Development of a Biofeedback System for Motor Rehabilitation Support

Summary of thesis to obtain the Master of Science Degree in Biomedical Engineering

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Abstract

The advances in human motion tracking systems, gaming technologies and Virtual Reality have led to the creation of applications where it is possible to interact with virtual environments in real time through the performance of motions, receiving feedback. The use of these systems to create serious games for physical rehabilitation is an idea that is still in development. This thesis proposes the creation in Unity of an application that would allow patients to perform therapy exercises by playing a game in which they interact with a virtual environment through the use of an inertial sensor system (F.A.B. System), receiving visual biofeedback regarding posture and movement. The application registers users in a database and after each session it is possible to save and display relevant data. A game was created with the aim of aiding in the physical rehabilitation of patients aged seven to thirteen years old who suffered an elbow dislocation. In order to adjust the game parameters to the target population, a control group of eleven subjects was created. Subjects played the game and provided qualitative feedback. The application was then tested on one subject suffering from the determined pathology, who played the game in six rehabilitation sessions. The results obtained show interest in the application and an increase in patient engagement, although it was not possible to assess influence on therapy efficiency, due to time constraints and small sample size. These findings encourage the further development and long-term assessment of game based biofeedback applications in motor rehabilitation contexts.

Keywords: inertial sensors; Unity; F.A.B. System; biofeedback; serious games; elbow dislocation.

1 Introduction

Maclean *et al* (2000) reports a lack of patient motivation as one of the main factors that might decrease the success of motor rehabilitation. Indeed, physical rehabilitation can be prolonged, painful and repetitive and current methods do not allow therapists to gather reliable quantitative information regarding patient progress. In order to tackle both these issues, approaches using biofeedback allied with serious games were created, aiming to motivate the patient, correct performance, reducing the need for therapist supervision, and gather clinical data.

One way to increase patient motivation is through serious games: games in which the goal is not only to entertain but also to achieve a certain goal (Matallaoui *et al.*, 2017; Groh, 2012). In this case, the goal would be a more efficient therapy. Serious games have been prominently implemented in exercise and health by companies like Nintendo, Sony and Microsoft, through the Wii, Move and Kinect systems, respectively (Tanaka *et al*., 2012).

However, not all serious games can be considered therapeutic. Mader *et al*. (2012) presents a model to analyse therapeutic games through the relations between its three main aspects: the player, the game and the therapy. A game is considered therapeutic if:

- The patient has a condition that can be improved with a certain therapy;
- The game has features that align with the process of the therapy or increase patient motivation;
- The patient is able to play the game and finds it enjoyable.

In order to allow the patient to interact with a game environment in a way that is engaging and provides information and performance correction, it is necessary to provide biofeedback, i.e. provide the patient with biological information that would otherwise not be available (Giggins *et al.*, 2013). Biofeedback involves the measurement of biomedical variables, being that in this case the focus was on biomechanical biofeedback through motion tracking.

Motion tracking can be done using visual (marker based or markerless) systems or non-visual tracking systems (Zhou and Hu, 2008). Visual marker based systems are currently the standard in human motion acquisition and analysis, with errors below 1 mm (Zhou and Hu, 2008; Ceseracciu *et al*., 2014). However, high costs, low portability and issues with the use of markers make these systems unsuitable for a lot of applications. (Best and Begg, 2006; Bonnechère *et al.*, 2014; Corazza *et al*., 2006). Visual markerless systems, although cost effective and comfortable, require intensive computation, can have problems with occlusion and tend to not be very robust at estimating joint orientation (Zhou and Hu, 2008). Non-visual systems, particularly combinations of inertial sensors (accelerometers and gyroscopes) and magnetometers, although still prone to drift, are being viewed as a way to avoid most of the problems other systems have, since these do not show issues with occlusion, are easy to wear and present robust results in joint estimation (Zhou and Hu, 2008; Hansson *et al*., 2001; Roetendberg *et al*., 2013). However, it is not possible to obtain sensor position relative to one another (Schepers *et al*., 2010).

In order to develop an application that allows the patient to interact with a virtual environment and uses the appealing nature of games for therapeutic purposes, it was necessary to choose a game engine that would allow for efficient development. Unity was chosen due to its ease of use, the active online developer community and the fact that it provides full documentation, making the process of application development easier (Antonín, 2017; Craighead *et al*., 2007). Unity's asset store also provides several items that can be used to aid in the development.

