Gait Rehabilitation System based on Mixed Reality

Teresa Vilar Paredes  
Instituto Superior Técnico, IST  
Instituto de Telecomunicações, IT-IUL,  
Lisbon, Portugal  
Teresa_paredes97@hotmail.com

João Monge  
Instituto Universitário de Lisboa, ISCTE-IUL  
Instituto de Telecomunicações, IT-IUL,  
Lisbon, Portugal  
jpdm@iscte-iul.pt

Octavian Postolache  
Instituto Universitário de Lisboa, ISCTE-IUL  
Instituto de Telecomunicações, IT-IUL,  
Lisbon, Portugal  
opostolache@is.iit.pt

Pedro Silva Girão  
Instituto Superior Técnico, IST  
Instituto de Telecomunicações, IT-IUL,  
Lisbon, Portugal  
psgirao@tecnico.ulisboa.pt

Abstract—Throughout the years, physiotherapy has become increasingly crucial in recovering members of the human body. However, for a faster recovery, physiotherapy requires a commitment from the patients to embrace therapy outside of its sessions. This commitment is not always accomplished due to a lack of motivation. To help with this problem, Gamification was introduced in treatment. Patients strive to achieve every level, which allows a better and more efficient recovery. To obtain an even better and faster recovery, augmented reality and virtual reality started to be used in this field of medicine. This primary project goal is to create a challenge game to improve the inferior members’ functional recovery. This game will be built with the Unity3D platform, using the RFduino microcontroller, Structure Sensor, and Apple Watch. To help code this project, platforms such as Swift, PHP, MySQL, and Arduino will also be used. The obtained results were satisfying. Rehabilitation games help patients improve in therapy and give information that otherwise would not be available. In the future, having an integrated sensor to monitor a real-time heart rate would improve this project.

Index Terms—Mixed Reality, Lower Limb Rehabilitation, Physiotherapy, Sensors

I. INTRODUCTION

EACH year, the number of episodes that cause the injury or deformity of a particular lower limb has been increasing [1]. Physical Therapy is often prescribed to patients following certain surgeries or illnesses to decrease the pain, treat tissue trauma, and improve functional capacities. The profession has already grown to include sub-specialties, such as orthopedic, sports, chronic pain syndrome, neuro-rehabilitation, and others [2]. Despite doing this type of therapy, the sessions may not be sufficient for an effective treatment for the members mobility. The physiotherapists recommend a series of repetitive tasks outside the therapy sessions to exercise more on the injured limb.

The problem with this type of recovery is that the patient does not feel motivated nor can recognize whether he is performing the exercises correctly. There are already some games whose goal is to stimulate and entertain the patient while fighting this negativity towards self-rehabilitation. This is called Gamification.

Gamification is the possibility of designing a game through everyday routines and tasks. With this platform, people feel the need to prove their potential by achieving every game-level, due to competition, and showing off their progression.

To go beyond traditional games and achieve more significant and better patient interaction, using a technology called Mixed Reality (MR) is suggested.

Mixed Reality (MR) is a modern computer technology that stimulates the human senses through an interactive simulation. This technology is already in use in some medical rehabilitation areas and has shown results in the specific area of neuro-rehabilitation. Neuro-rehabilitation is a healing process whose primary goal is the recovery of an injury of the nervous system. It is a long recovery that can sometimes be tedious and monotonous [3]. The use of Mixed Reality (MR) in this area helps the patient rehabilitate muscles and stimulates the cognitive part while undergoing fun environments.

Although neuro-rehabilitation is the area where most researches are being held, having shown significant improvements, this work aims to assess the applicability of MR in physiotherapy by building a serious game that will essentially focus on the functional recovery of the lower limb.

II. RELATED WORK

Over the past decades, human-computer interface research has been developed, leading to the discipline known as Human-Computer Interaction (HCI). The latest progress in sensors is giving rise to a new area of computer input from environments. Without environmental information, backgrounds cannot blend between physical and digital realities.

