Remote Monitoring of Physical Rehabilitation of Stroke Patients Using IoT and Virtual Reality

Octavian Postolache, D. Jude Hemanth, Ricardo Alexandre, Deepak Gupta, Oana Geman, and Ashish Khanna

Abstract— **The statistics highlights that physical rehabilitation are required nowadays by increased number of people that are affected by motor impairments caused by accidents or aging. Among the most common causes of disability in adults are strokes or cerebral palsy. To reduce the costs preserving the quality of services new solutions based on current technologies in the area of physiotherapy are emerging. The remote monitoring of physical training sessions could facilitate for physicians and physical therapists' information about training outcome that may be useful to personalize the exercises helping the patients to achieve better rehabilitation results in short period of time process. This research work aims to apply physical rehabilitation monitoring combining Virtual Reality serious games and Wearable Sensor Network to improve the patient engagement during physical rehabilitation and evaluate their evolution. Serious games based on different scenarios of Virtual Reality, allows a patient with motor difficulties to perform exercises in a highly interactive and non-intrusive way, using a set of wearable devices, contributing to their motivational process of rehabilitation. The system implementation, system validation and experimental results are included in the paper.**

Index Terms— **Physical rehabilitation, virtual reality serious games, wearable smart sensors, Internet of Things.**

I. Introduction

THE changes in the industry of healthcare for some years this part has been one of the most transformative. The industry that was previously restricted between doctors and patients, now has a third-party member attached – Technology. Although the information and communications technology has already found its place in the field of medicine and its operation, nowadays it is an integral part and dominates the market of healthcare at the patient level. The objectives of personalized interactive training with higher motivation from the patient side are nowadays satisfied joining technologies such Virtual Reality (VR) and wearables devices. Both technologies, while impacting, are allowing themselves to create a greater presence and impact in the lives of patients and physicians in partnership with devices that are always with them. Due to technological evolution, healthcare mobile apps becoming an integral part of users' home screens, when mixed with transformative technologies like VR and wearable healthcare devices, they have the immense potential to change the way the health ecosystem interacts with the masses and are increasing in Healthcare domain. The mobile devices together Mobile Apps are used as computation platform, as communication platform and as Graphical User Interface (GUI) for patients and clinical staff. One of the motivations of this research is to improve the quality of physical therapy services and to decrease the costs in the context of the pressure on the services caused by aging phenomena [1]. Ageing as a natural process it is in generally accompanied with degradation of daily motor activity associated with muscle-skeletal impairments that may also occur after stroke events.

The post-stroke patients are another group of the population that requires physical rehabilitation services to improve their motor skills. The reported statistics underline the stroke as the number one cause of severe physical disability in world [2]–[4]. If secular trends continue it is estimated that there will be 23 million first ever strokes and between 7-8 million stroke deaths in 2030 [4]. Strokes can usually cause severe physical disabilities, such as attention deficit, pain, weakness and paralysis, usually on one side of the body. Such deficiencies may result in loss of ability to perform typical day-to-day activities [5]–[7]. Several methodologies can be developed for improving the lifestyle of stroke patients [5]–[15].

Patients need to practice physical rehabilitation exercises to improve their motor condition, the exercises being recommended in the physical therapy clinics but also at home to reduce the rehabilitation times which will help patients to improve their psychological conditions. In addition, recent studies reveal that early and intensive rehabilitation may lead to recovery of motor function capacity [16], [17]. The traditional rehabilitation process based performed with classical physical rehabilitation equipment requires repetitive exercises that may be annoying and mundane [18]. Consequently, this could lead to patients' lack of interest and reduced motivation for the rehabilitation process, which can have serious

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consequences for their rehabilitation quality and rehabilitation period with higher costs for the healthcare system. Daily physical rehabilitation program requires that patients go to the hospital or rehabilitation center for training. This requires a lot of effort in patients who are already suffering from mobility difficulties. Often, some of the patients cannot go to rehabilitation centers because of the cost involved [19]. Even if the cost is not the problem, the patient may not have the incentive to go to a rehabilitation center to perform the exercises. The reported research underlines the relation between the improvements of motor functionalities and patients' motivation [20] and good communications based on objective data between the patients and caregivers.

In times of continuous high technological and economic progress, many people are affected by physical and/or motor limitations due to a variety of reasons, as well as depression caused, among other things, by the need to resort to rehabilitation sessions. Scientists are constantly on the lookout for new ways to prevent and treat physical disorders, as well as ways to intervene in diagnosis to make it more prosperous and effective for those in need of permanent care, using the latest achievements in computer science. The health community has shown an increasing interest in therapeutic approaches based on different Virtual Reality scenario applications [21]. Stimulated by the progress in game development and computer graphics hardware, serious games are getting involved in many institutions like military, health, education and entertainments. Virtual reality (VR) has been used in physical rehabilitation to engage patients who suffer from stroke to train upper limb motion. In the literature several VR games are reported regarding the physical rehabilitation [22]. The used games are giving to patients the ability to interact with virtual objects in real-time during physical training sessions improving their particular motor skills. The therapists are responsible for setting the system for patients according with particular prescription.

On the other hand, there has been an exponential increase in the market offer on the level of body measurement sensors available as wearable devices, allowing users to create monitoring applications - starting with a simple heart rate to a limb movement response. These sensors create different datasets available in real time for different data discovery techniques by the researchers, for example, in the feedback process. The big growth of the measurement sensors capabilities and the networking technologies are found to be very useful for healthcare applications [20]–[34]. The IoT healthcare solutions are already visible on a global scale, where traditional equipment are replaced by new ones IoT compatible devices that provide the possibility to develop and apply new practical methods as part of healthcare services. The wearables solutions are able to revolutionize healthcare services where physiological and motor parameters are monitored to provide personalized healthcare based on information regarding health status, physical activity, behavior and other parameters such air quality that affect the quality of daily life [26].

II. Related Work, Research Challenges and Novelty

Wearable devices have become a very convenient solution to track a patient's health status. There are now reported an increased number of medical wearable devices that not only help monitor but also for treat and rehabilitate chronic diseases, such as devices equipped with ECG and EMG biosensors to detect cardiovascular diseases [19], devices equipped with electro-muscular stimulation to promote muscle activation and recover injuries [20], or pressure and force sensors applied in insoles and connected to software tools (mobile or web apps) to allow the analysis and monitoring of a patient's gait [21].

