Wearable Device for Immersive Virtual Reality Control and Application in Upper Limbs Motor Rehabilitation

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Abstract. Virtual Reality (VR) has been used in several areas such as video games, technical training, movies and teaching. VR-based interventions have also been applied for motor rehabilitation, e.g., to help the patient recovery from disabilities provoked by stroke, cognitive deficit or musculoskeletal problem. VR combined with wearable tracking devices creates new possibilities to apply immersive approaches during motor rehabilitation. This can enhance the health care making it more interesting and pleasant for patients as well as more effective for physicians and physiotherapists. However, the costs related to this technology may be impracticable for a wide application by public health system. Therefore, this paper introduces preliminary results for a low-cost wearable device, which is integrated to VR environments aiming to provide a better quality rehabilitation process for most patient with motor disabilities.

Keywords: Virtual reality · Rehabilitation · Wearable device · Immersive environment

1 Introduction

Virtual Reality (VR) is a new technology that is expanding year by year. In the 1950s the VR emerged as a promising innovation for entertainment. Nowadays, it is used in several areas such as video games, technical training, movies and teaching [2,10,11,33]. VR is also applied in clinical interventions for rehabilitation processes. There are applications in motor recovery therapies [15,17,29,31,32], such as those used to help patients recovering from disabilities caused by stroke, cognitive impairment or musculoskeletal problems. One of the reasons for using VR environment to stimulate, e.g., a post stroke's brain is the immersion level of the surroundings, making the procedures look like a day-to-day activity [15].

© Springer Nature Switzerland AG 2020
O. Gervasi et al. (Eds.): ICCSA 2020, LNCS 12255, pp. 741–756, 2020.
https://doi.org/10.1007/978-3-030-58820-5_53

The stroke is the third leading cause of disability worldwide [37]. To reduce stroke's side-effects and prevent serious sequelae, the rehabilitation process must start as soon as possible after a stroke event. The rehabilitation is conducted mainly through physiotherapy and occupational therapy sessions [20]. The authors [28] describe that repetitive motions during the physiotherapy sessions can help the rehabilitation process, but to keep the patient motivated while doing all repetitions is a challenging process.

VR interaction usually relies on controllers with buttons and joysticks, or visual-based controllers such as Kinect. These type of controllers are not always adaptable to a patient with a low movement of her/his arm. Thus, a tailor-made wearable device can become necessary to control better the objects within the virtual environment. The combination of VR with wearable tracking devices creates new possibilities for therapists, when using immersive approaches during motor rehabilitation. This approach can enhance health care, making it more interest and pleasant for patients as well as more effective for physiotherapists.

However, the costs related to this technology may be impracticable for a wide application by public health systems. Therefore, the present paper reports the preliminary results achieved by a research project where a low-cost virtual reality (VR) device has been developed. The device will help stroke patients and therapists to improve the motor rehabilitation process. The proposed device has two main parts: software and hardware. The first one includes the VR environment itself, which means everything that the patient will see in the smart-phone with the VR headset. The second part is the wearable device that will track the patient's motion and send them to the smart-phone.

The aim is to make available a more immersive treatment for patients as well as affordable for public health systems, without compromising the quality of the rehabilitation process. To pursue such a goal, we integrate the VR environment into a wearable device that controls interactive parts of the virtual space. We use a VR headset for smart-phones with a wearable device customized for reaching such a goal. The integration of the VR headset (with a smartphone) and the wearable device becomes this framework portable and easy to set up and handle. As everything developed must be low cost, we design the VR environments to run on a wide variety of smartphone models.

2 Related Works

In recent years, interventions using VR have found applications in complementary therapy for more traditional neurorehabilitation methods [1,17,21,26,31,32,35]. However, the effectiveness of using VR as a tool for rehabilitation is still a topic raising discussion among therapist [29]. In this scenario, the treatment within a virtual environment is based on the Mirror Neuron System (MNS), which is a group of neurons that can replicate the functions of other neurons [3,23]. The Mirror neurons, when stimulated by VR, may accelerate the reorganization and functional recovery in post-stroke patients [4].

