addition, the configuration of the human body joint weights is supported to achieve the comparison of the motion by giving emphasis to specific joints depending on the nature of the performed motion. The outcome of the evaluation consists of partial and overall score in percentage and also semantic feedback to guide the users how to refine their technique. Last but not least, the enabler supports the comparison of human motions independently from their type, thus the service can be used for general purposes depending on the developer desires. The enabler is deployed on FI-STAR catalogue and offers a RESTful API, the documentation of which can be found in a public domain[21].

The sections below describe the methods and the algorithms of the human motion analysis and evaluation of the enabler. The methodology is divided into two main parts: synchronization and comparison. The first section describes the motion synchronization and the second one the feature extraction and the motion comparison modules. These modules constitute the main core of the service.

3.1.1. *Motion Analysis and Synchronization*

The scope of the human motion synchronization is the non-linear matching of two motion data sequences due to their different speeds during the exercises. A synchronization algorithm is applied to synchronize two motions based mostly on the technique and not on the speed of the performance. Dynamic Time Warping[22] (DTW) is used to synchronize the two human motion signals. Applying DTW, an appropriate deformation of the sequences in time can be achieved so the speed differences can be overridden. The two motion sequences are cropped and only the active part is kept to achieve a fair comparison, by using the optimal warping path.

3.1.2. *Feature extraction and comparison*

The enabler extracts motion features from the reference and recorded motion. The features are the relative position, rotation, linear and angular velocity 3D vector measures of each human joint. To evaluate the performance of the user on a specific exercise, the method focuses on the pre-specified features of that motion, which are the significant ones for that case. The overall evaluation score will take all the selected features into account to extract the final result. In our system, the medical expert has the option to insert different weights per exercise. The weights for all joints,

Fig. 2. Gamification Modules a) Warm Up scene: the patient is trying to catch the fresh apples and to avoid the rotten ones b) Work Out and Evaluation scene: the patient performed the exercise and is watching his/her feedback c) Shooting with turret scene: the patient is trying to hit the boxes by shooting with the turret.

including the scull base, left/right wrist, left/right shoulder, left/right hip, left/right knee, left/right ankle, cervical vertebrae 7, lumbar vertebrae 5, sacroiliac, left/right stern clavicular and left/right elbow can be set. Each feature is then multiplied by its corresponding weight $w \in [0, 1]$ where $\sum_{i=1}^{N} w_i = 1$ and N is the number of joints.

The human motion evaluation is based on the comparison of the features of the representative joints. The representative joints and their features should be defined for each type of exercise by using the described features and weights. The calculated time-sequences are the differences of position, rotation, linear velocity and angular velocity of the joints.

3.2. Gamification

The desktop application is built with Unity3D game engine and integrated development environment. Users interact with the application via gestures, exploiting the mocap data, through a Natural User Interface (NUI) that allows users to control and interact with their console/computer, giving the user a greater level of immersion.

3.2.1. Gamification Modules

The first phase of the application is to encourage users to slowly warm-up. This is achieved by creating a scenario that instructs the user to slowly avoid incoming rotten apples and to catch the fresh ones, as it is pictured in Figure 2a. To do this, the users must move their body with their arms and legs for 60 seconds. This mild warm-up is beneficial for people susceptible to cardiovascular disease as it is over strenuous and any able-bodied person can complete it. During the phases of the game, the user body is portrayed as an in-game avatar which allows the user to correctly judge the movements required to complete the level.

After the warming up, the application instructs the user to perform the prescribed rehabilitation programme, a sequence of different types of exercise repetitions. This is the core workout required to increase the cardiovascular health of the user. Successful performance of the exercises gives additional benefits to the gamification stage next. After each repetition, a message that consists of numerical and textual feedback plus instructions for performance refinement is shown, as it is figured in Figure 2b.

Since the work out is complete, additional ammo and additional power for the turret depending on the accuracy of the performance are added. The more boxes the patient knocks over, the more points is gaining. The user fires the missile by performing a displayed movement gesture, as it shown in Figure 2c. Thus, this type of gamification encourages repeat plays and therefore is beneficial to the overall health of the patient.

