Gamified 3D Orthopaedic Rehabilitation using Low Cost and Portable Inertial Sensors

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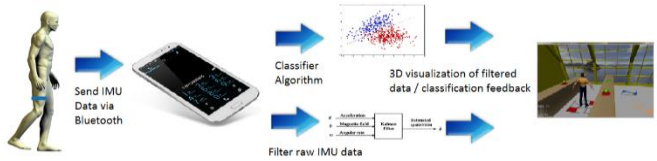
***Abstract*—This work introduces an innovative gamified 3D rehabilitation application intended for patients that have undergone Total Knee Replacement surgery, in collaboration with the General Hospital in Chania, Crete, Greece. The application uses a single custom-made, light, portable and low-cost sensor node consisting of an Inertial Measurement Unit (IMU) attached on a lower limb in order to capture its orientation in space in real-time, while the patient is completing a physiotherapy protocol. The aim is to increase patient engagement during physiotherapy by motivating the user to participate in a 3D game. The proposed sensor node attached on the lower limb drives a graphical image of the patient's limb motion as part of a 3D computer graphics scene displayed on a tablet or phone. It then classifies the exercise performed during physiotherapy as accurately performed or not and increases patient compliance via a reward system. Our goal is to reduce the need for the physical presence of a physiotherapist by aiding the efficient performance of exercise at any location, e.g. indoors and outdoors by just utilizing a light sensor and an Android device. A novel algorithm is proposed that automatically classifies an exercise in real-time. It is shown that patient engagement is enhanced when dynamically connected with a gamified app.**

***Keywords*—Binary classifier; IMU; Virtual Rehabilitation; Serious Game; TKR**



1. Application Procedure. Motion data are send to the mobile application and are visualized in a 3D environment.

I. INTRODUCTION

Among diverse areas, research has shown that Serious Games (SGs) are effectively enhancing motivation as well as efficiency of rehabilitation training [9], [11]. Research challenges include accuracy of training performance and motion capture, efficient feedback to the doctor in clinical settings as well as to the patient at home or in any location so that training environments are portable and at least equally efficient as traditional rehabilitation [10]. Portability is most often restricted because of motion capture and other equipment. The aim of this paper is to present the design and implementation of a custom-made ultra-portable, mobile and low cost 3D rehabilitation application intended for patients that underwent Total Knee Replacement (TKR) [5]. The first weeks following knee surgery are crucial so that the Range Of Movement (ROM) of the operated knee is deemed fully operational. If the patient fails to perform the exercises appointed by the physiotherapist during this recovery period, an, otherwise, technically accurate operation might result in poor functional outcome leading to reduced quality of life. The aim of our gamified application is to motivate the patient to exercise efficiently by providing feedback, while the physiotherapy exercises are performed in any setting, e.g. clinical, at home, indoors, outdoors or even in public areas.

Initially, a randomly selected control group performs the exercises under physiotherapist supervision who marks them as accurately performed or not. An Inertial Measurement Unit (IMU) node is utilized worn by the patient recognizing limb rotation and acceleration. It is challenging to identify whether the proposed application classifies the exercises reliably utilizing just a single sensor node. Providing gamified performance feedback to the patient using mobile devices is also challenging, minimizing expensive physiotherapy under supervision, resulting in engaging and accessible rehabilitation. This paper focuses on the description of the rehabilitation system involving the hardware sensor as well as the gamified 3D environment and the initial testing of the software framework in the hospital, while patients are undergoing physiotherapy treatment commonly performed after TKR surgery (Figure 1). The main goal is to improve compliance to the physiotherapy protocol, increase patient engagement, monitor physiological conditions and provide feedback based on rewards via a gamified experience.

II. BACKGROUND

There exists an increasing number of past work that employ IMU nodes for evaluation of limb rehabilitation exercises [1], [7], [8]. Previous work achieved promising results indicating that the number of IMUs employed achieve comparable classification results (3, 2 and 1 IMUs were tested [1]). Such results drive the further investigation of the classification problem using a single IMU, enhancing maximum portability compared to multiple IMU systems, in conjunction with sufficiently high success rates of movement detection. Employing 2+ sensor nodes achieves higher accuracy in ROM

measurement [8], however, such systems are difficult to operate and of limited portability.