The fast-paced improvement in technology and the growing interest in VR applications make this type of approach to rehabilitation a growing sector, particularly with the opportunity to create home-based VR therapeutic exergames that would allow patients to complement therapy sessions at home without needing supervision. Furthermore, the possibility to store data from the exergames to be analysed by therapists and doctors promises to provide relevant quantitative data to assess patient progression and to create more personalized exercise prescriptions. In fact, companies such as Jintronix, BTS Bioengineering, Reflexion Health, KineLabs, Indra and SWORD health have already applied principles of biofeedback and/or serious games for motor rehabilitation through interaction with virtual environments, using mainly commercially available motion tracking systems like the Nintendo Wii, the Sony PlayStation Move and the Microsoft Kinect.

Elbow dislocations are the most common paediatric joint dislocations (Rasool, 2004), particularly in children who practice sport (Hickey and Loebenberg, 2006; Halstead, 2017) and usually require the patient to go through motor rehabilitation in order to fully recover elbow flexion and extension. Therefore, in this project a therapeutic game that addresses the movements required in physical rehabilitation of children who have suffered this injury and provides therapists with relevant clinical data was created.

2 Methods

In terms of software, the objective of this thesis was to develop an application that allowed several patients to create accounts which would be stored in a database, select a therapeutic game that is adequate to the therapy of their pathology and the injured articulation, play the game receiving visual feedback in real time by animating an avatar in real time through the use of inertial sensors, allowing for immediate visual feedback and then store and view information regarding each session in the database. This process involved defining a structure for the application, establishing a connection between the sensors and Unity, animating an avatar in real time with information provided by the sensors, designing a game that could have therapeutic value and that was adequate to the population in study and managing the database information in order to store it and visualize it in the application correctly.

In order to animate an avatar using the patient's motions, it was necessary to manipulate the orientation of a rigid body in relation to another rigid body. Orientations can be represented on the 3-D vector space in several ways, being that the ones relevant for this case are rotation matrices, Euler angles and quaternions.

Euler's theorem states that "any two independent orthonormal coordinate frames may be related by a minimum sequence of rotations (less than four) about coordinate axes, where no two successive rotations may be about the same axis" (Kuipers, 2000). Each rotation about a single coordinate axis is a coordinate rotation. Rotations of ϕ, θ and ψ about the x, y and z axis can be given, respectively, by:

$$\boldsymbol{R}_x(\phi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\,\phi & -sin\,\phi \\ 0 & sin\,\phi & cos\,\phi \end{bmatrix} \quad (1)$$

$$\boldsymbol{R}_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & cos\,\theta \end{bmatrix} \quad (2)$$

$$\boldsymbol{R}_z(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & cos\,\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The angles $\boldsymbol{\phi}$, $\boldsymbol{\theta}$ and $\boldsymbol{\psi}$ are called the Euler angles. Of the 27 possible sequences of the three angles, only 12 satisfy the constraint that no two successive rotations may be about the same axis. The sequence used in this context is $\boldsymbol{z}-\boldsymbol{x}-\boldsymbol{y}$, yielding a rotation matrix given by:

$$\boldsymbol{R} = \boldsymbol{R}_y(\theta)\,\boldsymbol{R}_x(\phi)\boldsymbol{R}_z(\psi) \quad (4)$$

Movement acquisition was done using a wireless inertial sensor system (Biosyn's F.A.B.™ System). The system consists of IMU (inertial measurement units), which are placed over the skin or clothes using elastic bands, and a receiver (F.A.B Belt Clip receiver) responsible for receiving sensor data in real time and transmitting it to the computer to which it is connected. The computer will run a program (frd2fab.exe) responsible for processing the sensor data into packets which are then sent to an established UDP (User Datagram Protocol) port.

An SDK (Software Development Kit) was created in order to access the UDP port data and retrieve the values of the Tait-Bryan Angles transmitted. These values were then manipulated to fit an interval of [0 °, 180 °[U [-180 °, 0 °[and a Unity three-dimensional vector was created for each sensor, consisting of the pitch (x), yaw (y) and roll (z) values.