The authors [14] show that using VR as a complement to conventional rehabilitation achieved better results than just the conventional ones. The study used a control group, under only traditional recovery, and an experimental group under traditional and VR rehabilitation. The focus of such research was in upper limb rehab, aiming to get a better evaluation of both treatments. One of the conventional approaches for upper limb rehabilitation is the exoskeleton robot. This kind of robot helps the user to make movements almost without applying any force. A compilation of exoskeleton devices to assist in rehabilitation is presented by [18]. The use of VR with these prototypes is also evaluated by [8,27]. These devices have many advantages, but also two main issues: a high cost and low mobility for patients. The present paper tries to introduce a device able to fill such a gap.

The study conducted in [6] shows the effectiveness of VR training in motor performance and cognitive recovery of post-stroke patients. The proposed solution is the BTs-Nirvana, a high-cost device. The results reported that VR promotes better results than conventional rehabilitation protocols.

The study in [1] show a smart glove (FlexiForce and FlexSensors 2.2) with inertial measure unity (IMU) to control a VR world for rehabilitation purpose. The smart glove provides the finger's flexion and force, and in other words, this device could help in the patient hand's rehabilitation.

The author in [5] show an IMU's sensor as an evaluation system for measuring the degree of shoulder joint movement. In the study, the author evaluates the IMU in comparison with traditional protractor evaluation. The results concluded that the sensor is precise and can be used to assess the range of motion of the patient shoulder.

The work in [7] presents a device to control a virtual reality environment for lower limbs. The device has a sonar with a gyroscope/accelerometer to track the position of the leg, used for gesture control. A VR city was developed to facilitate the patient immersion during the treatment.

The VR-based procedures in stroke patients show relevant improvement in their upper limb performance as reported by [29] and [21], when compared against traditional treatments. The study in [35] indicates that VR can help, when associated with a conventional rehabilitation process, once the visual feedback from VR becomes the process more enjoyable and attractive for patients. The engagement in the rehabilitation process can be enhanced using the VR [22]. A recent scoping review about the VR applications in rehabilitation is provided by [9] and [30].

The authors in [19] report that VR technology is progressing year-by-year, becoming a useful tool to improve the recovery of the patient's cognitive function. It is described the improvements achieved in the cognitive domains of patients that used the VR as an auxiliary treatment. These improvements are based on the results reported from eight clinical studies. In the study made by [16], the VR therapy was used with functional electrical stimulation (FES) to evaluate the benefit of the VR in the rehabilitation of upper limbs. The authors in [16]

concludes that the VR stimulation associated with FES presented better results than FES alone.

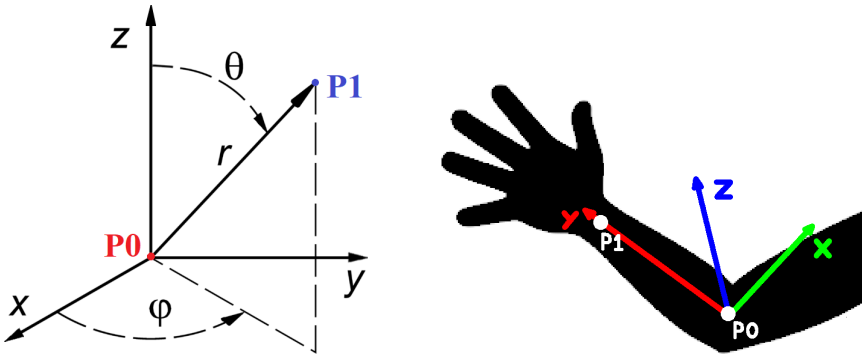
3 VR Device

The development of this device has taken place in collaboration with an experienced therapist and meets the need for rehabilitation procedures defined by them. The main objective of the device is to translate the movement of the patient's arm into the virtual environment, amplifying or decreasing her/his sensitivity based on the rehabilitation process.