Combining human input with computer processing and environmental input sets the platform for creating real Mixed Reality (MR) experiences is obtained. Movement within the physical world can translate to action in the digital world. Boundaries in the real world can affect application experiences, such as gameplay, in the digital world.

MR brings together the physical world and digital elements. In MR, the user interacts with and manipulates physical and virtual objects, using sensing and imaging technologies. Mixed reality allows you to understand and immerse yourself in the

Patients strive to achieve every level, which allows a better and more efficient recovery. To obtain an even better and faster recovery, augmented reality and virtual reality started to be used in this field of medicine. This primary project goal is to create a challenge game to improve the inferior members’ functional recovery. This game will be built with the Unity3D platform, using the RFduino microcontroller, Structure Sensor, and Apple Watch. To help code this project, platforms such as Swift, PHP, MySQL, and Arduino will also be used. The obtained results were satisfying. Rehabilitation games help patients improve in therapy and give information that otherwise would not be available. In the future, having an integrated sensor to monitor a real-time heart rate would improve this project.

Index Terms—Mixed Reality, Lower Limb Rehabilitation, Physiotherapy, Sensors

I. INTRODUCTION

Each year, the number of episodes that cause the injury or deformity of a particular lower limb has been increasing [1]. Physical Therapy is often prescribed to patients following certain surgeries or illnesses to decrease the pain, treat tissue trauma, and improve functional capacities. The profession has already grown to include sub-specialties, such as orthopedic, sports, chronic pain syndrome, neuro-rehabilitation, and others [2]. Despite doing this type of therapy, the sessions may not be sufficient for an effective treatment for the members mobility. The physiotherapists recommend a series of repetitive tasks outside the therapy sessions to exercise more on the injured limb.

The problem with this type of recovery is that the patient does not feel motivated nor can recognize whether he is performing the exercises correctly. There are already some games whose goal is to stimulate and entertain the patient while fighting this negativity towards self-rehabilitation. This is called Gamification.

Gamification is the possibility of designing a game through everyday routines and tasks. With this platform, people feel the need to prove their potential by achieving every game-level, due to competition, and showing off their progression.

To go beyond traditional games and achieve more significant and better patient interaction, using a technology called Mixed Reality (MR) is suggested.

Mixed Reality (MR) is a modern computer technology that stimulates the human senses through an interactive simulation. This technology is already in use in some medical rehabilitation areas and has shown results in the specific area of neuro-rehabilitation. Neuro-rehabilitation is a healing process whose primary goal is the recovery of an injury of the nervous system. It is a long recovery that can sometimes be tedious and monotonous [3]. The use of Mixed Reality (MR) in this area helps the patient rehabilitate muscles and stimulates the cognitive part while undergoing fun environments.

Although neuro-rehabilitation is the area where most researches are being held, having shown significant improvements, this work aims to assess the applicability of MR in physiotherapy by building a serious game that will essentially focus on the functional recovery of the lower limb.

II. RELATED WORK

Over the past decades, human-computer interface research has been developed, leading to the discipline known as Human-Computer Interaction (HCI). The latest progress in sensors is giving rise to a new area of computer input from environments. Without environmental information, backgrounds cannot blend between physical and digital realities.

Combining human input with computer processing and environmental input sets the platform for creating real Mixed Reality (MR) experiences is obtained. Movement within the physical world can translate to action in the digital world. Boundaries in the real world can affect application experiences, such as gameplay, in the digital world.

MR brings together the physical world and digital elements. In MR, the user interacts with and manipulates physical and virtual objects, using sensing and imaging technologies. Mixed reality allows you to understand and immerse yourself in the
world around you, even while interacting with a virtual environment. Since Mixed Reality combines both physical and digital worlds, these two realities define the polar ends of a spectrum known as the virtuality continuum. Most Augmented Reality (AR) and Virtual Reality (VR) contributions accessible today represent a small part of this spectrum and are considered subsets of the broader Mixed Reality (MR) spectrum.

The MR hardware aims to create an environment without the barriers that are usually associated with daily technology. Mixed Reality (MR) improves the game’s quality with realistic scenarios; it simplifies complex problems and creates interest by conceiving an immersive experience while still aware of the real world.

