WrEx - Wrist Exercise Trainer a System for Monitoring Physical Therapy Exercises

Daniel Silva
Department of Computer Science
NOVA School of Science and Technology
Lisbon, Portugal
email: dp.silva@campus.fct.unl.pt

Carmen Morgado
Department of Computer Science
NOVA School of Science and Technology
Lisbon, Portugal
email: cpm@fct.unl.pt

Fernanda Barbosa
Department of Computer Science
NOVA School of Science and Technology
Lisbon, Portugal
email: fb@fct.unl.pt

***Abstract*—Repetitive movements can be enough to cause joint damage. This is a problem that often arises, in particular on the hands and wrists, due to the intensive use of smartphones and computers. That is why it is important to have tools and apps that can help in some way, first in prevention and then in possible injury recovery exercises. It is very interesting to have the possibility to perform some types of prevention/treatment exercises continuously over time, and not only when in a clinic and in the presence of a healthcare professional. In this paper we present a physiotherapy exercise monitoring system for the wrist that can be used autonomously by patients. The system consists of an interactive mobile application and a set of devices that will be placed on the wrist and hand. The devices are able to detect movements made by the wrist joint and send this information to a mobile application. Through the application, the patient can access a set of exercises, previously defined by a physiotherapist, and have access to information collected in real time about the exercises and also if they are being done correctly. Our system also provides an application for physiotherapists where they can monitor and manage the exercises performed by their patients.**

***Index Terms*—Wrist Movements; Motion Sensors; Wearable sensors; Mobile Computing; Interactive Mobile Application.**

I. INTRODUCTION

Technological innovation has allowed the rise of new communication and information technologies which are increasingly replacing or extending in-person services with remote services, since these are powerful tools capable of breaking the barriers of time and space [1]. Telehealth services take advantage of communication technologies, allowing patient diagnosis to be made anywhere in the world and information to be accessed, evaluated, and delivered through wireless communication services.

Thus, the opportunity arises to explore new tools that aim to contribute to this area, in order to promote greater convenience and quality of health services. Through the integration of devices that use simple and easy-to-use sensors, it is possible to perform measurements automatically and outside the clinical environment, thus reducing the need for intervention by specialised personnel.

The system presented in this paper aims to develop an interactive mobile application that connects to a wearable motion-sensing prototype to monitor physiotherapy exercises, in particular musculoskeletal rehabilitation of the wrist. In order to assess wrist mobility, four physiotherapy exercises are evaluated: flexion and extension, as well as radial and ulnar deviation, which can be performed with or without load, and with the left or right hand. In these movements, the forearm is fixed on a surface, and only the wrist joint is rotated, as shown in Figure 1.

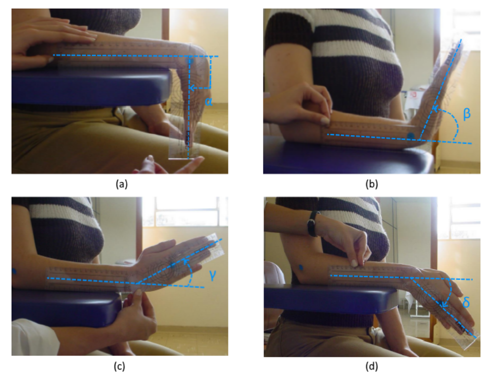

Figure 1. Measurement of physiotherapy movements of the wrist [3]. (a) Flexion. (b) Extension. (c) Radial deviation. (d) Ulnar deviation

The wrist flexion and extension movements occur in the sagittal plane at the radiocarpal and intercapal joints [2]. In these exercises, the arm should be in pronation and the elbow flexed to about 90° with the axis on the medial side of the wrist. The wrist flexion consists of moving the hand downward in a joint range between 0º-90º, the α angle illustrated in Figure 1(a). Alternatively, wrist extension is the opposite movement, in a joint amplitude between 0º-70º [3], angle β shown in Figure 1(b).

The movements of radial deviation (abduction) and ulnar deviation (adduction) of the wrist occur in the frontal plane. The elbow must be flexed and the forearm in neutral position, i.e., between supination and pronation with axis at the radiocarpal joint, where forearm supination consists of rotating it upwards, while pronation is the opposite movement, rotating the forearm downwards. The radial deviation occurs when the hand is moved upward, in a range of motion between 0º-20º, angle γ shown in Figure 1(c) while ulnar deviation is the opposite motion, with a range of motion between 0º and 45º [3], angle δ illustrated in Figure 1(d).

