A Virtual Reality Exergame with a Low-cost 3D Motion Tracking for At-Home Post-Stroke Rehabilitation

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ABSTRACT

Stroke is one of the main causes of long-term disability worldwide. Conventional upper limb physiotherapy can be tedious, expensive and require physical transportation. Virtual Reality (VR) video games can help solve these problems. In fact, recent studies show that health professionals are increasingly interested in using VR games for post-stroke rehabilitation. However, commercial possibilities can be inaccessible, in terms of time, space and cost, and also inadequate to the needs of patients and therapists. Thus, in this work, a VR video game with an innovative alternative for tracking the 3D movement of the upper limb is proposed. As a result, a system that uses optical capture with a regular camera and colored sphere markers, while maintaining lightweight real-time processing on mobile devices was done. The fact that the controller can be handcrafted by the users makes the game very low-cost, possible to be distributed worldwide, reaching a large number of people, and possible to be played and monitored remotely. This new form of motion capture can make the VR exergame interaction more intuitive, therefore increasing the user's immersion in his therapy exercises. The proposed system was tested in order to find out how accurate it can be, compared to a gold standard system (a goniometer). It has been found that the system has limitations, such as low accuracy in obtuse angles and camera distortions. Still, it seems promising, due to its accessibility, very low cost, customization to the needs of patients and therapists and good tests results, as a complementary alternative for VR post-stroke rehabilitation.

CCS CONCEPTS

• **Computing methodologies**; • **Computer graphics**; • **Graphics systems and interfaces**; • **Virtual reality**;

KEYWORDS

Stroke, Rehabilitation, Virtual Reality, Computer Vision, Video games

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1 INTRODUCTION

Stroke is a major cause of long-term disability. In Brazil, in 2013, it has been estimated that 568,000 people had very severe limitations after a stroke [2]. Furthermore, according to the Global Burden of Disease 2016 Lifetime Risk of Stroke Collaborators, the mean global lifetime risk of stroke has increased from 22.8% in 1990 to 24.9% in 2016 [4]. In 2020, on average, every 40 seconds, someone in the United States suffered a stroke [19]. Also, studies indicate that, in 30% [7] to 66% of patients [13,20], the affected arm remains without function for at least 6 months later, while only 5% to 20% demonstrate complete functional recovery [7,9], which has a negative impact on the quality of life and daily activities.

A physical therapy routine can improve motor function of the upper limb. However, conventional programs can be time-consuming, labor- and resource-intensive, and dependent on patient compliance. They also have limited availability depending on geography, modest and delayed effects, can be tedious, expensive and require physical transportation [12]. Virtual reality (VR) video games can help solving these problems, as they are engaging for players, generate entertainment, motivation, in addition of being able to be played at home, without the need for transportation of the patient [10,11]. They can be combined with conventional rehabilitation for the functional improvement of the arm, cognition and quality of life after stroke [12].

For these reasons, recent studies show that health professionals are increasingly interested in using computer games for post-stroke rehabilitation. To this end, commercial alternatives, such as games that use the Wii Remote and Kinect sensors, are the most sought after, due to their relatively accessible hardware and exercise games [14]. However, a 2016 study found that gaming was currently used by only 18% of therapists, but 61% (68/112) stated that they would

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use this intervention if the equipment was readily available and other barriers, such as lack of time, space and high cost [14].

In addition, most commercial games are not well-designed for stroke patients and their motivational needs in rehabilitation [10]. It should be noticed that they are designed for young and healthy people and for entertainment purposes only. In this way, the difficulty of the game can be excessive and is not adjustable for different levels of disability; games do not transmit feedback on motor progress; the therapist's participation in the follow-up is not considered; the theme and motivational content are not directed at stroke patients; and the movements required may not be suitable for post-stroke physical therapy [10].