A. Medicine

Medicine is one of the greatest beneficiaries of the progress of Augmented Reality (AR) and Virtual Reality (VR). The use of these technologies has been proved efficient in the healthcare segment. Even though the medical field is yet to be adequately explored, it is possible to find many examples that show the positive effect of these technologies in patients’ lives.

1 Physiotherapy

Neuro-rehabilitation steps in to help patients overcome brain injuries. Patients can benefit from the MR based treatment since it helps enhance movements, communication, and, most importantly, the brain’s cognitive part [4].

The nervous system is a sophisticated system that manages and controls all the body functions. If something goes wrong with a portion of it, people can struggle to move, speak, swallow, breathe, or learn. Physiotherapy is remarkably relevant for patients who have had or that currently have neurological diseases. Without physical therapy following a neurological injury, patients may suffer numerous functions losses, be unable to complete regular activities, or lose their independence.

Although some techniques are already used for neuro-rehabilitation, such as compensatory, psychoeducation, therapeutic, and cognitive treatments, these technologies have been providing higher value for rehabilitation [3]. For neuro-rehabilitation, Leap Motion and Oculus Rift are one of the most effective in a good improvement.

The Leap Motion controller is a natural user interface with an infrared camera, mainly designed to track fingers, hands, and arms [5]. It tracks up to 20 bones per hand, at up to 200 frames/second with a 150° field of view and about eight cubic feet of three-dimensional interactive space. Leap Motion is usually used as the primary interactive device for tracking motion and helping target acquisition within the virtual world [6].

Oculus VR was presented as an economical three-dimensional VR head-mounted display. With a 3-D inertial sensor, the Oculus Rift uses a customized Oculus VR algorithm to track and monitor head movement. The content displayed can be compensated in an immersive Virtual Reality environment [7]. Despite being initially designed for the gaming business, researchers have recently explored using it in rehabilitation [8] and pain distraction. It contains a 7° screen with high resolution and a 90° field of view, allowing head positional and rotational tracking enabling the user to control the viewpoint within Virtual Reality [6] [7].

The neuro-rehabilitation Mixed Reality (MR) therapy system technology introduces advantages in every aspect of the therapy and, from the patient’s testimonials, and overall more satisfying physical and mental wellness [3].

Orthopedics, another branch of physiotherapy, focuses on surgery or the manipulation of the musculoskeletal system. Orthopedic physical therapy involves the treatment of muscles, bones, ligaments, and tendons. The treatment depends on the injury, but patients usually undergo therapy with joint mobilizations, strength training, and mobility training.

Physical rehabilitation based on Kinect Serious Games is an already developed game to help in therapy. Kinect was produced by Microsoft and is a line of motion sensing input devices. This technology also incorporates RGB cameras, infrared projectors, and detectors that mapped depth through flight calculations or structured light and a microphone array. All of these, along with software and artificial intelligence from Microsoft, allows the device to recognize gestures, voice, and body skeletal movements [9].

The Kinect allows the interaction with the system in a 3D atmosphere, where they perform multiple movement combinations without an appended device or a controller. It provides a rehabilitation service that increases adherence to therapy by adding entertaining and exciting features. Besides, it also reduces the high cost compared with traditional rehabilitation making it more affordable and available to everyone.

As an alternative to Kinect, wearable motion sensors based on accelerometers and gyroscopes are excellent solutions to evaluate gait dynamics. Numerous vital features can be obtained from the sensors based on the linear and angular motion measures obtained from body kinematics [10].

Following this approach, Bertolotti et al. [11] developed an ingenious wearable device based on an Inertial Measurement Unit (IMU) that obtains information from back and limb movements. The method allowed the motor and balance control skill assessment based on linear accelerations, angular velocities, and heading. The writers compared the center of mass displacements on the X and Y plane obtained using the center of pressure of the Wii balance board, which was considered a robust tool for these kinds of measurements.

