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Monitoring 3D movements for the rehabilitation of joints in physiotherapy

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Abstract—**This article tackles several problems faced by professionals in physiotherapy: the performance of the rehabilitation exercises by the patients, the control of the course of the illness and the patient's ignorance about whether or not he is properly performing the exercises. We propose a solution based on the use of the Wii$_{TM}$ Controller to control the exercise movements, along with software that provides the patient with an easy, intuitive and interactive control system. Finally, web services are used to allow the remote monitoring of the treatment by physiotherapy professionals.**

I. Introduction

OVER the last years, different techniques have been applied to record the movements of people and animals as accurately as possible. This movement capture has been performed for several reasons, including military reasons as well as entertainment systems (movies and video games). According to the evolution of these techniques, new roles have been given to them. One of these new roles, appeared in the entertainment field, is the replacement of the traditional video game controller with a new system based on the recording of the different user's movements. Analogue accelerometers are used for this recording, working together in order to complement each other, depending on the performed movement. We are talking about the controller of the Nintendo® Wii$_{TM}$ console [1], the Wiimote (figure 1).

Analysing the new possibilities offered by this device, we studied the opportunity of solving certain problems currently faced by physiotherapy professionals and their patients. The main problem is that patients do not feel obligated to do the exercises and ignore the treatment. Furthermore, patients who do indeed perform the exercises prescribed by the physiotherapist do not know how to do them properly and they end up doing the exercises wrong, undermining the efficiency of the treatment and, therefore, prolonging the treatment time.

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Taking these problems into account, we have developed two applications: the first one is patient-oriented and will explain the proper performance of the exercises through the Wiimote and the screen; the second one provides the physiotherapist with remote patient monitoring.

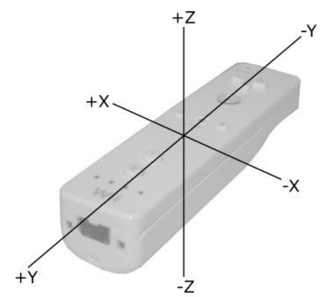

Fig. 1. Wiimote and possible movements. Here we can see the different analogue accelerometers, used into the controller, to record the movements into the three space dimensions (X, Y and Z).

Throughout this paper, we will first approach a retrospective from the origins of motion capture systems until now. Secondly, we will analyse in detail the problems to be solved. Next, we will explain the solution proposed by the authors of this document, followed by the results of the tests carried out and, finally, will present the conclusions reached after the experiment.

II. State of the Art

Motion tracking was first used by Disney in 1937 in order to ensure that the movements of the animations were closer to reality. The technique used was called rotoscope [2] and consists in filming the scenes with real life actors, then tracing the animated scenes over the pre-recorded live-action film. This technique offers the advantage of an easy recording of the movement, but, as a disadvantage, there is the difficult task of re-drawing all the pre-recorded film frames and the lack of depth.

Motion Capture [2] was developed between 1970 and 1980 and is based on the use of a suit with markers located at the performer's joints. Although it was originally developed for military purposes, in 1990, the technique was also used for non-military purposes: the animator Chris Walker developed the first commercial Motion Capture system with a cost of $300000 (currently the most basic system has a cost of around $50000). Since then, Motion Capture has been used for different applications: video games, movies, virtual reality, medicine, etc.

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The Motion Capture technique offers the advantage of a more rapid recording of the movements, as it can be done in real time. This makes possible the record of movements whose animation using traditional techniques would be very complex, due to the amount of changes at the same instant of time. Against this system, specific hardware and software is required and need to be operated by qualified personnel, conditions that increase the cost of the technology. Moreover, problems may occur if proportions given to the software are different from the capture performer (different distances between joints), obtaining unexpected results.

In 2004, a system to improve swing performance by golf players was put on the market by the US Company Austin Technology [3]. This system consists in using a club with three attached accelerometers (at the ends and the middle of the club). Using the software developed to be sold together with the system makes possible to real-time record, display and analyse the movements made. In the beginning, the invention was sold for between $649 and $799, depending on whether it was bought with display or data analysis, respectively.