Several studies are being carried that present new ways to adapt the new technologies from IoT industry [21], [22], and VR gaming tools [23], [24] to create new healthcare solutions with focus on physical rehabilitation. The immersion provided by games and capacity of measuring various types of data with advanced wearable computing technology and miniaturized sensors, has been considered an excellent solution to response to physical rehabilitation challenges. Serious games involve different technologies such as Virtual Reality (VR), Augmented Reality (AR) or Mixed Reality (MR), sensors, telecommunication technologies, computing interfaces and dedicated servers or cloud services, as well as related in [25]. These technologies can support accurate and detailed capture of kinetic and kinematic complex variables during motor rehabilitation (e.g. standing or walking pressure, time and speed of limbs movements).

Virtual Reality (VR) is described in [26] as "a high-end user computer interface that involves real-time simulation and interactions through multiple sensorial channels" has induced a sense of "presence in" and "control over" the simulated environment [27], [28]. In the reported research presented in [29], the authors proposed a platform that might use various devices (such as Microsoft Kinect, Nintendo Wii Remote, Data Glove or CyberGlove, Leap Motion Controller) and open source software to create low-level keyboard and mouse events that most games treat as input from a real peripheral device. In order to approach the physical rehabilitation services with all the technologies reported in the relevant literature presented, this study is conducted with the objective of exploring a viable solution to fill the need for a rehabilitation system that will help patients and physical therapy clinics, whether in the evolutionary process of patient monitoring as well as the points of reduction of costs associated with each rehabilitation process.

We identify that such a system should be able to allow patients to perform remote physiotherapy at home according to some indications which will be provided by the caregivers. This will reduce the number of patients that need to go to the clinics and increase the commitment of the patients with their rehabilitation process. Such a system was designed to perform the physical therapy assessment of the patients analyzing their progress. This publication results from the further development of the studies presented and reported by the authors in [35]–[49].

III. Materials and Methods

A practical approach regarding optimized physical rehabilitation process based on VR serious game with emphasis on data analyses of the data extracted during the training

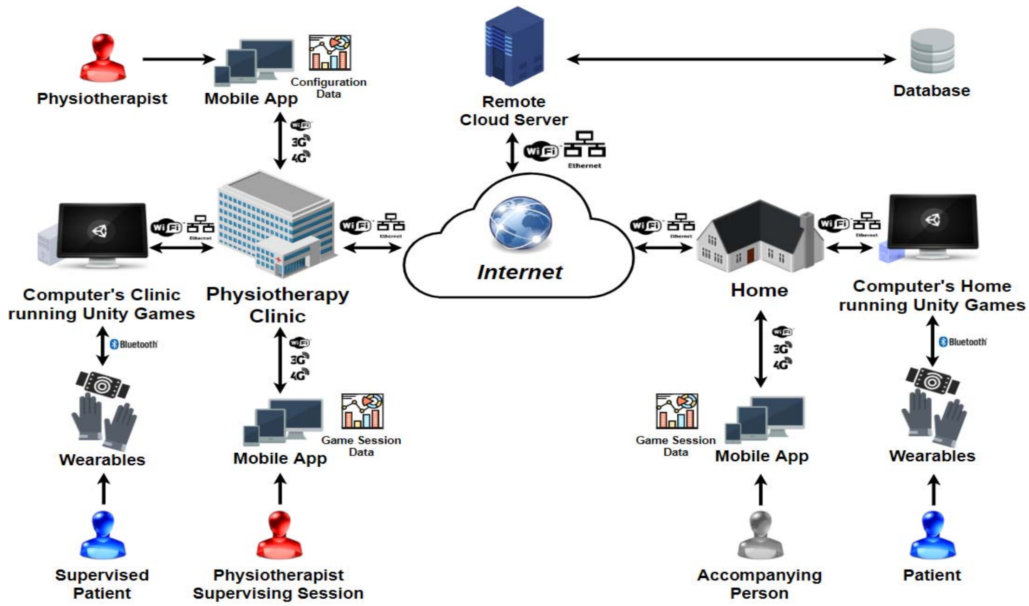


Fig. 1. The VR serious game physical rehabilitation system with wearable user interface.

session where the patients are using wearable sensor devices to interact with VR game scenario. The proposed system in Fig. 1 is expressed by a low-cost hardware and software components that provides Virtual Reality (VR) interaction during therapeutic serious games. As core of the system can be mentioned an IoT Wearable Sensor Network (WSN) expressed by a set of smart sensors embedded in a pair of gloves and a headband.The VR serious games were implemented using Unity 3D software which also includes an IoT module and sensors. The smart gloves materialize a natural interface applied to motor and physical rehabilitation of in users with hands and fingers motion impairments.

The headband device that includes an Atmel AVR based computation platform connected to an IMU is responsible to the measurement of the rotation values (Euler Angles) and linear accelerations of the head with the aim of integrating the patient into First-Person Controller, allowing the navigation in the VR environments of serious games, in a semi-immersive way. These measurements can be also used to evaluate the posture of the user during the training using the serious games.

The wearable devices are using Bluetooth communication to deliver the data from the measurement channel to clinic computer or to the home computer that it is connected to the Internet. The mobile devices are using Wi-Fi Internet connectivity and can be used by physiotherapist, patient or accompanying person. The clinic manager performs the management of physiotherapists. While playing the serious game the patients interacts with the system and motion characteristics performed by these users are registered by the system. The physical therapy training sessions are performed in physiotherapy clinics where the patient is under physiotherapist supervision or at home environment without specialized supervision, such as it is shown in Figure 1. At home accompanying person may give support and also can verify through the mobile APP the results of the performed sessions. Either way, the user's experience is the same. Following this, the therapists access this information through the mobile application, using a computer, a tablet or a smartphone. The patient's motion calculated metrics are presented through graphical representations. A textual report can be generated by physiotherapists based on calculated metrics that also assure a feedback for the patients, improving communication physiotherapists and patient for active commitment to the rehabilitation process.

System software modules and interactions are:

- **Physio Wear Mobile Application** is developed in Microsoft Xamarin using C# programming language. These are used by the clinical administrators, physicians and the patients.
- **Smart Wearable Devices** (smart gloves and headband) developed with the Arduino Platform for use with therapeutic serious games by patients, connected to host computer with serious games via Bluetooth.
- **Physio Wear Gaming Application** helps the patient to assess the therapeutic virtual games.
- **Web Server** is mainly used to store the large amount of data. It can be both the inputs and the results.