Unity represents all game object rotations as unit quaternions. Quaternions can be defined as a vector space over reals. A quaternion $\mathring{q}\epsilon\mathbb{H}$ may be represented as a vector:

$$\mathring{q} = [q_0 \quad q_1 \quad q_2 \quad q_3]^T \quad (5)$$

Where $q_0, q_1,$ q_2 and q_3 and scalars called the components of the quaternion. Alternatively, a quaternion may be represented defining a scalar part, the real number q_0, associated with a vector part $\boldsymbol{q}\epsilon\mathbb{R}^3$, defined as:

$$\boldsymbol{q} = \boldsymbol{i}q_1 + \boldsymbol{j}q_2 + \boldsymbol{k}q_3 \quad (6)$$

Where $\boldsymbol{i}$, $\boldsymbol{j}$ and $\boldsymbol{k}$ are standard orthonormal basis in $\mathbb{R}^{\mathbf{3}}$. Diebel (2006) presents the equations to obtain a rotation matrix in terms of unit quaternion components, and the reverse mapping.

In order to animate the avatar, it is necessary to get the relation between a sensor's orientation ant the respective avatar segment's orientation. Consider $\boldsymbol{R}_S \in \mathbb{R}^3$ the matrix that corresponds to a sensor's orientation and $\mathring{q}_A \in \mathbb{H}$ the quaternion storing the orientation of the respective avatar segment. By applying equation 18 to the respective quaternion $\mathring{q}_A$, it is possible to get a matrix $\boldsymbol{R}_A \in \mathbb{R}^3$ corresponding to the orientation of the avatar segment. The relation between $\boldsymbol{R}_S$ and $\boldsymbol{R}_A$ can be given by:

$$\boldsymbol{R}_A = \boldsymbol{R}_S^A \, \boldsymbol{R}_S \qquad (7)$$

Where $\boldsymbol{R}_S^A \in \mathbb{R}^3$ is the rotation matrix that transforms the orientation from global Unity coordinates to the avatar coordinates. This matrix must be calculated when the patient enters the game in the required position, as:

$$\boldsymbol{R}_S^A = \boldsymbol{R}_A \, \boldsymbol{R}_S^{-1} \qquad (8)$$

This matrix remains fixed, and during the game equation 7 is applied in order to obtain the avatar segment's orientation as a matrix. The matrix to quaternion mapping is then applied to obtain the corresponding quaternion.

3 Application Design Specifications

The game included in this application was created for physical rehabilitation of children aged 7 to 13 years old who suffered elbow dislocations and no other health issues. It consists of a scenery where several characters appear and launch spherical projectiles of two different colours. The game objects used to represent the characters and the scenery were obtained through the asset store, being part of an asset called Voxel Scifi Environment. The patient avatar was placed at a distance of 17u (Unity distance units) of the characters and has two disks of two different colours attached to its hands. After a period of adjustment where the patient will see the full body of the avatar and experiment with the movement, the game view changes and the actual game begins, where the patient will be moving the two disks and must catch the spheres with the correspondingly coloured disk a predetermined number of times in order to destroy the character that launched it. This means the player will be performing movements similar to those they would perform in conventional occupational therapy sessions in a more motivating and challenging way, while receiving visual feedback. Besides, torso lateral flexion is restricted to a determined angle in order to prevent patients from using this movement instead of elbow extension, effectively correcting patient performance. When the patient exceeds the determined angle, the game pauses, resuming once the patient assumes an adequate position. The game is divided in three levels that require progressively more elbow extension and have progressively more characters to destroy. Parameters like projectile speed, time between launches, number of required successful catches to destroy a character, percentage of projectiles of the colour of the disk on the injured side and maximum torso lateral flexion angle allowed can be manipulated to adjust the game to each patient's condition.

The application is also able to save and display quantitative patient data throughout sessions, to be later analysed by the therapist. Two assets were acquired from Unity's Asset Store to achieve this goal: Database Control Pro, by Solution Studios and MeshChartFree.

Database Control Pro is a solution made for creating an online server back end, allowing for the implementation of the login and register systems of the game, along with the ability to save and load data. Data can be stored and displayed on the Unity application through the creation of Command Sequences, a visual scripting solution that can be used to read and write data to and from the databases, as well as perform some operations with the data.