The diary is an additional gamification module of the platform. Users are allowed to track their progress over time and to compete against themselves while improving their heart health. The diary keeps the patient adherence analytics, in other words the frequency of each performed exercise per day and the degree of success on each exercise, in order medical professionals to monitor their patients.

3.3. Integration with FIWARE components

For the usage of IdM and CB, a REST API wrapper was created in order to combine the usage of the enablers. The wrapper acts as a mediator binding the proposed SE and game interface with the GEs. Its purpose is to provide functionality and features in a more abstract way, hiding odd implementation details from the developers, and to secure private medical data by using authentication and high security protocols to access the database.

Such features include a basic user management system, a roles / privileges back-end (both supported by the Identity Management - KeyRock GE) and a simple interface to make inquiries to the context broker (Publish/Subscribe Context Broker - Orion Context Broker). The user registration is completely managed by the FIWARE Identity Manager (IdM)[23]. The wrapper provides added functionality that enables an interested party (medical professional or patient) to register to IdM. Through this registration, the user is allowed to access the rest of the features of the wrapper.

3.3.1. FIWARE Identity Management

IdM offers the capability to create applications based on user needs. Given that, an application was created in IdM in order to manage the users of the platform by giving roles / privileges. In HeartHealth, the user registration is completely managed by the FIWARE IdM GE and based on its API, the REST-based authentication operation is developed.

3.3.2. FIWARE Context broker

CB, an implementation based in Mongo DB in order to store data and discover information, keeps the information of the recorded and reference motion data, the weights of each exercise and also patient analytics and adherence in the system. Using CB gives the ability to register context elements and manage them through updates and queries.

4. Service Usage

4.1. Administrator

The administrator is responsible for the deployment of the Motion Evaluation SE and the wrapper, the management of the members of the platform and their permissions (via the roles / privileges) and the maintenance of HeartHealth system. The HeartHealth platform provides, through the wrapper, REST API operations in order to register or delete a patient or medical professional.

4.2. End Users

A HeartHealth end user can be a CVD patient or a medical expert. The aim of the platform is to achieve the adherence of CVD patients by using a home-based solution while medical professionals are remotely monitoring the patient's activity. A HeartHealth requirement, either for patient or carer, is to register in FI-LAB platform.

A CVD patient has to meet only once with his/her medical carer to record the correct exercises, used as reference, for his/her cardiac rehabilitation program. After that, the CVD patient has to install the platform in his/her personal computer, to plug the MoCap system, either one Kinect device or one Kinect and a number of WIMUs, and to play the game by performing the exercises. During this procedure, the system automatically stores, analyses, processes the patients data and finally stores and returns analytic feedback both to patient and medical professional.

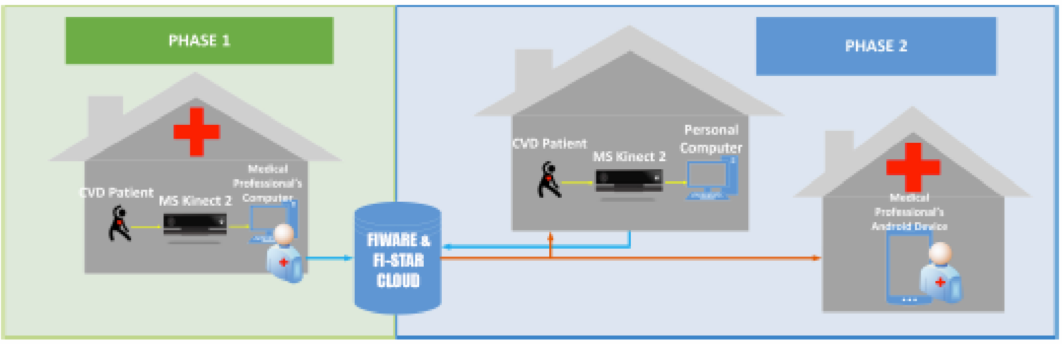

Fig. 3. High-level diagram of end-users phases and interaction in HeartHealth.