Several approaches have been employed to track limb motion of diverse precision, cost and complexity [2]: *Optical systems.* They use visual data captured by one or more cameras to triangulate the 3D position of a set of points detected. High precision can be reached, e.g., of a few millimeters, but at a high cost. A cheaper solution of lower precision, e.g., of a few centimeters, is achieved by Microsoft Kinect [14], which uses only one RGB camera and an infrared depth sensor but it is not portable; *Exo-skeletons* are rigid structures of jointed metal or plastic rods linked together with potentiometers or encoders that articulate at the joints of the body [12]. These systems offer real-time, high precision acquisition and are not being influenced by external factors, such as visual occlusion, quality and the number of cameras. Their main disadvantage is the movement limitation imposed by the mechanical constraints of the exoskeleton structures; *Electrogoniometers* are widely used to measure human joint movements. Their advantage over conventional potentiometric goniometers is that they adapt better to body parts and are not sensitive to misalignments. Their weakness is their high cost [6]; *Magnetic systems.* They calculate the position and orientation of a magnetic sensor probe. Their main disadvantage is that they are susceptible to electromagnetic interference from metal objects [13].

The system proposed in this paper based on a single IMU sensor aims to maximize portability while maintaining acceptable motion detection success rates along with patient engagement and training. Accurate measurements based on a single sensor node depend on conditions such as correct positioning of the sensor.

III. IMU Functionality

Inertial Measurement Units (IMUs) provide the leading technology used in wearable devices in order to measure rotational and translational movements. Here, the IMU MPU-9150 is used, which is small in size, cheap and portable containing several sensors: *3-axis Accelerometer*. The accelerometer measures inertial force caused by gravity and acceleration, also rotation, however, it is susceptible to noise caused by rapid changes of acceleration; *3-axis Gyroscope*. The gyroscope measures the rate of change of any angle at a specified frequency, e.g. 100 Hz. This makes it suitable for short-term observations and fast rotational signal changes. In relation to long-term observations, it is susceptible to drift errors. Then, measurements should be sampled in exact intervals in a specified frequency; *3-axis Magnetometer*. The magnetometer measures the earth's magnetic field. It is used in conjunction to the gyroscope sensor in order to capture rotation around z-axis. In order to obtain accurate orientation measurements and minimize cumulative errors we combine the accelerometer long term measurements (low pass filtering) with the gyroscope accurate short term measurements in order to capture fast changes in rotation (high pass filter) [2]. As a result, the accelerometer measurements of orientation are used at low angular velocities and the integrated gyroscope measurements at high angular velocities. Research literature puts forward a complementary filter process, using adaptive parameters [3], [4]. This algorithm structure has been adopted by our system providing a good trade-off between effective performance and computational expense, when compared to Kalman filtering that achieve optimal results in the expense of high computational load.

IV. Application Functionality

A. Application Procedure

Initially, a training session including healthy participants took place at the General Hospital in Chania which drove the classifier design. The IMU is fitted at a specified limb location depending on the exercise performed. The session starts with the person in a neutral pose ready to perform one of the predetermined exercises. The application computes an orientation measurement with through the use of a filtering method. Actual knee movement is visualized in real-time reflected as movement in a gamified environment displayed on a mobile platform in the form of a 3D game presented to the patient. The 3D visualization offers feedback to the patient in relation to whether physiotherapy exercises are accurately performed. The filtered data are inserted into the classifier algorithm that decides whether the exercise was accurately performed, which is communicated to the participant via the gamified app (Table I). At this point, the users are encouraged to offer suggestions for system improvement.

B. Gamification Feedback

The main goal of the application is to encourage patients to follow their personal physiotherapy protocol, monitor their progress and provide feedback using a reward process via a gamified experience, using the following methods:

a) Real-time IMU feedback. Raw data from the IMU are filtered and limb orientation is determined. For example, during a knee extension exercise, the patient can actually see a virtual character extending and flexing his knee. In this context, a user engages in a serious game of a specific objective, for instance, the patient is instructed to try and throw a dart while moving his knee. A mini-game is designed for each exercise specified by the physiotherapist. These exercises are briefly described in Table I. The user can select any combination of gamified exercises listed in Table II.

b) Classifier feedback. The filtered data of the IMU are inserted in the classifier. The classifier algorithm decides whether the exercise has been accurately performed. If the exercise was classified as accurately performed, the player is awarded, e.g., by increasing a score attribute or by playing an appropriate animation. If the exercise was classified as inaccurately performed, then the application informs the user of the correct movement, e.g. by providing a limb movement animation and encourages the patient to try again.