Fujitsu-Siemens produces the Lifebook P notebook series since 2005. These computers include a three-dimensional accelerometer that locks the hard drive when detecting a sudden movement (that could be considered as a fall), thus protecting the information.

During the last quarter of 2005, the last video game console of Nintendo® was announced at the E3 (Electronic Entertainment Expo), which was known by the name of "Revolution" in 2001 but eventually named Wii$_{TM}$. The main feature of this entertainment system is the use of a controller based on the motion sensing capability. The technique combines three one-dimensional accelerometers (thus covering the three dimensions X, Y and Z) and an infrared pointer. Moreover, the controller is wireless and communicates with the console via ULP Bluetooth (Ultra Low Power Bluetooth) wireless technology.

III. JOINT INJURIES

Joint injuries usually require total or partial immobilisation of the injured limb in order to avoid aggravation the injury (as in the case of sprains) or when a fracture occurs and the limb must be kept straight in a cast.

When the injury heals, the patient should perform rehabilitation exercises [4], in order to restore the joint to its normal condition. Two kinds of rehabilitation exercises are distinguished:

--Passive, when the movement of the joint is performed with assistance due to a loss of fitness or to the total inability to move.

--Active, when the patient performs the exercises on his own.

Passive exercises are performed by the physiotherapist, but if a long-term rehabilitation is required, he usually explains the procedure to someone close to the patient in order to do the exercises daily. In the case of active exercises, the patient is directly advised to perform the movements and follow the routine (number of times a day or a week). In both cases, when the exercises are performed by non-professional people, two situations may occur: either the exercises are not properly performed or they are not performed at all. Physiotherapists emphasize the need to make the patient understand the importance of rehabilitation exercises, and the improvements that he may get if the exercises are done as a routine: this is known as "adherence to treatment" and, usually, it only happens when the specialist controls the exercises performance in person.

In most cases, joint injuries cause the partial loss of the normal motion of the involved joint. This limited motion may affect to flexion-extension (bending or straightening the joint), abduction or deviation (moving a limb away from the central axis of the body) and rotation (swivelling of a joint). In order to evaluate whether a patient suffers from these losses, specialists use goniometry [5] which is the measuring of joint motion. An instrument called goniometre is used to measure a patient's actual range of motion; it consists in a system for measuring angles with two axes or arms mounted on a bevel protractor. To measure the range of motion, the therapist should measure the ends of the movements, aligning the axes of the goniometre with the bones surrounding the joint, thus obtaining an angle that refers to the range of motion in the different positions of the joint. The results are compared with reference data coming from uninjured joints (some examples of these measurements are shown in table 1). Such measurements are often inaccurate, as it is difficult for the patient to keep the injured joint in the same position.

TABLE I
DIFFERENT MOVEMENTS OF THE UPPER LIMB

Joint	Movement	Measurement degrees
Shoulder	Flexion-Extension	40º/160º-180º
Elbow	Flexion-Extension	150º/10º
Forearm	Pronation-Supination	85º-90º/85º-90º

During the treatment, the physiotherapist takes several measurements of the range of motion, this way he can follow the progress of the injury and is able to feedback the patient with this information, letting him know whether or not he is properly performing the exercises [6].

IV. APPLICATION

This project has developed a first application to be used by the patients themselves to perform rehabilitation exercises for the joints of the upper limb. Moreover, a second application has been developed to allow the physiotherapist to monitor the exercises performed by the patient, to modify them or follow the progress of the injury. Both implementations have been programmed using C# de .NET [7], as this code can be ported to and compiled for different operating systems (Mac OS X^{SM}, Linux and Windows Mobile®).

A. *Patient-oriented software*

This first application has been developed as a Windows form, using, as a support, the library of royalty-free distribution written by Brian Peek, named WiimoteLib. This library offers a programming interface that provides access to complete information about the Wii_{TM} controller.

The software developed is ready to help the patient to perform the following rehabilitation exercises:

--Elbow pronation-supination. This is an exercise that helps to improve the forearm rotation provided by the elbow. The movement starts from the supination position (the palm of the hand facing upwards) and ends in pronation (the palm facing downwards).