Table 1. Participants information and exercise program evaluation results.

Patient	Age	Gender	Exercises	Mean Numerical Feedback	Textual Feedback	Patient Feedback
1	74	Female	5	91%	Perfect	Interesting
2	44	Male	5	67%	Good	Comfortable
3	62	Male	5	84%	Very Good	Nice
4	55	Male	5	52%	Poor	Not interesting
5	65	Female	5	88%	Very Good	Great job
6	77	Female	5	79%	Quite Good	Useful

The medical expert can use both the game and the android interface. The game interface is used as the main tool to record the exercises since it supports the usage of the MoCap system. Thus, through the game, the opportunity to record the patient's performed exercises is given. Additionally, the medical professional can store the recorded exercises in the cloud, pinned on the patient he/she performed them, to be used as reference when he/she would run the home-based platform. Within the game, when the user is authenticated and recognized as Medical Professional, an extra option able to monitor his/her CVD patient's activity through the game is available. The monitoring, is also the main goal of the Android application for the medical experts, by using a more portable and flexible solution to achieve it. The whole high-level diagram of HeartHealth phases between the end users is presented in Figure 3.

5. Experiments

The first version of platform was accomplished in March of 2015. On 21st and 23rd of April, the platform was established in MedEx in order a group of 6 CVD patients to test and evaluate the system. All participants have established cardiovascular disease (CVD) and are currently taking part in the MedEx DCU structured exercise classes[6]. Medex Wellness is a series of medically supervised programmes where patients participate in exercise classes in a safe, friendly and supportive environment.

All of the participants for these patient trials were selected both by their willingness to provide constructive feedback and their ability to engage with technology. Patients with CVD and CHD (including those having had a percutaneous coronary revascularisation procedure), who are clinically stable, were considered. Participants were excluded if they have untreated ventricular tachycardia, severe heart failure, life threatening co-existing disease with life expectancy less than 1 year, and significant exercise limitations other than CVD. Furthermore, only appropriate individuals who had been medically screened for participation at DCU through formal procedures already in place for such scenarios were considered.

All participants completed the game in its entirety with HeartHealth team directing and answering questions. The level and type of interaction were observed by the HeartHealth team and the experimental results are reported in Table 1, listing also the age and sex of each participant. In particular, the table presents the mean score (numerical feedback in percentage) of the 5 performed exercises and the textual feedback based on the mean score. Each trial lasted 10 minutes and consisted of 5 different skills: slow jumping, slow punching, squat, slow jumping jack and stretching.

All participants took part in a semi-structured interview immediately post completion of the game. These interviews took between 10-15 minutes and responses were captured digitally via an audio device. The participants reviewed HeartHealth and most of the comments were positive, their feedback was that HeartHealth is a quite novel and useful tool for their cardiac rehabilitation programme. Additionally, the clinicians who were helping and monitoring the CVD patients during the execution of the exercises reported that such systems can empower the procedure of rehabilitation in real life. The participants suggested refinements concerning the instructions for the navigation into the platform and the way they had to perform the exercises in front of the MoCap system. Most of them have already inserted in the last version of HeartHealth platform.

6. Conclusion

The significant benefits of integrating exercise into rehabilitation are well recognized for a broad range of medical conditions [1]. However, despite the known benefits of exercise, uptake and adherence are very low, especially amongst those with medical conditions such as Cardiovascular disease (under 10% - W.H.O.). Patient adherence to prescribed exercise **is crucial** in both disease prevention and rehabilitation. The development of intuitive, low-cost, personalized home-based exercise monitoring systems can help address these issues by encouraging exercise adherence through a captivating Serious Game in a home-based Rehabilitation System that provides real-time feedback.

In this paper, we have presented a CVD home-based Rehabilitation System, which utilises enablers from the FI-WARE project and FI-STAR project that we are a part of. We have highlighted the novelty of our HeartHealth system where we have built on the, currently existing, state-of-art in serious game application to rehabilitation. We have achieved this by incorporating individualised human based biomechanical analysis to produce a truly personalized home based Rehabilitation System that incorporates real-time multi-modal patient monitoring.

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