This paper presents the objectives and motivation that inspired its development in Section 1, while Section 2 covers an investigation of different projects and applications with the aim of particularly improving the condition of the wrist through physiotherapy exercises. Sections 3 and 4 describe the system and the evaluations conducted to validate the system's

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effectiveness and usefulness. Finally, Section 5 concludes and describes future work.

II. Related Work

The number of applications aimed at joint rehabilitation has been increasing, with the goal of encouraging the practice of physiotherapeutic movements in order to improve and make the rehabilitation process more effective and attractive. Sometimes these applications are only informative and for communication between the physiotherapist and the patient, with only a small percentage of these applications incorporating a sensor component that theoretically allows a more effective treatment [4]. Through monitored exercises, or even interactive games to capture the user's attention and interest over long periods of time, it is possible to enhance the patient's prevention and rehabilitation process.

The system presented in [5] integrates an Inertial Measurement Unit (IMU) sensor to evaluate the amplitude of various wrist movements, such as flexion, extension, ulnar and radial deviation, as well as pronation and supination. The system incorporates a micro-controller and an Android application to process and visualise, respectively, the data obtained by the sensors through Bluetooth communication. This work analysed different ways to perform the measurements of the different wrist movements, varying the positioning of the device on the back of the hand, with the best results being obtained when the device was placed at the central and end point of the back of the hand. The results obtained in [5] indicate that this device collected quite reasonable and acceptable data on the amplitude of wrist movements.

In the work [6], the focus is on finger rehabilitation. In this work, resistance-based sensors are used and compared with inertial measurement unit sensors. The device presented in this work was a glove consisting of three 6-axis IMU sensors and two 2.2-inch flex sensors to detect the movement of the finger joints. This system includes a graphical interface with a 3D visualisation of a rectangle that moves according to the movement made by the finger, which is very useful for the patient to better understand how the movement is being performed. In this study, they concluded that the IMU sensor is the most suitable due to its higher accuracy and efficiency in readings, as well as having a lower percentage of error compared to resistance-based sensors.

Another interesting study is the use of a combination of tele-rehabilitation technologies with advanced robotic technologies, allowing the development of semi-autonomous physiotherapy training with greater control and complicity between the professional and the patient [7]. The presented system motivates the patient to perform certain wrist movements through a rehabilitation robot controlled by a web application via Internet protocol. The therapist can modify the parameters, such as the limit of the angles of each movement, the speed and the number of repetitions, and can supervise the exercise in real time while the rehabilitation robot performs the desired movement.

In general, there are many interesting and well accomplished works for the intended purposes using different sensors, such as inertial measurement units, flexible sensors, and tactile sensors. The comparisons observed in these works regarding the efficiency of the different types of sensors are useful to understand and study the best options to implement our system. Some of the solutions presented have limitations due to not using enough or adequate sensors, or sometimes the system itself is not easy and convenient to be used autonomously by the patient, as well as does not present graphical and interactive interfaces in real time about the exercise that is being performed. Thus, the system presented in this paper intends to combine these features and present simple and intuitive interfaces for both patients and physiotherapists in order to promote better rehabilitation of the wrist joint. The system uses two 9-axis IMU sensors that work together to validate and correct the movement being performed.

III. System Description

WrEx trainer system consists of an interactive mobile application capable of measuring and monitoring wrist physiotherapy exercises through the use of a simple device with sensors. The exercises considered are: flexion, extension, ulnar deviation and radial deviation movements. The system can be used with the assistance of a physiotherapist, as well as autonomously and independently. In other words, this system can be used in everyday life and outside of a clinical setting. Supported exercises can be performed by both the right and left wrist, with or without load.

A. System Architecture

The system consists of three main components, which are: the wearable motion-sensing prototype component, the application component, and the server and database component (see Figure 2).