The Wii balance board is part of the Wii video games console developed by Nintendo and has built-in wireless capabilities that communicate via Bluetooth with the Wii. This board has load sensors to determine the players center of gravity and track his movements, allowing physiotherapists to help patients improve. Even though this game is not as effective as one built for physiotherapy, it contains many activities designed to engage the user in physical exercise. These challenges, such as yoga poses, strength training, aerobics, and balance games, have been used to help rehabilitation.

III. System Description

This work aims to evaluate the applicability of MR in the functional recovery of balance and lower limb movement. The rehabilitation process will be more beneficial for patients since an MR serious game will be built using the Unity3D platform,
which will allow the coding of the different levels. Some sensors will be used alongside this platform, such as 3D IMU and 3D Occipital Structure sensor. The IMU is associated with an RFduino computation platform that communicates with the mobile game computation platform via Bluetooth Low Energy (BLE). The second sensing system will enable the room's mapping and allow the user to immerse himself in the serious game. The Apple Watch Series 5 will be used to obtain physiological information about the patient. A database will also be developed to store information about the patients and their improvements. Swift and PHP, two c programming languages, will also build an iPhone Operating System (iOS) application that facilitates access to the game.

A. Hardware:

1. Structure Sensor

Structure Sensor adds a perfect 3D vision to Apple mobile devices (iPhone or iPad). It enables a growing set of advanced capabilities such as 3D scanning, indoor mapping, and mixed reality experiences. In this project, it will be used Structure SDK for iOS, which grants developers a stable, easy-to-use, flexible, and constantly-improving framework for designing applications [12] (Figure 1).

The Structure SDK built by Occipital allows users and developers to scan objects and people and enables the Three-dimensional (3D) mapping of interior spaces.

When used as a 3D scanner, the sensor concedes the capture of solid geometry in real-time. This capture enables the developer to simulate real-world physics and create high-fidelity 3D models [13]. This device is of utmost importance in this project since it will scan the room where the game player will do the physiotherapy, allowing Mixed Reality (MR). With this, the user can enter and feel immersed in a virtual world while still staying comfortably aware of the real world.

It is relevant to highlight that this sensor not only allows the creation of a Virtual Environment (VE) but also enables the use of an Augmented Reality (AR). If the Structure Sensor moves in the real world, it runs the same way in the VE, without prior knowledge of the physical space.

2. IMU Sensor

To extract the user balance information, and the kinematic and dynamic parameters during the game, an IMU smart sensor based on MPU9250 and RFduino was considered.

RFduino is a small, slim, and Arduino-compatible device with an on-board Bluetooth Low Energy (BLE) radio created by RF Digital. This microcontroller combines an RF module, a few connectors, and a built-in antenna.

The BLE radio, which is inside the RFduino, is a system-on-chip for ultra-low power Bluetooth Low Energy (BLE) applications with an "ARM Cortex M0 microcontroller, memory (Flash and RAM), the BLE radio itself and some other functional blocks" [14] (Figure 2).

A Microprocessing Unit (MPU) is a device that executes the critical elements of a computer system on a single integrated circuit, in the case of this project.

MPU9250 provides the most reliable data quality, with nine degrees of freedom than other processors [15]. The MPU magnetometer allows us to measure magnetism, such as the direction, strength, or relative change of a magnetic field at a distinct location. The accelerometer is an electronic sensor that measures the acceleration forces acting on an object to define the object's position in space and monitor its movement. A gyroscope is a device applied for measuring or maintaining orientation and angular velocity. The last two are used in this project to obtain the user's position and acceleration and the angles pitch, yaw, and roll in real-time.

3. Apple Watch

The iWatch used for the development of this project is the Series 5. This watch features an innovative new display that always allows the time and essential information to remain visible.

The possibility of creating an application with Swift for the Apple Watch is a great advantage for this work. Swift User Interface provides event handlers for delivering touches, gestures, and other types of input into the application and tools to manage the flow of data from the desired app's models down to the views and controls that users will be able to interact with.