V. Classifier Design

The exercises are selected by the physiotherapists based on the American Academy of Orthopaedic Surgeons TKR exercise guide [5] supervised by the physiotherapists. The sensor is worn by the user on the Shin of the limb.

TABLE I. COMMON REHABILITATION EXERCISES FOR TKR

Exercise	Placement	Description
Knee Extension	Shin	From sitting position, the leg is extended, then lowered back to starting position.
Straight Leg Raise	Shin	From lying on back position, the leg is lifted and then lowered back to starting position.
Heel Slide	Shin	From lying on back position, the heel is moved up, then down to starting position.
Lying Kicks	Shin	From lying on back position, an object is inserted under the knee, thus, raising it. Then, the leg is raised and lowered back.

A binary evaluation indicates if an exercise is successfully or unsuccessfully performed under the specified criteria. In order to optimize the classification algorithm parameters, we used a random group of healthy adults of diverse ages and sex. The training procedure took place at the General Hospital of Chania under the supervision of a physiotherapist, guided by an orthopedic surgeon. For this purpose, a novel automatic exercise classification algorithm is employed that utilizes the sensor filtered data using complementary filtering [3], [4]. The first iteration of this algorithm checks the filtered accelerometer and gyroscope measurements. If these measurements exceed a predefined threshold, inferred from the training procedure, the user is advised to lower his rate of limb motion. Along with the filtered gyroscope measurements, an estimation for the current user ROM is evaluated.

TABLE II. IMPLEMENTED GAMES FOR EXERCISES IN TABLE I

Game	Screen Shot	Description
Run Around		Essentially the main concept that leads to other mini-games. The user moves the avatar by performing knee exercises.
Dart Game		The user shoots darts by performing exercises. Largest ROM means more precise hit to the target.
Draw Circle		The user tries to draw a circle based on limb motion while his largest score is visually recorded.

The angle of rotation of the limb must be in a specified range and speed during motion. If each movement is performed too fast, then the participant is informed indicating inaccurately performed movement and is advised to try again.

VI. IMPLEMENTATION

A. Node Hardware & Software Setup

The accelerometer and gyroscope readings received by the IMU are independent of the hardware setup (Figure 2). This configuration provides 2 axes of rotation which is adequate for the majority of simple rehabilitation exercises and applications. The current project setup can be used by any wearable device that employs an accelerometer and gyroscope. The sensor node consists of a Raspberry Pi, the IMU MPU-9150 and a 1200 mAh Li-Ion battery that enables continues transmission of data for up to 6 hours. The IMU is connected to Raspberry Pi and sends the raw data captured signifying rotational motion. The connection to Raspberry Pi is achieved via the I2C protocol. This protocol employs the use of 4 pin connections: VCC, GND, SDA and SCL. Raspberry Pi Zero W integrates Bluetooth 4.1 and LE which makes it possible to send the raw data received from the node to our designed application that runs on an android device. The data are collected by Raspberry pi using Python. Then the sensor node acts as a bluetooth server waiting for incoming connections from Android devices. When a connection is established, the sensor enables the IMU, e.g. sets up the gyroscope at a rate of 100 Hz and begins sending the raw data to the client.

2. Custom Sensor Node and placement on the shin of the limb

B. Application Software Setup

The client receives the data using an Android activity implemented in Java. The Unity Game Engine is utilized for visualization. The Java Native Interface (JNI) is used in order to transfer data from Java to C# in the Unity Game Engine. The user is represented by an avatar in 3D Space. The avatar explores a 3D house by performing limb motions captured by the IMU filtered readings [3], [4]. The user selects the exercise to be performed, e.g. Knee Extension. The system then guides the user in order to perform a few initial training exercises. When the user feels comfortable performing the selected exercise, he can select to engage with a series of mini-games in order to improve his ROM. By performing the limb motion, e.g. moving his knee, the user navigates in 3D space. When the user reaches the highlighted destination, he/she can engage in a new mini-game such as the Dart Game and Draw Circle Game (Table II). When selecting the Dart game, the user tries to hit the target with a dart while performing the physiotherapy exercises. If this is successful, then the ROM percentage of the movement indicates how close to the center the dart will hit. A user with larger ROM will be closer to the center compared to a user with smaller ROM. Both users are rewarded by hitting the target. If the exercise fails, the dart is thrown out of the target. When a movement is incorrect, the system will not reward the users but will give them hints in order to continue by correcting limb motion. The reward is greater for larger ROMs engaging the user to improve his movement.