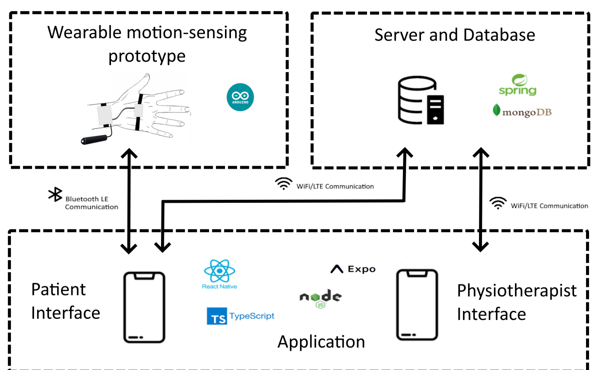

Figure 2. System architecture overview

The code that runs on the wearable prototype was developed in the Arduino IDE [8], the server in Spring Boot [9] and the database is a MongoDB [10] instance. The mobile application was developed in React Native [11], a framework that allows hybrid application development. Since a Bluetooth Low Energy (BLE) communication support is needed for

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the mobile device to communicate with the micro-controller, and a 3D animation support for the physiotherapy movement is also needed, the application was developed following a simple workflow. This way, it was possible to install the Expo animation libraries, as well as other native libraries, such as the React Native BLE library Manager [12], which supports BLE communication, that is essential for this application. In general, the application communicates with the wearable motion-sensing prototype component via BLE, as well as with the server and database component using the Wi-Fi communication protocol to establish bi-directional connections.

B. Wearable Motion-Sensing Prototype

The component device with sensors consists of two boxes and a powerbank, which supplies power to the system, as illustrated in Figure 3. Box number 1 contains an ESP32 micro-controller and an IMU MPU9250 sensor that has as the main function to assess whether there is movement of the forearm during physiotherapy exercises, and box number 2 contains an IMU MPU9250 sensor that will measure the wrist angles during all exercises.

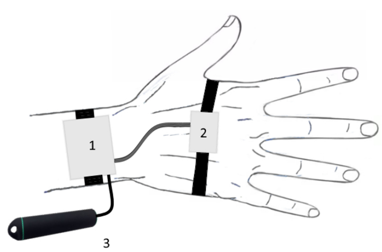

Figure 3. Schematic of the wearable motion-sensing prototype

The placement of the device must be as follows: the box number 1 should be in the area between the wrist and the forearm and the box number 2 on the back of the hand, by using elastic bands with velcro. This way the x-axis of the sensor in the box with the number 2 goes along the arm, the y-axis is perpendicular to the forearm, and the z-axis points upwards. The angles that are measured relative to the wrist movements correspond to the rotation about the y-axis. For the sensor in the box with the number 1, all the axes are considered, since it is necessary to detect when there is any movement of the forearm.

1) Communication Between the Micro-controller and the IMUs: Communication between the ESP32 and the two MPU9250 sensors is performed using a simple serial communication protocol called I2C, which is composed of serial data and serial clock signals [13]. In order to allow separate communications with the sensors, each MPU9250 has its own I2C address.

It is important to perform data fusion to get more reliable information after collecting the sensor values. This preprocessing of the data is done in the micro-controller, so there is no need for a connection between the prototype and the server application or component to read and process the data collected by the sensors. The library chosen to support the communication between the IMU MPU9250 sensors and the ESP32 micro-controller, as well as the processing of the data obtained when collecting and filtering the sensor signals to improve data quality, was created by hideakitai [14]. This library also allows to apply the Madgwick filter [15], which uses a quaternion representation of the orientation to describe the orientation estimates [16].

2) Communication Between the Micro-controller and the Application: The communication between the micro-controller of the wearable motion-sensing prototype and the mobile application is done through the BLE communication protocol. This communication protocol is widely used in the IoT world and in systems integrating sensors, as it transmits and receives small amounts of data, with low power consumption, so it can easily work for long periods of time [17]. In this communication, the ESP32 micro-controller acts as the server and the client is implemented in the mobile device application [18].

The composition of the data transmitted between the micro-controller and the mobile device consists of a quaternion value that is an average of about 63 readings performed by the sensors during a time interval of approximately 508ms, followed by the respective conversion to Euler angles. Therefore, the size of the data sent to the application is around 40 bytes. This data is used to visualize in the application the different angles performed in real time, but only the values collected during the validation time of the angle to be reached during the exercise are sent to the server and stored persistently in the database to be accessed by the physiotherapist, since the purpose of the system is to evaluate and verify that the exercise was well performed.