Both the Unity game application and the mobile application require an Internet connection (Wi-Fi, 3G or 4G) as well as the server side itself, to allow the Web API to perform in the processes of reading or writing the data in the database.

A. System Description: Sensors

The kinematic and dynamic characterization of the hand usage during the training sessions implies the usage of different measurement channels that are associated with:

- Acceleration (tri-axial acceleration);
- Orientation (tri-axial orientation);
- Force (compression and extension).

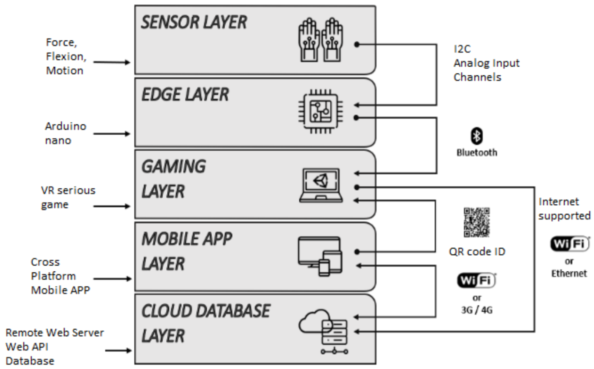


Fig. 2. Healthcare IoT architecture for VR serious game.

The measurement channels are including the sensors, conditioning circuits and/or wired communication interface connected to the computation platform (Arduino nano) that materialize the sensor and edge layer of Healthcare IoT architecture for physical rehabilitation presented in Fig 2. As it can be observed the force, flexion and inertial qualities measurement are associated with sensor layer. Thus, for the finger applied force and finger flexion two sets of piezo-resistive sensors were considered as part of smart gloves (Fig.2). Thus, a set of 5 piezo-resistive Flexi Force A201 sensors to extract the pressure values exerted on the tips, as well as a set of 5 piezo-resistive FlexSensors 2.2", to obtain finger flexion values are considered. The measured values of finger flexion and the finger applied force by fingertips are visualized in the VR scenario developed on Unity 3D gaming platform. Considering that the analog inputs of microcontroller are voltage compatible the conditioning circuits for the force sensor channels are expressed by resistance to voltage converters expressed by voltage divider and a follower based on operational amplifier LM324.

The acquisition of the signals associated with 10 analog sensors for each glove is performed using the Arduino Nano that will be later described. To reduce the number of analog input channels time multiplexing methods was implemented on the level of the microcontroller. So, it was possible to acquire reliable readings from two different analog sensors associated with each finger using a single analog input channel.

To extract hand motion information a set of SparkFun MPU-9250 IMU Breakout were used. The MPU-9250 IMU is a 9-axis MEMS sensor that combines two chips: the MPU-6500, which contains a 3-axis gyroscope as well as a 3-axis accelerometer, and the AK8963, which features a 3-axis magnetometer. The acquisition of 9-axis information is performed by 16-bit analog-to-digital converter. By data fusion it is possible to obtain the linear acceleration values and reliable values for the rotational movements.

B. System Description: Computation Platforms

The implemented system that supports VR serious games is characterized by different computation platforms materialized on the edge layer, gaming layer mobile APP layer and cloud database layer. The edge computation layer is expressed by

TABLE I

COST ESTIMATIVE OF HEALTHCARE IoT ARCHITECTURE FOR VR SERIOUS GAME

IoT layer	Components	Cost Estimative
Sensor Layer	10xForceS, 10xFlexionS, 3xIMU, Conditioning circuits, gloves, band	350$
Edge layer	3xArduino nano 3xBluetooth HC05	100$
Gaming layer	1xminiPC Gigabyte 1xHDMI monitor	900$
MobileAPP	1xTablet	450$
CloudDatabase Layer – Remote server	Cloud Service for year 128GB, 4GB RAM, dual core Xeon	<100$

Arduino nano that is based on low power consumption (Power Consumption: 19 mA) of Atmel AVR ATmega328P microcontroller, breadboard-friendly board with reduced dimensions (PCB size: 18mm $\times$ 45mm), very light (Weight: 7g) and works with a Mini-B USB cable with operating voltage of 5V, that it is characterized by 10bits ADC and 8 multiplexed analog inputs, with built-in input/output support, a standard programming language, which originates from Wiring, and is essentially C/C++.

The acquired data from the sensors are primary processed by an Arduino nano, the processed data is wireless transmitted to the gaming platform. The wireless transmission is based on Bluetooth protocol which use Module HC-05 connected to the Arduino board using serial port. With the Bluetooth Module, any communication between an Arduino and mobile APP layer or gaming layer can be carried out. The edge layer that includes the Arduino with Bluetooth communication module is powered by a battery pack of 3.7V 2050mAh.

The system was designed to be applied in common physical therapy clinics and in these conditions the system costs become critical in regarding system adoption in the large scale. A cost estimative can be considered as one of the starting points of the adoption. In the Table I is presented the cost estimative of the architecture presented in Figure 2.

Using the implemented prototype, which costs were considered for an easily adoption, the following data associated with the rehabilitation session are obtained:

- Euler Angles (head and upper limbs rotation values);
- Linear acceleration associated with head and upper limbs dynamic and kinematic characterization;
- All five Fingers' flexion (based on flexion sensors embedded in the glove devices);
- All five finger to finger contact force values (based on force sensors embedded in the glove devices).

Fig. 3 shows the developed final prototypes of wearable devices used for user VR serious game interaction that was already reported by authors in [49].

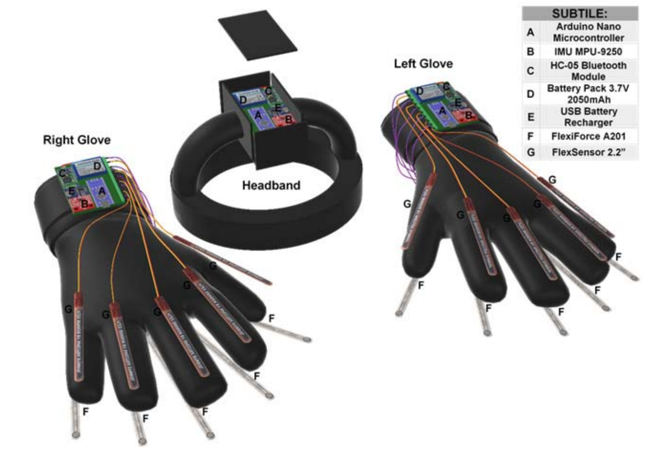


Fig. 3. The final prototypes of wearable devices developed, presented on a 3D object schematic with all smart sensors connected in right places. The green board represents the Printed Circuit Board where are placed all hardware components. The black cover on the headband represents the box of devices and are opened in figure.