The aim is to have the main page in the watch to start the therapy measurements. This page will have a start and stop button that must be touched when the game begins. As soon as the start button is played, the heart rate measurement and the number of steps will begin to be counted. With the REST API's help, this information will be sent to the database and displayed on the GaitMR mobile application.
B. Software

1. Unity3D

Unity3D is a real-time creation platform that provides users the basic set of characteristics to build games quickly and efficiently. The platform also provides a workspace that combines component-driven design with artist-friendly tools, creating a comfortable and intuitive game development [16].

Unity3D has an approach to develop games that revolve around Assets. An asset represents any item used in the game, and it may come from data that Unity supports or from ones that were built outside the platform [17].

The creation of a project in Unity3D implies the use of different game assets. As the game progresses, a technique based on reusing the same asset in various game areas is practiced. This technique is vital for speeding up both the asset creation process and the level design and is called Prefab.

The significant advantage of using the Unity3D engine is that with the support of most operating systems, games developed in Unity can be deployed to any platform. Besides the cost efficiency, the visual platform and assets store is also reportedly better than other platforms [18].

2. Database

To have a full assessment of the patients movements, a database in MySQL was built. MySQL is an open-source relational database management system based on Structured Query Language (SQL). SQL is a programming language used by almost all relational databases to query, manipulate, define, and provide access control. It is most well-known for its quick processing, proven safety, and flexibility of use.

![Figure 3: Serious Game Database](image)

This database organization is beneficial since it provides all the patient's data to the physiotherapist. Later, he can check whether there has been improvement and what therapy is more suitable for each patient.

3. Mobile Application

Swift is the result of the newest research on programming languages, combined with decades of practice building Apple platforms. It is a powerful and instinctive coding language for these platforms, such as the Macintosh Operating System (MacOS) or iPhone Operating System (iOS), and Linux.

Swift code co-exists along with Objective-C files in related projects, with full access to the Objective-C Application Program Interface (API). Working with this API is a great benefit since it supports many core concepts. A mobile application that offers a direct line to the game is a unique advantage to this project. The main goal is to give the physiotherapist easy access to the patient's information and improvements and the users easy access to the game and their training schedules.

![Figure 4: Mobile Application Flowchart](image)

Figure 4 presents the flowchart from the mobile application. The start button represents the initialized application. When this APP opens, the login menu is displayed. If the user has not registered yet, he can load the register menu to create an account. After such, the user has to validate his account on his email, and then the login menu will be displayed so that the user can login. As soon as the login is done, the menu is opened. This menu shows two different buttons, the "Train" button, and the "View Data" button. If the user presses the "Train" button, the user has to add a "Train name" and be redirected to the game. If the "View Data" button is tapped, the user is asked to select a date. If the date has no data, then an alert is showed to the user. If the date has information, then this information is displayed for the user.

IV. GAME DESCRIPTION

The implemented iOS application includes two types of menu: one to perform login and register the patients. This application will allow the user and the physiotherapist to track the patient's data and check whether there have been improvements or not. This data tracking is possible since every time the game is played, the information about the patient's points, collisions, and time, as well as the RFduino information, such as the position, and the angles pitch, yaw, and roll are stored in the MySQL database.

This game is divided into three different levels with different purposes. The first level aims to help the user balance himself between two straight walls. There will be a time counter to monitor how long it takes for the patient to go from one point to another. This level informs the user if he touches the wall and loses balance. This level has no time constraints since each user
needs his time to perform the level, depending on their pathology. After each train, the physiotherapist has access to the patient's performance and will arrange adequate training to correct common mistakes. Figure 5 represents the serious game first level, with a timer and the real-time angles pitch, yaw, and roll, in brackets.

![Figure 5: Serious Game First Level](image)

The second level's goal is to check how many bottles the user can catch in 30 seconds. The user can grab all the bottles by colliding with them in the mixed reality. As soon as the user is in the same position that the bottle is, the bottle is grabbed. Every time the user holds a bottle, a cheering sound is heard, and the number of grabbed bottles appears on the screen. When the ten bottles are gained or the training period (30 seconds) is finished, the level updates to the last one (Figure 6). The information regarding the time the user took to catch all the bottles or how many bottles he grabbed during the 30 seconds will allow the physiotherapist to comprehend the patient's balance and movements.