In this communication it was necessary to define an increase in the Maximum Transmission Unit (MTU). The method used to increase the MTU limit was through packet length extension (DLE) [19], introduced in Bluetooth 4.2.

The calibration of the accelerometer and gyroscope sensors that are part of the two IMUs is performed after the communication is established.

C. Mobile Patient Application

The patient application provides a set of core functionalities for the patient: (1) consult and begin a training plan and (2) perform the physiotherapy exercise.

1) Training Plans and Physiotherapy Exercises: The patient has access to the training plans and respective exercises proposed by the physiotherapist, as well as the interface to perform each exercise. A plan is a set of exercises, where for each exercise the type is defined, the angle to be reached, the number of repetitions and sets, the time intervals to perform each repetition and validate the objective angle, and also in which of the wrists the patient must equip the sensor component to perform the exercise. In the plan list interface, it is possible to see which plans are available, unavailable, completed and in progress, which means that a training plan has been started and can be resumed. A plan is unavailable

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when the date set by the physiotherapist for its completion has not yet arrived. On the other hand, plans are available and can be performed when they have not yet been completed and the date set for their completion is the current or previous day. A completed plan cannot be repeated, which means that the patient has completed the proposed physiotherapy exercises and finished the plan. The physiotherapist can define different training plans according to the patient's physical condition and based on the evaluations of previous plans, i.e. whether the exercises previously performed by the patient were successfully completed or whether problems or disabilities occurred during their execution.

When a patient decides to perform a physiotherapy exercise, an interface is presented to establish the connection between the mobile device and the micro-controller, as well as to perform the calibration of the sensors. After a successful calibration, the patient's mobile app presents an interface where the 3D model of the wrist or an interactive graph showing the angle being performed is displayed, as well as all the information needed to perform the exercise (see Figure 4). In the interactive graphical interface, a circular graph is presented and filled according to the angle performed by the wrist. The colour of the graph changes from red, orange, yellow to green as the value of the angle performed with the wrist approaches the objective angle value. There is also other information, such as progress bars for repetitions and sets, the time required to perform each repetition, as well as coloured borders to indicate correct and incorrect movements. In addition, there are temporary messages that indicate the progress stages of the exercise, such as whether a repetition has been started or completed, or whether a movement is being validated or is incorrect, with these messages being followed by different sound effects that help alert the patient to these situations. There is also a button to enable or disable the sound effects.

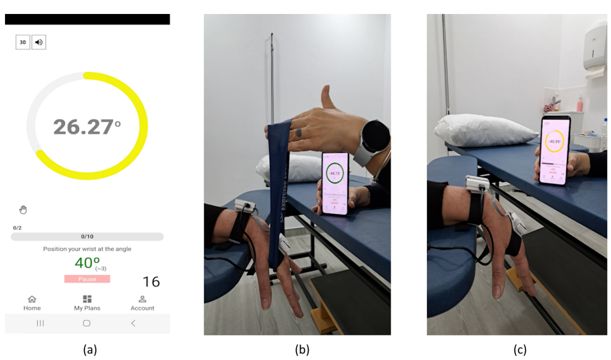


Figure 4. Patient's mobile application interface and performance of exercises with and without load. (a) Interactive graphic display while performing the first repetition. (b) Exercise with load. (c) Exercise without load

2) Perform a Physiotherapy Exercise: Every repetition of an exercise is started with the patient placing the hand that is wearing the wearable motion detection prototype in a position where the angle of inclination is 0° for a time interval of three seconds. Then the repetition is started, the patient must perform the exercise for a time interval determined by the physiotherapist until the objective angle is reached. For the repetition to be validated and successfully completed, when the proposed objective angle of the exercise is reached, the patient must hold the angle during a given time interval, defined by physiotherapist. During the angle validation time, an average of the angles performed with the wrist is calculated, which end up being minimally different from each other, since the patient has to keep the angle equal or very close to the objective angle, with a 3º deviation.

The correct position of the forearm position is defined at the beginning of each repetition, using the sensor placed on the forearm. Thus, if the forearm rotates up to 10° on either axis of the sensor, the movement is considered incorrect, so the repetition is stopped until the posture is corrected. The number of times the patient has been in an incorrect position is counted during the execution of the exercise.