Therefore, these gaps between rehabilitation and motivational needs of stroke patients and existing game technologies must be bridged. To this end, an alternative for tracking the 3D movement of the upper limb was developed, using optical capture with a regular camera and a special algorithm that enables real-time capture on mobile devices, for use in a custom-made VR game taking into account the needs of post-stroke patients and their therapists. The main advantage of this system is the fact that it uses artifacts that the patient already has at home or are easily obtainable, that is, either a smartphone, tablet or computer with a webcam, even some of the most basic models, which 79.3% of the Brazilian population has access to [8], and small colored spheres, which can be made using craft materials. Also, the developed system requires a low set up time for each session; allows the patient to do a higher number of exercises, at any moment, anywhere he/she desires, without the therapist being present at every training session; does not need a big space to store equipment; does not need the patient to be standing; does not need a large distance to be captured by the camera; can be used in a large range of processing devices; and does not need any wearable electronics. This work describes the development and preliminary accuracy tests of this new system.

2 MATERIALS AND METHODS

2.1 System Requirements

Seeking system accessibility (low cost and wide availability), the following requirements were considered: 1) The software must be easily distributed. For this reason, the system was developed for both Android and Windows platforms, being possible to be used on smartphones, tablets, notebooks and desktops. 2) The hardware should have a low implementation cost. Thus, a hardware totally free of electronic devices has been chosen.

2.2 Software Tools

The system was developed using Unity [16] game engine. Three-dimensional modelling, texturing and animation was done with Blender [3]. The vegetation used was procedurally generated using TreeIt [15]. The 2D vectors were created using the Vectr web editor [18] and GIMP image manipulation software [6]. It was used the free version of all these tools. The 3D models for the scenery were adapted from Unity team demonstration projects. The OpenCV-Unity integration was done using the OpenCV plus Unity free plugin [17]. The main audio theme of the games is from Kevin MacLeod [5].

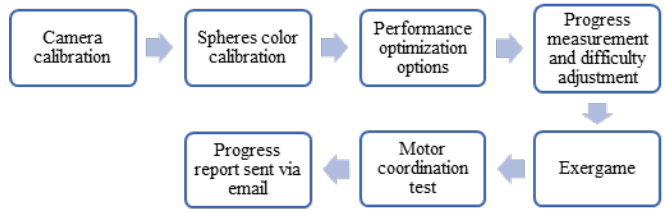

Figure 1: System usage flow

2.3 Usage Flow

The system has the usage flow of Figure 1, which will be described here.

When playing for the first time, the user must perform the camera and color calibrations. This calibration will only be necessary again if the device camera or the device position or the illumination of the room is greatly changed. Also, the user must print a checkerboard pattern, and paste it on a rigid surface (a book, for example). He may need help from the caregiver at this stage. Then, he must take a few pictures of this object, from different angles, until satisfactory results. To take photos, the user must press the "Take Picture" button, which will count for five seconds and capture a photo from the camera, recognizing the chess pattern. When finishing the calibration, the user must click on "Calibrate and Apply", to calculate the matrix with the calibration parameters. This panel was done with a simplified interface, for the post-stroke user to be able to do it with one hand.

Now, the user must calibrate the colors of the spheres that he has, in relation to his environment. For this, he should move the arrows in the "Calibration panel", choosing the maximum and minimum limit of the colors he wants to calibrate, according to their hue, saturation and value. Calibrating correctly, he will see his spheres surrounded by a line. The user must also set his half arm length on "Half Arm Length (cm)" and the diameter of his sphere on "Ball Size (cm)". In the lower left corner, he will see the angle of his elbow that the system is accusing.

Once the calibrations are done, the user can change some game settings in "Options". For instance, he can change performance options, if the game is too slow on his device, and choose to see himself or not during the game.

After that, he can play by clicking on the "Play!" button of the main menu. Then, the user enters the difficulty adjustment panel (Figure 2), which collects data on his current joint range and speed of movement. For this, he should flex the arm as much as possible and then extend it as much as possible, as fast as he can. When clicking on "Done", a question will appear, in the form of a scale from 1 to 7 (Likert scale), of how difficult the patient wants the system to be.

By clicking "Play!", the game will start. The VR game takes place on a beach. The main character is a green-winged macaw, which will be moved by the user's interactions (exercising). The game narrative is that the bird must capture all fruits randomly distributed on the scenery (Figure 3).