C. System Description: Embedded Software

The development of new devices that include the use of IMUs, by definition are MEMS (Micro-Electro-Mechanical Systems) [50], can contemplate accelerometers, gyroscopes and magnetometers (and also barometers), allowing accurate measurements on the positioning of the devices themselves through the use of sensor data fusion algorithms. However, MEMS IMUs are vulnerable to various types of noise and errors. An Attitude and Heading Reference System (AHRS) algorithm [51] is necessary for such arrangements. In this algorithm, the new position is calculated from the previous calculated position (equation 1), the measured acceleration and the angular velocity, these errors accumulate approximately in proportion to the time since the initial position was introduced.

$$Position_{x,y,z}(t_{final}) = Position_{x,y,z}(t_{start}) + Position_{x,y,z}(t) \quad (1)$$

The double integration of residual accelerations over time to obtain a change in position values is simple at first, but not really that simple. Accelerations can be mathematically integrated once for speed value changes and twice for position value changes.

By utilizing the acceleration values, the rotations around the X-axis (Roll) and around the Y-axis (Pitch) can be calculated. Thus, if AX, AY, and AZ are the values of acceleration for X, Y and Z axes respectively, the Roll (2) and Pitch (3) angles (in radians) are given by:

$$Roll = \tan^{-1}\left(\frac{\mathrm{A_y}}{A_Z}\right) \wedge Pitch = \tan^{-1}\left(\frac{-\mathrm{A_X}}{\sqrt{((\mathrm{A}_Y)^2 + (\mathrm{A_Z})^2)}}\right) \quad (2)$$

$$Roll = \tan^{-1}\left(\frac{\mathrm{A}_Y}{\sqrt{((\mathrm{A}_X)^2 + (\mathrm{A_Z})^2)}}\right) \wedge \ Pitch = tan^{-1}\left(\frac{-\mathrm{A_X}}{A_Z}\right) \quad (3)$$

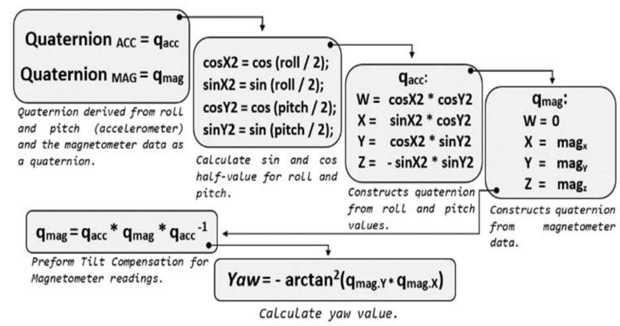


Fig. 4. Flowchart showing calculation of yaw using quaternions based on RTIMULib-Arduino [52].

In order to measure rotation around the Z-axis (Yaw), the other sensors data need to be considered together the accelerations' data. The following flowchart (Fig. 4) shows the same process using quaternions [52]:

In our case, for the implementation of an AHRS algorithm, we base the sketches on the available libraries in github public repository to perform the set of many IMUs, as the case of RTIMULib-Arduino from richardstechnotes' github [52], and MPU9250 library from the kriswiner' github [53].

During the game, the finger flexion values (extracted from FlexSensors 2.2" [54]) and tips finger force (extracted from FlexiForce) are visualized on the VR developed in Unity 3D. In other words, for each clock cycle, two sensors are read on the same analogue input port. The Arduino function digitalWrite(HIGH) command sets to 1 the digital input value that feeds the electrical circuit of the first analog sensor, then the digitalWrite(LOW) command sets this value to 0, a very short time delay (order of milliseconds) is applied and repeat the process for the second analog sensor. This procedure is performed simultaneously in each of the analog ports that will make the data acquisition of piezo-resistive force sensors.h axis.

The corrections are done using quaternions, to obtain reliable values of the Euler angles (roll, pitch and yaw). A Kalman Filter, as it is presented in [53], is used to perform the tilt compensation of the readings obtained from the accelerometer and the magnetometer. For such uses the quaternions to merge with the Gyroscope readings. From this fusion results the AHRS algorithm for reliable object orientation. The data fusion algorithm can be found in the RTIMULib-Arduino library in the RTFusionRTQF.cpp file. In Figure 11 is demonstrated how create AHRS algorithm in different stages using quaternions based RTIMULib-Arduino [55].

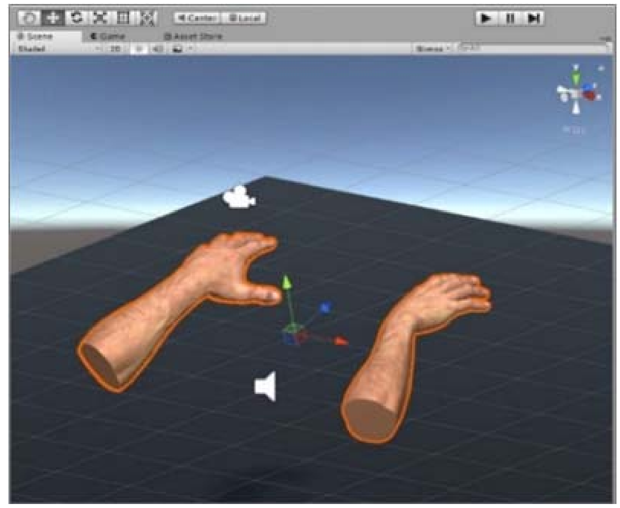
IV. System Description: Virtual Reality Serious Game

The gaming mechanism is a fundamental component in the development of a video game. It is a computer program or a set of libraries that helps to simplify the development of video games or other type of applications with real-time graphics. There are several gaming mechanisms that can be used to develop 2D or 3D video games, each with certain features to assist the developer in developing. In our case, the application that contains the VR scenarios was developed in Unity Game Engine using programming language over C# scripts, to re-create all interactions by users. The main aspects are the physical interactions between the scenario and the present objects. The communication between Arduino microcontroller and the PC where Unity is running is mediated using the serial port associated to the Bluetooth communication. The class SerialPort is the one that mediates such communication in C# language. The first tests of communication between the Arduino and the PC were realized with USB cable, and later it was configured the Bluetooth connection, that also is based on a serial communication.