C. Automatic Exercise Classification Algorithm

A first iteration of the novelty automatic exercise classification algorithm uses angular and acceleration thresholds inferred by the training procedure to fine tune the system manually. A significant requirement in order to maximize success rate is the correct and stable sensor placement on the *Shin* of the patient's limb. Correct placement can be illustrated by a doctor or physiotherapist. If the wearable device isn't placed with the correct orientation, when the patient tries to perform an exercise he will be prompted that the sensor is not positioned correctly. The input data of the algorithm are the

filtered smoothed data of the sensor listed below and are acquired using complementary filtering [3], [4]: *mainAngle.* The angle in the direction of the exercise movement. It determines the maximum achieved ROM of the patient. *sideAngle.* The angle that detects sideways limb motion. It is used along with *mainAngle* to determine when user movement deviates from what is perceived to be an accurately performed exercise; *acceleration.* Limb acceleration detects motion activity and probable wrong movement, e.g. if the limb movement is too fast.

The output of the algorithm is a computational decision whether the physiotherapy exercise is performed correctly or incorrectly. The training parameters are the following angle and acceleration thresholds: *minimumMainAngle, maximumMainAngle.* The main angle's minimum and maximum thresholds in the direction of motion; *minimumSideAngle, maximumSideAngle.* The side angle's minimum and maximum thresholds in the direction of motion; *maxAcceleration.* The maximum allowed acceleration. If *mainAngle, sideAngle, acceleration* exceed their respective thresholds the exercise is deemed incorrectly performed. The implemented algorithm is designed to work for each one of the specified exercises (Table I) and can be generalized to additional exercises of similar format. Each exercise will just require different training parameters. Future work will include automatization on the choice of these parameters..

VII. Initial Results and Conclusions

The initial formal testing of the application on patients after TKR surgery has been conducted at the Chania General Hospital under the supervision of a physiotherapist. Patients were operated by the same surgical team using the medial parà patellar approach and started their physiotherapy protocol 48h post op after the removal of the drain. A small number of TKR patients (3) have been currently tested providing encouraging results. The users were male above 60 years old. The patients were consistently trying to improve the score compared to previous efforts. This, in certain occasions, resulted in poor performance according to the criteria set in relation to the correct body posture to be achieved during each exercise. For instance, while trying to achieve larger ROM (*mainAngle*), they deviated their limb motion sideways, resulting in *sideAngle* measurements beyond the acceptable thresholds, or accelerated suddenly also violating acceleration constraints resulting in incorrect movement. This testing resulted in fine tuning angle and acceleration constraint parameters in order to achieve better precision when labeling a movement as incorrect.

Physiotherapists observed enhanced user engagement in all cases and patients applied enhanced personalized effort into their physiotherapy protocol when utilizing the gamified application. Several visualized games were tested linked to each knee exercise, on each person. Simpler games and immediate visual stimulation were more helpful while performing demanding exercises that required postoperative limb motion. On the Draw Circle game the fact that the maximum ROM was visually highlighted helped patients achieve accurate limb motion compared to score indicators.

The current framework introduces an ultraportable rehabilitation application comprising of just a single IMU sensor linked to a 3D gamified environment, to be adopted by patients that have undergone TKR surgery for their highly repetitive, but very significant post-operative physiotherapy, ultimately minimizing physiotherapist supervision, at most locations. This framework can run on Android smartphones with the use of a single sensor node maximizing portability and ease of use. Through application feedback, accurate patient exercise and compliance can be achieved by succeeding at each mini-game objective. Future development should overcome limitations of few testing samples and derive a reliable accuracy result from the classification process. We now compare patient engagement between a control group that uses traditional physiotherapy treatment and a group that uses the proposed gamified approach and validate whether patients are motivated and satisfied by using gamification strategies.

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