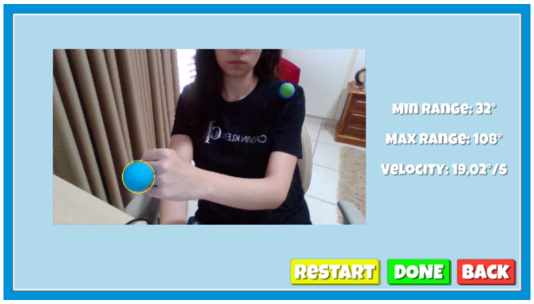

Figure 2: The difficulty adjustment panel captures the current angle range and extension velocity

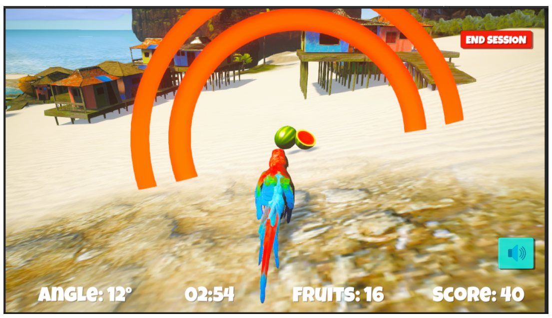

Figure 3: The exergame developed in this work

At the end of the session, the user will be asked to do a drawing motor coordination test. After that, the session is finished and a progress report is sent via email.

2.4 User Interaction

It was decided that the 3D tracking would be done as follows: two colored spheres, distinct from the surrounding environment, would be affixed to the body of the user, using masking tape, so that they are at the same distance from a central joint. Then, a regular camera is used to capture frame by frame. In each frame, the software will segment each sphere of the rest of the environment, through its colors, calibrated by the user. Then it will identify the 3D position of each sphere for calculating the angle of the joint, which is used to control the game.

Thus, the user, when interacting with the system proposed in Virtual Reality, can make the following movements: internal and external rotation of the shoulder, elbow flexion and extension. This will translate, respectively, into the main character's movements on the x (left-right) and y (up-down) axes (Figure 4).

This was done as follows: by rotating the shoulder internally and externally, the movement of the patient's hand is captured through the XY projection in the plane of the image captured by the camera. Therefore, the XY position of the spherical hand marker, in pixels, as captured by the camera, will be translated directly into the main character's movements on the X axis by translating it left and right. In the case of capturing elbow flexion and extension, what is actually used is the angle measured by the system developed here, which will move the main character on the Y axis, translating it up and down, thus, achieving complete interaction.

2.5 Test Methodology

The system had to be tested without real patients at the moment, due to the COVID-19 pandemic. Thus, it was chosen to test the accuracy of the angle measured by the system in the following ways:

a) Angle accuracy

To test the accuracy of the angles measured through the game, a comparison between these angles and those of a gold standard measurement instrument, a goniometer (angle measurement instrument used by health professionals) has been chosen. For this, the two sphere markers used by the proposed system were attached to a goniometer, one at the end of each arm, as if it were the patient's upper limb. Then, it was positioned parallel to a laptop, 40 cm away, with the spheres approximately in the center of the image. The laptop webcam (standard HD - 1280x720), calibrated with 50 photos, was used to measure the value of the angle read by the game at every 10 degrees of the goniometer, from 10 to 180°, obtaining 200 samples per angle. The distance in centimeters between the spheres was also measured. After that, the values obtained were plotted, highlighting the arithmetic mean for every 200 samples. Also, the error of the mean was calculated for every angle and plotted. The testing environment was a furnished room with controlled artificial lighting.

b) Sphere X and Y center pixel coordinates

For this test, the goniometer was positioned at 60°, with the two sphere markers attached, one in each arm of the goniometer. First, both spheres were placed in the same x coordinates, on the far left of the frame, near the x = 0 coordinate for the centers of both spheres. Then, they were slowly translated to the far right of the frame, close to x = 1280 pixels, keeping y constant and measuring the angle. Subsequently, the goniometer was placed in the upper coordinate, close to y = 0 for both spheres and translated to near y = 720 slowly, measuring the angle. The objective was to find out if the proximity of the sphere to the corners of the picture, where there are more distortions, influenced the values of the angles.