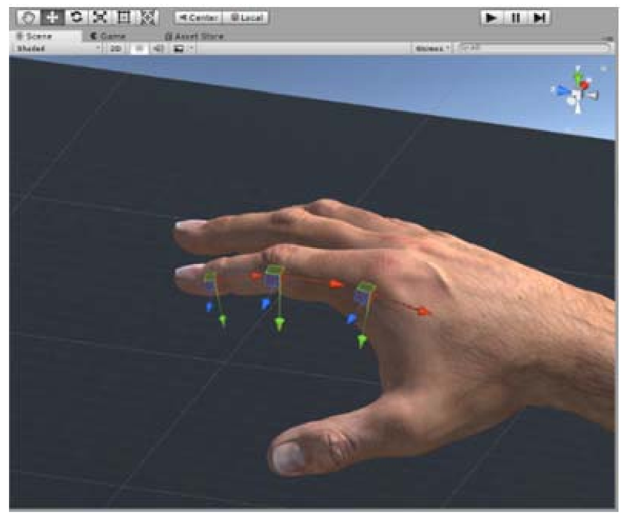
For virtual hands materialization some object textures were considered. A software suite provided by the Leap Motion Company was used, which provides a Unity 3D project that has several examples [52] to help the programmer create new applications (Figure 4). These project does not just provide examples, it also has different objects representing hands and arms of different colors, genres and sizes, and provides several scripts already programmed and ready for use. Figure 4 (a) shows the hand (and forearm) object textures for a male avatar, placed in the correct positioning. Some methods have been developed to allow the representation movements of the virtual objects defined by the fingers. Therefore, each reading obtained from the Flex Sensors 2.2" will act on 3 finger segment joints, allowing the creation of fluid movements to open and close each finger in the virtual scene. These values, then multiplied by a constant scale factor, are placed with a rotation input value at the junction between two segments of each finger (which has 4 segments per finger). The combination of these methods to act simultaneously in each of the fingers, allows creating interactive virtual movements of the hands and fingers. Figure 4 (b) shows the fingers object textures with points were the flexion readings obtained from gloves will be applied.

The possibility of interacting with virtual scenario, such as grabbing and dropping virtual objects, implied the inclusion of some Collider components in the hands, that define the shape of an object for the purposes of physical collisions (Figure 5). A collider, which is invisible game component, don't need to be the exact same shape as the object's mesh, and in fact, an approximation is often more efficient in data processing time and indistinguishable in gameplay. The Figure 5 (a) shows all collider components (Green Shape Lines) included in both hands texture objects.

The smart headband will be responsible for collecting the head rotation value of the patient, which will be used as the rotation input of the player's avatar head that is the scene camera. Figure 5 (b) shows the scene camera placed on the avatar's head in the game. The remaining elements of the scenarios were created from simple objects (cubes, spheres, capsules...) and colored with their own textures, such as tennis balls or beverage cans, or imported as whole 3D objects from tools available on the web, such as ping pong paddles or table tennis. Considering the exercising in physical rehabilitation and the main goal to recreate a virtual environment that enhances the physical performance of some people with motor disabilities on upper limbs, two games were developed: The Cans Down challenge and the Coffee Pong challenge.



(a)

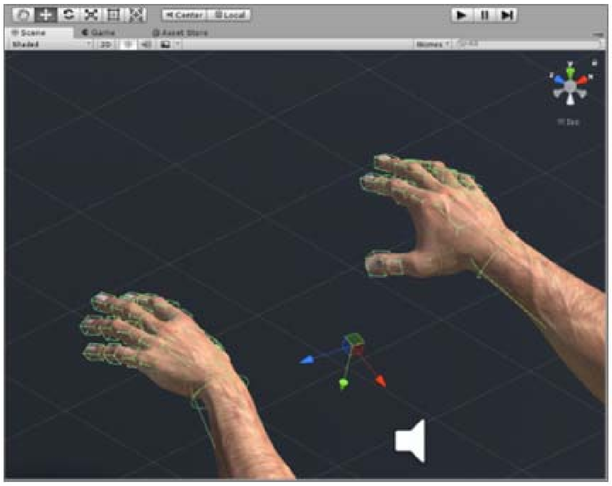


(b)

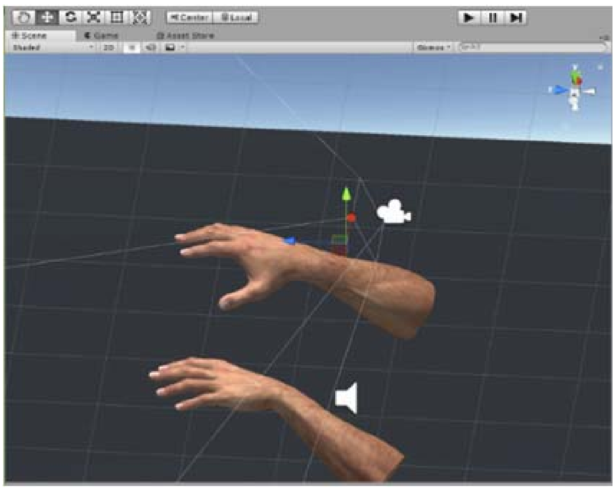
Fig. 5. (a) Hand (and forearm) object textures for a male avatar imported from Leap Motion project [54]; (b) Finger object textures with points were the flexion readings obtained from gloves will be applied.

Both games are played by direct user interaction with the VR scenario using the smart devices created (smart gloves and smart headband) described above. The main goals of our serious games are performing movement of the fingers and arms grabbing virtual objects and throw them in a certain direction, training in this condition also the posture of the body.

In the first developed game, the goal is to knock down the stack of cans by throwing the tennis balls that appear in the golden goblets (Figure 6 (a)). A virtual ball will be grasped if two fingers of a virtual hand touch it simultaneously (the thumb and the other finger of the hand). The ball will be thrown if the fingers of the hand are open and without contact with the virtual object at the end of the arm movements. The user can earn points if he can hit the cans (one point for each can knocked down).