D. Mobile Physiotherapist Application

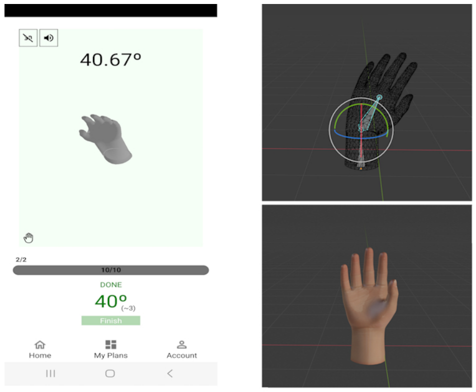
The purpose of the physiotherapist application is to allow a more complete diagnosis of the patient's condition, so it provides a number of essential features for the physiotherapist: (1) search and view patient information (2) manage the patient's training plan and physiotherapy exercises (3) observe the patient's evolution.

The physiotherapist can check and evaluate the data and statistics of the exercises performed by patients during a session in the clinic, or afterwards, by accessing the management area in the mobile app. It is possible to view the specific angle values for each type of exercise, which means that it is possible to identify which angle values are reached during the movements and therefore check whether the target angle has been achieved. The execution times and the number of failures for each repetition of a given set performed by the patient are also displayed. Thus, the physiotherapist can carefully monitor patients, adapting new physiotherapy plans and exercises based on an analysis of the exercises already performed.

Each physiotherapist can access and observe any physiotherapy plans and exercises, but can only create, edit and delete physiotherapy exercises from plans created by themselves, as well as edit and delete plans of their own authorship.

The interface to observe a patient's progress during the physiotherapy exercises includes a bar graph with the different angles achieved during the various repetitions that can be filtered by a certain set to allow a more focused evaluation of the progress in that set, general statistics, and a list with detailed information about each repetition, such as the time used to complete the repetition, the angle reached, and the number of faults. The general statistics has information about the number of successfully completed repetitions, the total number of faults during the movements, the average of the angles performed in the repetitions, and also the average time interval for the execution of the movement.

The physiotherapist can also observe the movements made by the patient during the physiotherapy exercises through the animation of a 3D model of the wrist (see Figure 5). This model was provided by Hugo Colauto through the Sketchfab



(a) (b)

Figure 5. Wrist 3D model. (a) Interface when all repetitions and sets have been completed. (b) Wireframe and material preview

platform licensed under CC BY 4.0, which is imported into the Blender software to add a skeleton, which consists of two interconnected bones, where one bone is associated with all vertices of the hand region of the model, and the other bone to the remaining vertices of the model in order to deform the mesh.

IV. Evaluation

Several tests were performed to find the best way to use and position the wearable motion-sensing prototype component on the wrist in order to obtain more accurate readings, as well as provide more comfort and less interference during physiotherapy movements. Also, an evaluation of the patient and physiotherapist mobile applications was performed to ensure that each component of the system was performing well, such as integration testing and usability testing.

1) Sensor Placement: The placement of the sensor located in the box with the number 2 (see Figure 3), which was used to measure the wrist angle values, was tested in 3 locations on the back of the hand: the central area, an area closer to the fingers, and another area closer to the wrist. The central region of the hand proved to be the most suitable for measuring the angles of the four physiotherapy exercises within their respective limits, which are the maximum angles that can be achieved in each exercise, without introducing significant errors. Some complications occurred during the flexion movement when the sensor was placed closer to the fingers, due to the fact that the sensor hardly made readings of angles above 70º. On the other hand, there were some problems during the ulnar deviation movement when the sensor was placed closer to the wrist, with the problem again being related to the sensor's inability to take readings from certain angles, in this case reaching angles above 30º. The sensor in box number 1, was placed between the wrist and forearm area, and proved to be able to perform its function of detecting any movement of the forearm.

A. Measurement Evaluation and Correction

Some experiments were conducted to determine if the wearable motion-sensing prototype component is collecting and processing the motion orientation data correctly. Three different angles were chosen for each physiotherapy exercise and ten repetitions were performed for each angle. The goal of these measurements is to evaluate whether the proposed angles were achieved correctly, that is, whether the values of the angles measured by the sensors correspond to the actual angle made by the wrist.

In general, the system proved to be both suitable and correct in reading the different values of the angles defined for each physiotherapy exercise, and the angles obtained oscillated very close to the objective angle and within the defined limit of 3º.