In the created database, each patient has an identifying row and then a set of data rows, each corresponding to one therapy session. In the identifying row, it is stored the patient's name, a password, the patient's date of birth and laterality and the number of sessions. After each session, the number of sessions column is updated and a row is created, starting at the third column, containing the following information:

- Name of the injured articulation;
- Pathology;
- Injured side;
- Name of the chosen game;
- Percentage of projectiles catched with each side;
- Maximum flexion angle;
- Maximum extension angle;
- Date of the session;
- Time spent on each level;
- Average time per successful catch of a projectile;
- Patient's perceived pain and satisfaction levels;
- Speed;
- Time between projectile being launched;
- Evolution of the extension angle throughout the session;
- Evolution of the flexion angle throughout the session.

The data relative to flexion and extension angles can then be displayed as a chart, through the use of the MeshChartFree asset. It is possible to display either the evolution of maximum flexion or extension throughout all sessions, or the variation of these values during one session.

4 Results

In order to assess the viability of the created application, a control group and a work group were created. Both groups were registered in the database and equipped with the inertial sensors and proceded to try the game, providing qualitative feedback regarding enjoyability, perceived game speed and equipment comfort. The control group consisted of 11 subjects 10±3 years old (4 female) with no physical conditions, while the work group consisted of one 13 years old male subject who had suffered a complete lateral elbow dislocation on the left side and was performing occupational therapy at Lisbon's Children's Hospital (Hospital D. Estefânia – CHLC) following 3 weeks of immobilization. The subjects in the control group used the application only once, while the work group subject for a total of 6 sessions. The parameters used were a speed of 10 u/s, minimum time between launches of 1.5 s, 2 hits to destroy a character and torso lateral flexion restriction at 20 °. In the control group, the percentage of projectiles on each side was 50 %, while it was 70 % for the injured side on the work group subject, as suggested by the occupational therapist. During two sessions, speed and minimum time between launches for the work group subject were changed to 15 u/s and 0.5 s, respectively. Since all participants were underage, an informed consent form was signed by their legal representatives.

4.1 Control Group

The control group presented mostly positive results in terms of enjoyment, parameter adequacy and comfort, with only one subject reporting a low level of enthusiasm. The average percentage of projectiles caught in the work group is 49.9 % for the left arm and 50.1 % for the right arm which shows the game was designed properly to promote movement of either arm. The average time per catch was 18 s and through Figure 1, it can be seen that this value increased greatly on 13 years old subjects. While this can be explained by a lack of interest in the game in older subjects, it is worth noting that there was only one subject that age, who was tested in a different environment where the game projection was further away, leading the subject to report visual difficulties. For subjects 9 to 12 years old, the average catch time decreases with age, indicating that for older subjects the game difficulty may be increased. Male subjects also appear to have a lower average catch time than female subjects (Figure 2). These results, however, are taken from a small sample of population and might not translate into bigger samples.