--Elbow flexion-extension. This exercise is used to restore main elbow mobility by alternating between flexions and extensions to the patient's maximum range of motion. This exercise starts from the anatomical position of the elbow (arm and forearm flexed to 90º).

--Shoulder flexion-extension. The same as the elbow flexion-extension but for the shoulder. The movement starts with the shoulder extended position (with the arm by the side) and is finished with the shoulder flexion (lifting the arm up).

At the beginning of each exercise, the program asks the patient to input the starting and ending positions of the movement (these positions correspond to the actual range of movement of the patient's joint). Once these measures are introduced, the application waits for the patient to perform the repetitions advised by the physiotherapist. When the last movement is performed, the software uses XML (Extensible Markup Language) to store the data regarding the rehabilitation session: date, time, kind of exercise, starting and ending points; which may be subsequently checked by the physiotherapist.

At the end of the exercise, the program shows the kind of result obtained, basing on the points recorded the first day of the exercise (initial range of motion of the joint): positive if the range of motion has increased or negative otherwise. The calculation has been made on the basis that the slope angle formed between the starting point of the exercise and the ending point should go declining. This is because the range of motion increases and, therefore, the resulting inclination decreases. The formula to obtain this data corresponds to the trigonometric definition of cosine of θ between two vectors a and b, between 1 and n dimensions [8].

$$cos\theta = \frac{a_1 b_1 + a_2 b_2 + \cdots + a_n b_n}{ab} \quad (1)$$

The patient will receive the information, obtained through this angle, as a biofeedback, since he can perform a complete exercise but without making any effort with the joint.

The application contains instructions shown on the screen (figure 2) that explain to the patient the exercise to be performed (textually and graphically): how to start it, how to perform it, the number of repetitions, the gain and the remaining battery of the Wiimote. Although the instructions are always available in the form, during the exercise, the screen will show the next step with a larger font, because the exercise should be performed away from the computer and it is more difficult to read the normal font of the application.

The program offers an easy-to-understand and intuitive interface that can be used with mouse, keyboard or touch screen. In order to provide a greater ease of use and convenience for the patient, an interface for the control of the application with the Wiimote has also been developed. This interface allows the user to change the exercise (using the D-pad of the controller), start the exercise (pressing the B button, located at the bottom of the controller), record the starting and ending points of the exercise (pressing the A button, under the D-pad) and exit (pressing a top-down sequence on the D-pad).

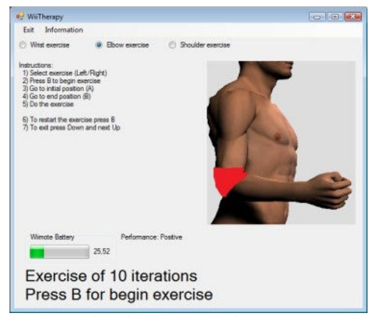

Fig. 2. Patient-oriented software: WiiTherapy. This is a snapshot of the program running, ready to begin an elbow flexion-extension exercise.

During the exercise, the program tells the user whether or not he is properly performing the exercise. This information is shown on the screen and on the Wiimote. Each exercise has three checkpoints: the starting point of the exercise, the middle point of the exercise and the return to the starting point. When each checkpoint is reached during the exercise, the program activates the Wiimote LEDs, the first when beginning from the starting point, the second when reaching the middle point and the third when returning to the starting point. If a repetition is properly performed, the Wiimote will rumble for a second quarter, indicating that the movement is correct (that it has been performed with the same range of motion determined by the points at the beginning of the exercise). When completely finishing the exercise, the Wiimote will rumble for a second to indicate it.

B. *Physiotherapist-oriented software*

The second application has been designed as a web form. This design allows the use of the software as a web service through the Internet. The application will be hosted at the patient's computer, which will be accessed by the physiotherapist. Non-remote access is also available: the patient stores the data in some portable device and the specialist checks them at his surgery.