The results of these tests will be discussed in the following section.

3 RESULTS AND DISCUSSION

A demonstration of the VR game developed can be seen at https://www.youtube.com/watch?v=Hc1aopgXaJ0. A pilot test with a post-stroke volunteer and her therapist can be seen at https://www.youtube.com/watch?v=SjdSlhz7lpU.

This section discusses the results of the preliminary tests of the system, which were carried out to find out more about the angle reading accuracy of this newly developed alternative.

a) Angle accuracy

This test generated the chart in Figure 5. It must be remembered that the distance is the triangle's side opposite to the angle, which the law of cosines should be applied to. In Figure 5, it can be noted that there is a pattern: instead of a straight line, which was expected by the authors, at high angle values, both the accuracy and precision of the measurement get worse.

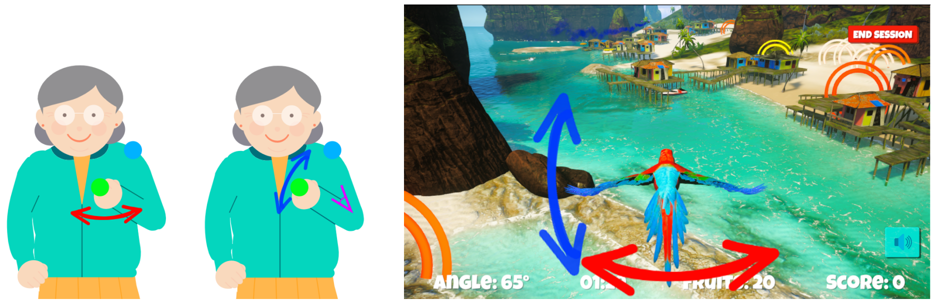

Figure 4: User interactions, internal/external rotation of the shoulder, elbow flexion/extension and translation into characters' movements

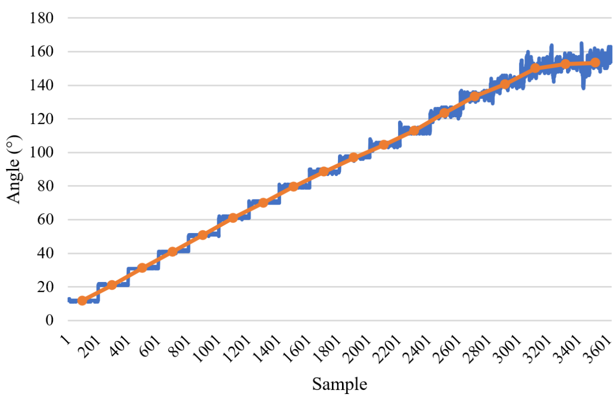

Figure 5: Graph of angle readings

Therefore, the circumferences properties were further investigated. Firstly, to calculate the joint angle. Then, the data: the coordinates of two 3D points in the same circumference, of which the joint is the central point. It is possible to be noticed that, without knowing the arc length or the radius of the circumference, it is only possible to get the joint angle by calculating the distance between the points in a straight line first, which is called the chord. A way to obtain the chord between two points in a circumference is to use the following formula [1]:

$$c = 2r \sin\left(\frac{\theta}{2}\right),$$

where c is the chord length and r the circle radius. Replacing r with 21 cm, which is the length from the pole of the goniometer to the center of the sphere, we have:

$$c = 2{*}21{*}\sin\left(\frac{\theta}{2}\right) = 42 \sin\left(\frac{\theta}{2}\right),$$

which generates a graph that has a similar pattern to Figure 5.

This property can also be visualized by measuring the distance in a straight line between the markings of the angles of a protractor, with a ruler, which generates a graph with the same pattern. In other words, the rate of increase in the distance, especially from approximately 110°, becomes noticeably lower, interfering in the accuracy and precision of the system, since a small error in the distance calculations will result in a big error in the angle. Apparently, this is a mathematical property, and, in this work, no way was found to work around the problem of lower accuracy on obtuse angles.