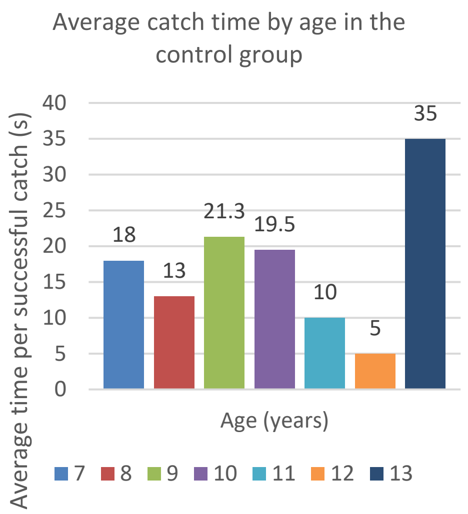

Figure 1. Average successful catch time by age in the control group

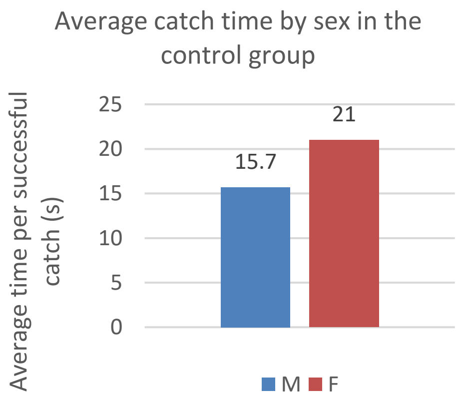

Figure 2. Average successful catch time by sex in the control group

4.2 Work Group

The work group subject reported a high level of motivation and interest in the application, comfort and no pain during the sessions. Due to the fact that the work group subject parameters were set so 70 % of the projectiles were meant to be caught with the injured side, the average percentage of catches in this case were 53.7 % on the left side, which was the side of the injury. Despite the fact that this value is still not close to 70 %, it shows that an increase in projectile percentage with the colour of the injured side can make the patient perform more movements with that side, theoretically increasing therapy efficiency. During the two sessions where speed was increased and time between launches decreased, the time needed to complete the game was much higher and the subject reported a higher level of exhaustion, potentially decreasing motivation. However, the average percentage of catches on the injured side was 68.1 %, indicating that increasing the difficulty might be a way to promote the use of the injured arm in subjects apt to play the game with more difficult settings. The results obtained in terms of maximum flexion and extension angle, shown in Figure 3, were corroborated by other methods for angle measurement (goniometers), showing that the results obtained from the software are reliable. However, the values fluctuated, showing no steady improvement, due to posttraumatic calcifications, making it more complicated to draw conclusions.

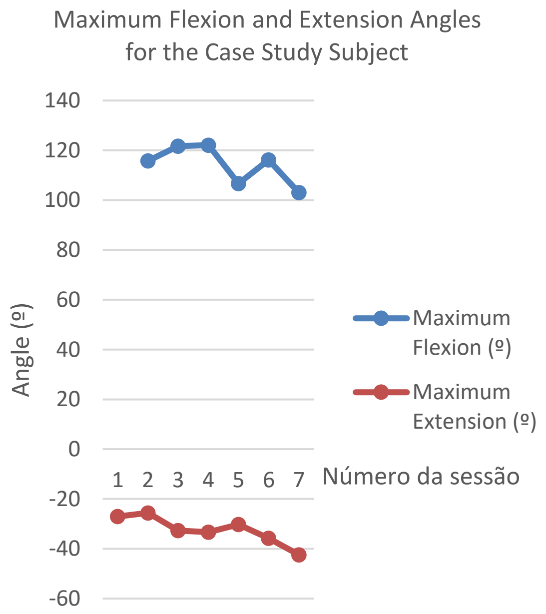

Figure 3. Maximum Flexion and Extension Angles for the Case Study Subject

4.3 Discussion

Although the small sample sizes of both the control and work groups make it difficult to draw accurate conclusions, it is possible to conclude that the game increased subjects' motivation and could lead to more efficient therapy results. Although it was indicated that the game could be made more difficult for older patients and/or male patients, in a clinical setting the most important aspects to be taken into account are the severity of the injury and the number of therapy sessions the patient has done before. In general, personality has a great influence as well.

The restriction on torso lateral flexion proved to be an effective mechanism to prevent subjects using this movement to increase their range, instead of extending the elbow. The negative feedback (inability to advance in the game) in these occasions made the subjects correct their movement faster than if they were simply being verbally corrected, meaning that the use of this system could increase efficiency in the treatment by reducing the number of incorrectly performed movements.

It is worth noting that some changes were made to the game during the time the tests were occurring, which might have interfered with some of the results. There were also issues with the way sensors were secured to the body, since the straps provided for the pelvis and trunk sensors were not adequate for younger/smaller subjects.

5 Conclusions

The results show that systems such as the one created may be used to increase patient motivation and potentially therapy efficiency. However, long term studies are needed to assess patient's interest in the application over time, as well as to assess clinical outcomes. In this case, the fact that the patient was not improving with any type of therapy and the limited time for tests made it difficult to analyze clinical results. With further development of this application, it would be relevant to compare results between patients being subjected to only conventional therapy and only therapy through serious games. It is also worth noting that Unity is a very versatile game engine, allowing for quick changes to adapt the same game for several age groups with changes of scenery, as well as the creation of more games for the same or different pathologies.

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