(a)



(b)

Fig. 6. (a) Set of collider components attached on hands texture objects; (b) Scene camera placed on the avatar's head position.

Considering the customization of the game for the users, a second VR serious game was developed (Figure 6 (b)). The second game focusses on accurate measurements of flexion, extension, adduction and abduction of the metacarpophalangeal, proximal interphalangeal and distal interphalangeal joints of the tiny finger motion. The aim is to promote combined movements of both members. The IMU modules required frequently calibration. Thus, the IMU's magnetometer is calibrated at the place where the exercises will occur before any type of data acquisition is performed. This is necessary because exist variations of magnetic field verified from place to place. It is a little demanding on a technical level since it involves placing in the Arduino devices a script (from a library) to acquire magnetic field readings while the devices are rotated in all directions. When there were no variations in the readings, the data is written to the internal memory of the devices, in order to construct reliable values of the rotational movements using the merge algorithms of the raw data. This process involves running a script on the Arduino before start gaming session to access the IMU's magnetic calibration data and rotate the devices in all directions to record the magnetic field mapping.

Fig. 7. Therapeutic Serious Games in Unity3D: (a) Cans Down challenge; (b) Coffee Pong challenge, respectively.

In order to be able to play the games on any Monitor / TV screen, at the beginning of each training session in the virtual reality scenarios, it is necessary to establish a reference for the wearable devices of the position where the monitor will be located in front of them. The user must be oriented with Monitor.

This process is performed automatically within the game software at the first 10 seconds of each session. The difference of the position of the monitor is calculated, against the reference of the magnetic NORTH provided by the IMUs as Yaw $= 0$ degrees. This process allows you to provide correctly orientation of devices to the monitor where the interaction exercises will be performed. Figure 7 represents how the process of IMU reference calibration is done on the gaming start. After the process is completed all rotation data for both limbs and head are collected based on the recorded yaw value for the monitor. This will correspond to the direction in which you want the user to direct their movements.

Figure 8 shows a sequence of moments of a movement in the Cans Down game, where the user uses his left hand to grab the virtual object (represented by the tennis ball) with his fingers closed (a), then flexes his forearm to simulate a movement of applying kinematic force to the object (b), and finally performs the movement of throwing the virtual object towards the Monitor, where is the objective of the game (represented by the stack of cans to be dropped), ending its movement with their fingers extended (c). Some considerations related to adaptability were included in the development of serious games. One of the points to be mentioned is the adaptability to the patient's gender, where for a male patient, the scene initiates the avatar of the player with a kit of masculine

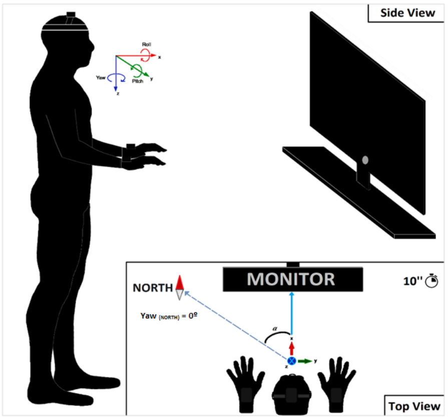


Fig. 8. IMU reference calibration to Monitor. The α angle represents the difference of the calculated angle (in degrees) between magnetic NORTH and TV/Monitor where the game runs.

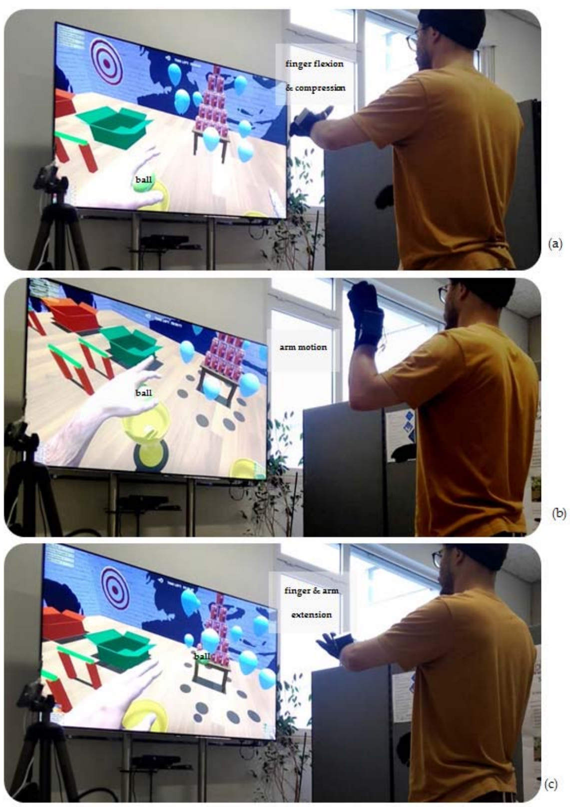


Fig. 9. Sequence of moments of a movement in the Cans Down game, to grab a tennis ball and hit the cans: (a) grab the ball; (b) flex arm to apply kinematic force; (c) throwing to the cans.

textures, and if the patient is female the textures to load refer to male / female hands. The feedback of the game is one of the most important components to encourage the patient to continue playing the game. In any game whether it is video game or a serious game, it must have a mechanism to respond to the actions performed by the user, for example, whenever the user correctly performs a goal a feedback must be given.