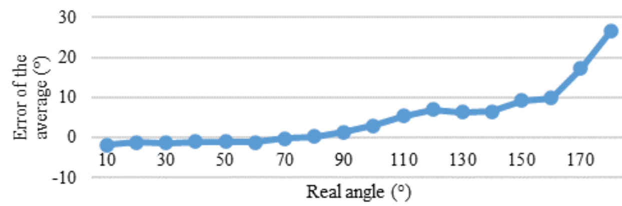

Figure 6: Error of the mean of each angle

Furthermore, the graph of the average error of the 200 samples from each angle can be seen in Figure 6. It is possible to see that, due to this property, at large angles, the measurement becomes less and less reliable. So, ideally, the system should be used by patients with lower joint amplitudes, under around 110°, that is where the error increases above 5°.

b) Sphere X and Y center pixel coordinates

This test was done to find out if the error in the estimation of the *(x,y)* coordinates of the center of the sphere was related to the *(x,y)* pixel coordinates of the frame captured by the camera. It is important to remember that the frame captured by the camera has stronger radial and tangent distortions along the lowest and highest x and y pixel coordinates. The methods used in this test are described in the previous section. The results of this test can be seen in Figure 7. They show that the x and y coordinates can influence the angle error, especially when closer to the corners of the frame, even with the distortion correction made in the calibration step. In this particular camera, there was a more significant error when near the corners on the x axis (up to 12°), while on the y axis, the maximum absolute error was 9°. In both cases, there was an increase in the angle value when closer to the corner coordinates.

This was expected, due to the radial and tangent distortions of the camera. Even with the algorithm calculating distortion coefficients and correction, this does not seem to work well with spheres, only with the chessboard pattern. When applying this algorithm to a photo containing both the distorted chessboard pattern and the sphere markers, it can be seen that the straight lines of the

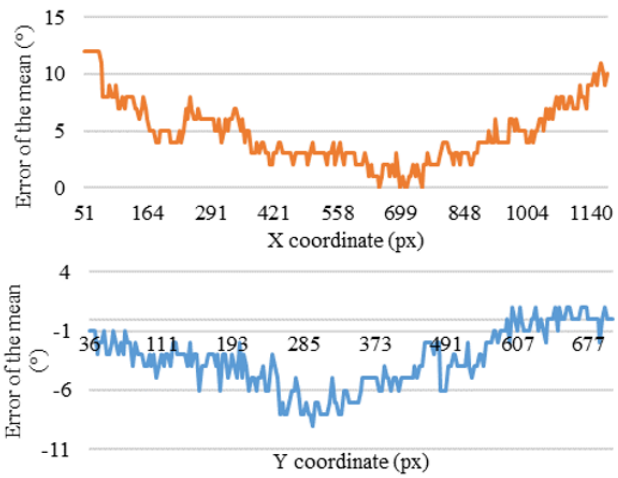

Figure 7: Influence of the sphere x and y coordinates on the angle error

chessboard pattern are undistorted easily, but the sphere still looks distorted, with an elliptical shape. This is read by the system as a larger diameter than the real one, that results in the difference related to the angle.

4 CONCLUSION AND FUTURE WORK

Virtual Reality and exergames have emerged as new treatment approaches in stroke rehabilitation. In this work, a system for post-stroke rehabilitation was developed, comprising of a VR exergame, which has a novel form of 3D motion capture, that utilizes a single regular RGB camera and an innovative Computer Vision strategy, that utilizes colored spheres, which could be made from any craft material, to estimate the body parts position and the joint angles in 3D in real-time. In this way, it is possible for the user to produce its own control at home, only needing the distribution of the software of the game to be able to readily play anytime, anywhere he/she desires.

The preliminary accuracy tests of the system show that it has limitations, such as lower accuracy (error above 5°) at angles above 110° and a variation in accuracy due to distortions in the camera lens. Still, it is relatively lightweight and can be very accurate when respecting the aforementioned problems.

Positive points of the system include its very low cost, the ease of playing anywhere, anytime, and perhaps data capture of some clinical importance, as it calculates the angle of joints, which would be important for checking the progress of spasticity (muscle rigidity) in such clinical patients.

For future works, it is intended to improve the consistency of the motion capture and, then, do a clinical trial and a usability study with real post-stroke volunteers.

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