Once the physiotherapist is successfully identified by the service, he can access the available options. Firstly, he can browse the exercises performed by the patient each day, using the calendar. This way he can check whether the patient has made the number of repetitions advised for the treatment, whether he performs the exercises at the times required and whether he does them properly. If the specialist selects one of the performed exercises, the gain obtained by the patient is displayed with regard to the first day, although gains regarding several days can also be calculated (to check whether the range of motion increases only with regard to the beginning of the treatment or it also does so with regard to sequential days).

Taking into account all this information, the physiotherapist may change the treatment (number of repetitions of each exercise or repetitions per day o per week). The changes are directly communicated to the patient via his application (WiiTherapy).

Finally, thanks to the monitoring properties offered the both applications (situation known by the patient), the patient is wanted to be involved in the exercise performance to a greater extent, achieving his adherence to treatment.

V. Experimental results

The graphics below show the gains obtained by a patient after recovering from radial head fracture of the left arm using the application WiiTherapy. The injury required total immobilisation of elbow and wrist as well as partial immobilisation of shoulder for twenty-four days. After this period, the patient had lost the arm muscle mass and a significant part of the mobility of the wrist (99.6%), elbow (77%) and shoulder (87%) as shown in figure 6. Gains shown correspond to the exercises performed twice a day, for sixteen days, until the patient recovered a mobility equivalent to 100% in every joint (see table 1).

With regard to the elbow rehabilitation, the results obtained are more consistent, as they show a daily average gain of 8%. After five exercising days, the patient had a range of motion of 43% and, in the tenth day, he had already reached 90 %. The evolution of the six remaining days was less dramatic but constant, reaching a mobility of 100% the fifteenth day.

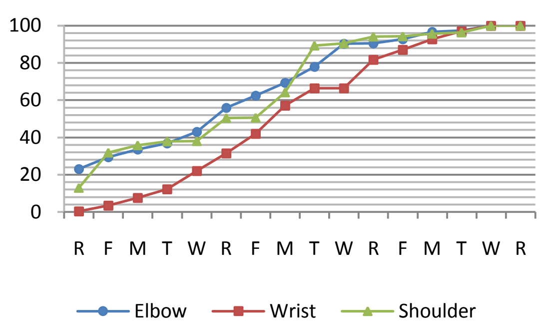

Fig. 3. Elbow, wrist and shoulder mobility evolution comparative.

After the injury, the wrist had the worst results, as the patient had a mobility loss of 99.6% and he cannot practically move it. During the first four days, the evolution is slow but constant (a 3% increase daily) until the fifth day, with a gain of 10%, which will remain constant until the end of the treatment. In this evolution, we can also see a slight deceleration in the day number eleven, which was recovered the next day with nearly a 20% gain the twelfth day.

The shoulder showed the most discontinued recovery because it was not totally immobilised, so that a part of the mobility was kept during the injury. After the first test, the range of motion was 13% and increased until 32% the second day (a gain of 19%). The trend reached 38% the fifth day and showed gains of up to 25% between sequential days, until it reached an 89% mobility the ninth day. During the remaining days, evolution was constant, reaching 100%.

Finally, figure 3 shows that the evolution of the three joints is constant, with the best results from the eleventh day on. The elbow shows the most constant evolution, the wrist has the slowest and the shoulder has the most discontinuous, however, all the three cases reach the total recovery of mobility in the end.

VI. Conclusion

In this project it has been developed an application that makes the monitoring of rehabilitation exercises easier, applying the optical sensor technology provided by the Wiimote peripheral.

We have designed a monitoring interface which is complete and intuitive for the physiotherapist and also allows him to make changes in the treatment easily.

The use of the application by the patient is easy and intuitive (using the Wiimote LEDs and rumbling), without requiring special knowledge from the user. We have a system that helps the physiotherapist to control that the patient is performing the exercises regularly, achieving the patient's adherence to treatment.

The carried-out tests have good results: the total recovery of mobility for the three joints thanks to the diary performance of the exercises by the patient. Rehabilitation has these good results thanks to the instructions provided by the Wiimote to properly perform each exercise: the system notifies when the range of motion of a repetition is not equal or greater than those set in the parameters at the beginning of the exercise.

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