The feedback can be divided into two aspects, visual and auditory. With respect to the visual aspect this can be used to show a message indicating that you have performed a sequence

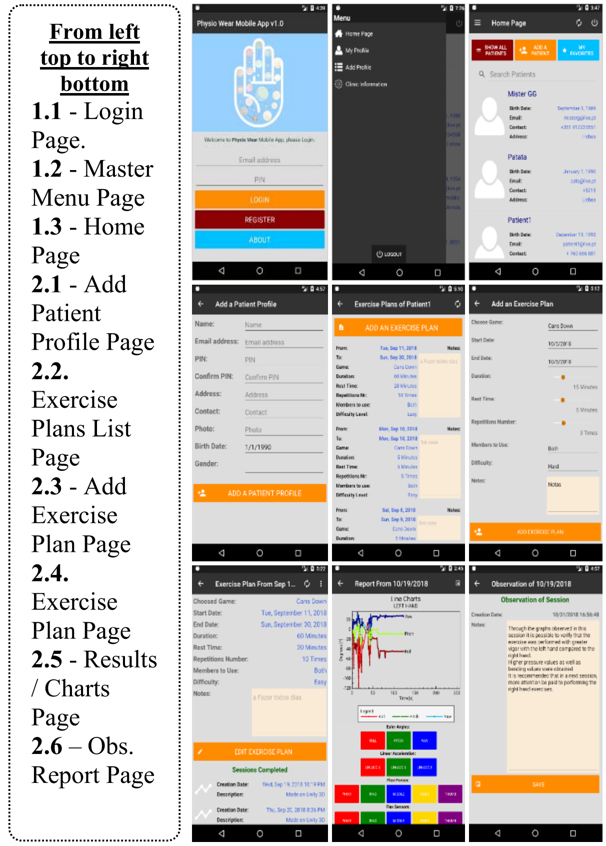


Fig. 10. Mobile APP navigation screens.

of objectives or even to indicate how many points the patient won or lost by performing a certain task. As for the auditory aspect, this can be used as background music, or in the case of performing a positive or negative task, for example, releasing a sound clip that conveys a sense of success in the case of a positive task, or a clip sound that conveys a sense of failure in the case of an unfinished or failed task. Developed application games provide feedbacks, both visual and auditory. In the case of the Cans Down game, auditory feedback is used when the patient throws a ball to stack of cans and the background music is used during play so as not to make the game monotonous if the patient cannot hit the cans with ball. Visual feedbacks are used in several situations:

- To indicate whether the patient gained points hitting the cans with balls;
- To indicate the patient how many balls are picked up.
- The timer present in all games informs the remaining time.

In Both games have visual feedback about Force measurements acquired from FlexiForce Sensors from each fingertip in real time are presented to the user for biofeedback purpose in lower corners.

V. Data Analysis

During rehabilitation sessions, data are collected and stored as part of Physical Rehab Electronic Health Record. The data is accessible through the mobile application, that serve

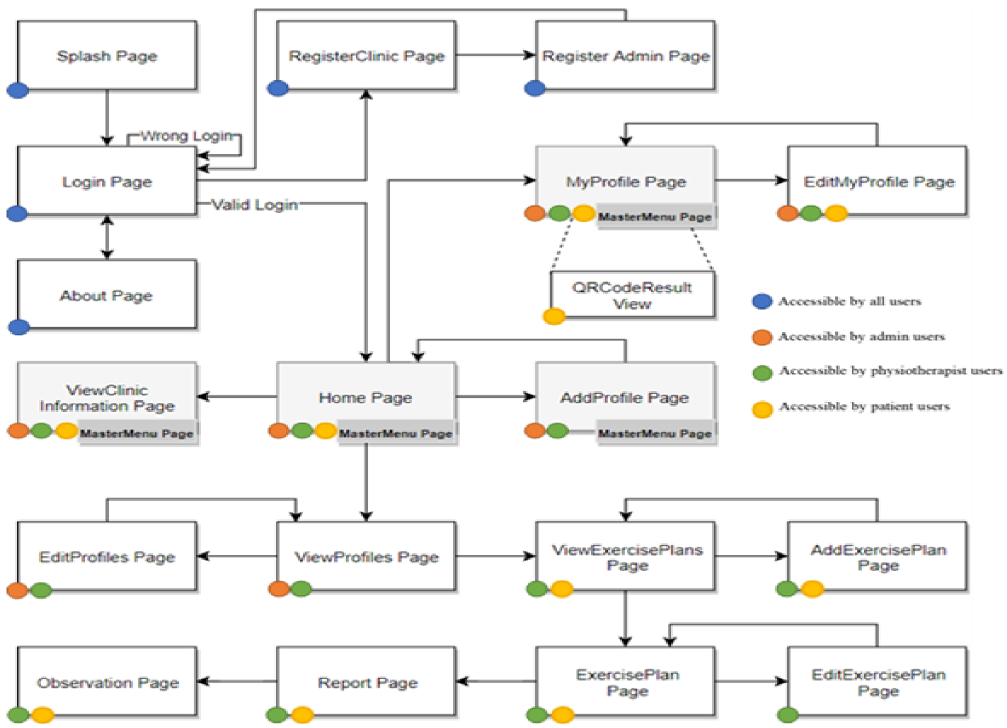


Fig. 11. Sequential diagram of the Pages in the Mobile application, for all type of users.

for future analysis on the physiotherapists' level. After being logged in, and after receiving the active exercise plan, the game scene for each exercise plan is loaded. After the connection is established with the three devices, the session is created, and the collection (through a parallel process independent of the reading thread) of the data received from the three devices during the execution of the exercises and recording in the database is initiated. The acquisition process starts after ensuring that the current session was created for the loaded plan. For each of the devices a set of readings is created, for our purpose defined in 200 rows of data, which each time this set is filled is sent to the database. At the end of each session, the scores for each game are also sent to the database together the corresponding parameters of hand motion. For each hand, the collected measured parameters are described below:

- The rotation (Euler Angles) values and linear accelerations of the forearms are obtained and validated by the IMU module. The values of rotations are stored in degrees ($-180°$ to $180°$) and linear accelerations are stored in m/s^2.
- The flexion sensors (FlexSensors 2.2") capture the angular flexion and extension values exerted by each finger on each hand. The values are stored in degrees (0 to 90°) of bending according previous calibration in local variables of the embedded software (Arduino Platform).
- The Force Sensors (FlexiForce A201) capture the pressure force values exerted by each fingertip on each hand. The values are stored in percentage of measured force according previous calibration in local variables of embedded software (Arduino Platform) where 0 % corresponds to no readings measured and 100 % to maximum value measured.