B. Usability Testing of Mobile Application

In order to evaluate the patient and physiotherapist application and obtain feedback from users, a set of user stories were described, consisting of descriptions of tasks with the information needed to accomplish them. An examiner was present during the test to note any difficulties or problems that the user might encounter. A questionnaire was conducted and the System Usability Scale (SUS) [20] was used, which is a reliable tool for measuring usability and provides an overview of subjective usability.

1) Patients: The tests were performed on twelve patients, aged between 21 and 60, and the results were positive.

Navigation and interaction with the different interfaces of the application were positive and all patients were able to easily access their plans and exercises, as well as start a physiotherapy plan and exercise without any difficulty. Overall, the wearable motion-sensing prototype was found to be comfortable and easy to use. The interactive graphical component was very well received and the sound effects were considered useful, as the patient did not have to be fully aware of the visual interface of the application to understand the status of the exercise while performing the movement.

Some questions were asked about the experience of using the system. The questions asked were as follows: (1) whether it was intuitive and easy to access the plan page and begin a physiotherapy exercise; (2) whether the wearable motion-sensing prototype was comfortable and easy to use; (3) whether the process of connecting the prototype wearable motion sensor to the mobile device and calibrating the sensors was easy; and (4) whether the exercise performance interface was useful and intuitive for completing the exercise successfully. Overall, as shown in the Figure 6, the responses ranged from 4 to 5 on a scale of 1 (Strongly Disagree) to 5 (Strongly Agree), with only the opinion on the usefulness and intuition of the interface for performing one of the exercises having some responses with a less good rating (3 out of 5). This way, the evaluation was positive and most of the comments and observations were related to the design of the interface and the way the information is presented in the interface, and not to the performance of the functionalities of the system. Based on the feedback, some changes were made to the system to improve the user experience.

Regarding the System Usability Scale (SUS) questionnaire given to the patients, the score was 83.3%, which on that scale

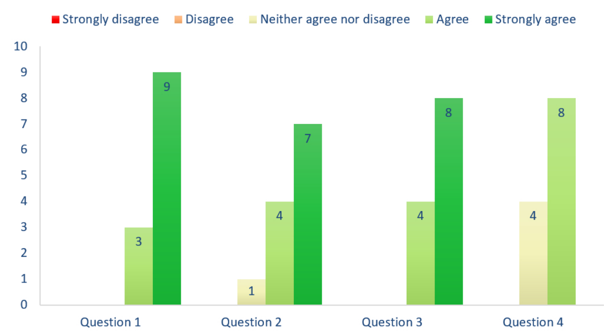


Figure 6. Patient evaluation graph

is equivalent to a good rating, being very close to excellent, which would be above 85.5%.

2) Physiotherapist: The tests were performed with a specialist at a clinic that provides specialised, individual and personalised physical therapy treatments.

The physiotherapist was able to easily access and manage the physiotherapy plans and exercises for a given patient, as well as identify and access the page showing the patient's progress throughout a given exercise. The creation of both the plans and exercises was successfully performed, and there was no difficulty in filling out the fields on the forms. Overall, the results were positive.

The physiotherapist suggested that it would be interesting to extend the system to also work with closed kinetic chain exercises, since currently the system only supports open chain exercises for the wrist, which consist of moving the distal part of the body, such as the hands.

Finally, the physiotherapist was also asked to answer the questionnaire presented by SUS, and the result was 75%, which on the scale is equivalent to a good.

V. Conclusion

The system allows a patient to perform physiotherapy exercises in a more controlled and correct way, using the application together with the sensor prototype at any time, autonomously and without any restriction. On the other hand, the physiotherapist can evaluate and follow the evolution of the patients during the rehabilitation process.

The sensor component is affordable so that it can be accessible and used by any physiotherapist and patient, and overall it is easy to use, with reduced volume and weight, in order to not limit or constrain any of the physiotherapy movements. The system performed well during the testing phase, being able to correctly reach and measure the angle values during physiotherapy exercises, and the results obtained in the tests performed with patients and physiotherapist were positive. The patient has all the information needed to complete the exercises, and the physiotherapist has access to an interface that provides the results of the patient's progress immediately upon its completion.

In the future, it would be interesting to include new physiotherapy exercises for the wrist and integrate new sensor devices to detect bad postures while performing movements.

Acknowledgment

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