![Figure 6: Serious Game Second Level](image)

Every level is also coded so that if the user falls, an alert is presented for him. The aim of giving an alert to the user is the possibility of asking for help. If the structure sensor's position equals the ground's position, then a message for the physiotherapist appears on the screen. It depends on the user if this message is sent or not. If the user stays motionless for more than 10 seconds, an emergency call is made automatically for the emergency services.

![Figure 7: Serious Game Last Level](image)

The third level will be similar to the second. The last level will have rewards along the way that the user should earn to gain points and objects that withdraw ends. The goal is to gain as many points as possible in the time-frame of one minute. As soon as the user gets the 3 bars of gold or the time finishes, the game ends (Figure 7). Even though this level is similar to the previous, it will allow the physiotherapist to comprehend the patient's movements because the goal is not to touch the trash bags. These bags of trash are placed strategically so that the patient needs to balance himself. Any undesired movement will make the user lose points and tell the physiotherapist that the patient is still not balanced, adjusting the rehabilitation.

![Figure 8: Heart rate from a patient starting rehabilitation](image)

V. RESULTS AND DISCUSSION

The results were gathered with seven different rehabilitation patients. Most of these patients went through surgery and were doing physiotherapy to regain balance. While doing the serious game, most patients felt anxious, with a heart-rate between 100-130bpm (Figure 8). This physical stress happened since patients were starting a new challenge and wanted to show improvements. In some other cases, the heart rate was high because the patients were making a physical effort to recover and in pain due to the surgery. While at rest, people should have a range of values from 60 to 100bpm. However, while doing exercise, young people expect higher heart rate values that can go up to 190bpm. On the other hand, older people are only expected to reach values of 120bpm. Even though this project does not require much training, being compared to regular walking, it creates physical stress in patients and demands physical effort due to the injuries, increasing the heart rate. We can then conclude that the patients' values are expected, taking into account these factors.
abilities reflected when she played the game. Patients that were doing physiotherapy for a long time felt more relieved to know what kind of game and achievements they needed to perform, making them less stressed.

In Figure 8 and Figure 9, it is possible to observe the different heart-rate of different patients. The y-axis presents the number of beatings per minute during the serious game, and the x-axis the time in seconds. Even though the zoom, these graphics represent the whole game, from the first to the last level.

![Figure 9: Heart rate from a patient that already played the game](image)

The values from the Inertial Measurement Unit were also obtained and displayed in the mobile application. These values depended on the patient's injury. Figure 10 represents the same train for the same patient at different times. The charts show peaks consistently on the roll and yaw angle, which means the patient moved around a lot. It is expected that every time the player plays a serious game, these charts start to improve and become linear. In the y-axis, it is possible to observe the angles itself, from [-200,200]°. These angles do not go to 360° because some restraints were implemented regarding the angles range. The x-axis represents the number of samples of the IMU.

![Figure 10: IMU values throughout the serious game](image)

In Figure 11, it is possible to see a balance chart from the first level, where we observe a patient who had a problem on the left knee. Because of this injury, the patient limps and has more collisions with the left wall. We can observe five collisions with the left wall and four collisions with the right wall. Sometimes, when the user is trying to balance himself, he touches the other wall. This is why it is possible to check collisions with both walls.

![Figure 11: First Level information of a patient with a left knee injury](image)

Figure 12 presents a graphic from a patient that had balance problems on his right. Therefore, similarly to the last illustration, it is possible to see four collisions with the right wall. This information will allow the physiotherapist to compare every training session and check if there have been improvements and what kind of exercises are more suitable for each patient.

![Figure 12: First Level information of a patient with a right knee injury](image)

**VI. CONCLUSIONS**

Rehabilitation games help the patients to improve in therapy and give information that otherwise would not be available. Information regarding the patient's balance and movements helps physiotherapist learn and adequate every training session so that the rehabilitation has a quicker process. In the future, having an integrated sensor to monitor a real-time heart rate would improve this project. This would be great since it would help display the heart-rate while playing the serious game, not making the patient look to the apple watch.

**REFERENCES**