The measured collected data associated with head are:

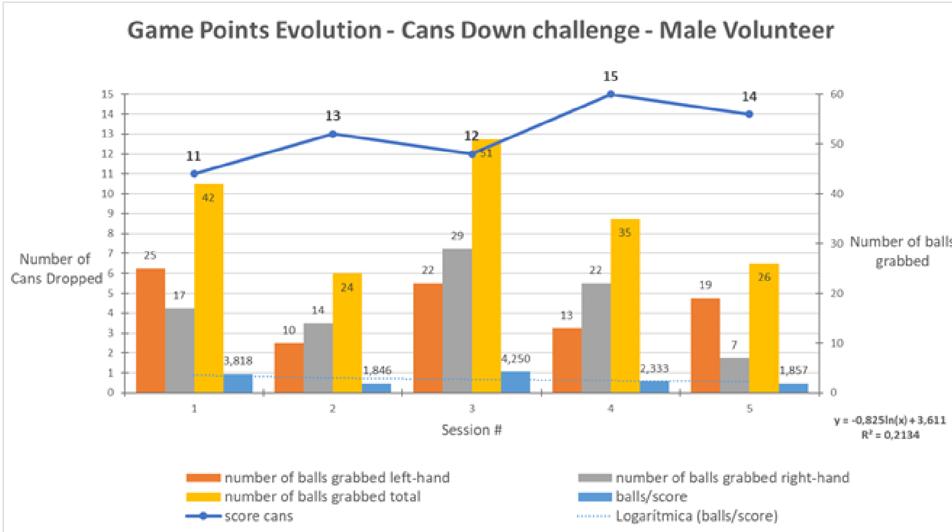
- The rotation (Euler Angles) values and linear accelerations are obtained and validated by the IMU module ($-180°$ to $180°$). The values of rotations are stored in degrees ($-180°$ to $180°$) and linear accelerations are stored in m/s^2.

The data is stored in a.CSV format to facilitate future analysis and exported to a folder in Game directory. It was created one file for each hand (LEFT and RIGHT) and other to the HEAD. Specific organization of the data was considered and following described. The data to be stored in independent files provides an extra analysis tool so that physiotherapists can perform other types of analysis through the mobile application.

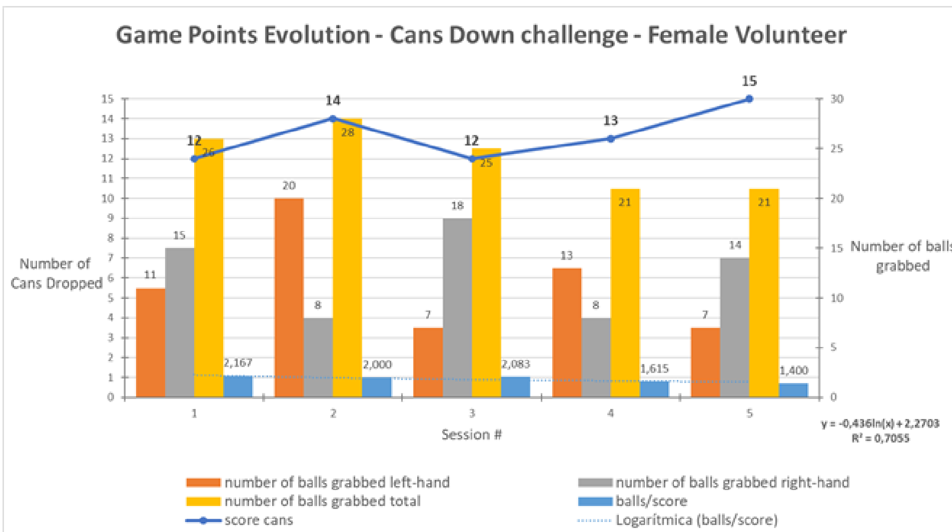
VI. System Description: Mobile APP

At the end of each training session, the physiotherapist has the possibility to visualize the results as well as the score obtained by the patient during the rehabilitation performance based on serious games, extracting information about the upper limb motor capabilities and their fingers using a developed Mobile Application which main navigation screens are presented in Fig. 9.

The data patient data management and data visualization APP was carried out using Microsoft Xamarin using programming language over C# using.NET on Visual Studio 2017 IDE. Xamarin allows developers to program a cross-platform application that can run over Android OS, iOS and Universal Windows Platform, with the same shared code. To run the application, the device (can be a smartphone, tablet or computer) must have access to the Internet, either through a mobile network (3G, 4G) or Wi-Fi.



(a)



(b)

Fig. 12. Game Points Evolution at Cans Down challenge in 5 sessions of 3-minute play: (a) Male Volunteer; (b) Female Volunteer.

The navigation screens provide to the physiotherapists possibility to perform login and visualize different information about patient as to add new patient and patient electronic health record. The APP permit to consider new training plan selecting the serious game (e.g. Cans Down) start date-stop date, training duration, hand selection. The physiotherapist can visualize in details kinematic and dynamic values (e.g. forces) associated with executed training plan previously imposed according with the patient needs.

Figure 10 illustrates the sequential diagram of the Pages in the application.

VII. Results

In order to obtain results of usability evaluation of the system developed in the area of physical rehabilitation, several tests to the games and underlying hardware devices were performed.

Two healthy volunteers (one male, 26 years old, 179cm tall, and one female, 24 years old, 170cm tall) performed 5 sessions of 3-minute play (180 seconds) at Cans Down challenge, using both limbs to grab the virtual objects (tennis balls appearing in the golden cups) in order to knock down the 15-can stack in front of the player in the game scenario. The data collected from the sessions were analyzed and are presented in the following graphs of Figure 11.

These graphs show per session the number of balls grabbed for each member, the total number of balls grabbed, the score obtained from the drop of cans, the relationship between the number of balls used and the score obtained and their logarithmic regression. The muscular capabilities are generally higher for male volunteers than for female volunteers and in this context were presented the comparative results. The number of balls grabbed can be considered an indicator about the upper limb motion capabilities for left and right hand.

VIII. Conclusion

The remote monitoring of physical training sessions could facilitate physicians and physical therapists with the information about training outcome that may be useful to personalize the exercises. This will also help the patients to achieve better rehabilitation results in short period of time process.

This research work aims to apply physical rehabilitation monitoring combining IoT, Virtual Reality serious games and Wearable Sensor Network to improve the patient engagement during physical rehabilitation and evaluate their evolution. Serious games based on different scenarios of Virtual Reality, allows a patient with motor difficulties to perform exercises in a highly interactive and non-intrusive way, using a set of wearable devices, contributing to their motivational process of rehabilitation. This methodology can be implemented in real-time situations for stroke and other neurological disorder patients. As a future scope, different methodologies can be incorporated within the IoT set-up to improve the performance of the overall system.

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