One of the requests for the device was that the therapist could move the user's hand without interfering with the tracking system. This requirement meant that a visual-based tracking system became almost impossible since there was overlap between the therapist and the patient's arms. The device and the related software are required to perform all the functionalities without the user pressing a single button.

Based on such requirements, this project proposes a device that tracks the arm using a spherical coordinate system. In other words, the device tracks a point such as P1 in Fig. 1(a), based on another fixed point P0, using two angles and a fixed value. The set value r is the distance between the point P0 and P1, while the angle ϕ is the angle between Z-axis and the vector $\overrightarrow{P0P1}$. The second angle φ is between the X-axis and the projection of the vector $\overrightarrow{P0P1}$ in the XY-plane, as P1 can see it in Fig. 1(b).

To apply this use of a spherical coordinate system in the real world, we included an Inertial Measurement Unit (IMU) in the patient's arm between her/his wrist and elbow as shown by Fig. 1(b). In this situation, P0 is set to the elbow while P1 in the wrist. This layout means that the device is tracking the wrist's angles concerning the elbow joint.



(a) Spherical Coordinate System (b) Device's Coordinate System

Fig. 1. Coordinate system

3.1 Device's Hardware

Arduino Nano microcontroller was used with one IMU (MPU-6050) and a Bluetooth module (HC-05) to develop the device. The microcontroller, powered by a 9 V battery, and all other components by the microcontroller. The current total cost is around $11.00.

The IMU sensor is responsible for getting the gyroscope, accelerometer and magnetometer data. The MPU-6065 uses the Digital Motion Processor (DMP) to fuse this data and reduce the errors of each one of the sensors. A quaternion Q returns the result of this fusion, which is given by Eq. 1 to describe the orientation of an object in a 3D space.

$$Q = q_0 + q_1 i + q_2 j + q_3 k = (q_0, q_1, q_2, q_3) \tag{1}$$

The quaternion is sent to the Arduino Nano and translated to the Euler angles (roll ϕ, pitch θ, yaw ψ) using the formula below:

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \arctan \frac{2(q_0 q_1 + q_2 q_3)}{1-2(q_1^2+q_2^2)} \\ \arcsin(2(q_0 q_2 - q_3 q_1)) \\ \arctan \frac{2(q_0 q_3 + q_1 q_2)}{1-2(q_2^2+q_3^2)} \end{bmatrix} \tag{2}$$

These angles represent the angles of the patient's wrist in relation to the elbows. The first angle (ϕ) is the rotation in the X-axis, the second angle is the rotation in the (θ) Y-axis, and the third one (ψ) the rotation in the Z-axis. We define the axes X, Y, Z in Fig. 1(b).

After the data is processed, it is sent to the smartphone (via Bluetooth module) and allows you to control the VR environment. The devices present a switch to power on and a button to reset the centre position of the VR environment as it will explain in Sect. 4.1.

3.2 Device's Encapsulation

As a device to be used by the therapist in the rehabilitation processes, it has to be simple, practical and versatile to reach all the complexity of each patient treatment. Thus, we encapsulate the device in a 3D printed box made using ABS (Acrylonitrile Butadiene Styrene) plastic, including another space to store the battery. We also used Velcro tape to wrap everything in the patient's arm as presented in Fig. 2.

4 Jigsaw Puzzle

The main focus of the software was to assist therapist and patients, based on the type of movements done by the patients following the therapist commands. The device is evaluated in a real-world situation through a VR jigsaw puzzle. The software for such game was made using the Unity3D engine [36]. We use a smartphone with a headset to simulate the immersive environment, and the



(a) Disassembled device

(b) Device mounted in the patient's arm

Fig. 2. Proposed device

3D puzzle must be able to run in low-cost smartphone models. At this step of our research project, the software can run from any smartphone with quad-core processor, 1.3 GHz and 2 GB of RAM.

4.1 Puzzle Settings

The jigsaw puzzle presents a few settings as shown by Fig. 3. The therapist can use these settings to optimize the VR experience during the recovery process. The parameter settings implemented until now are level of sensitivity, the number of pieces in the puzzle, in which arm the patient will hold the device, hitbox and image selection.

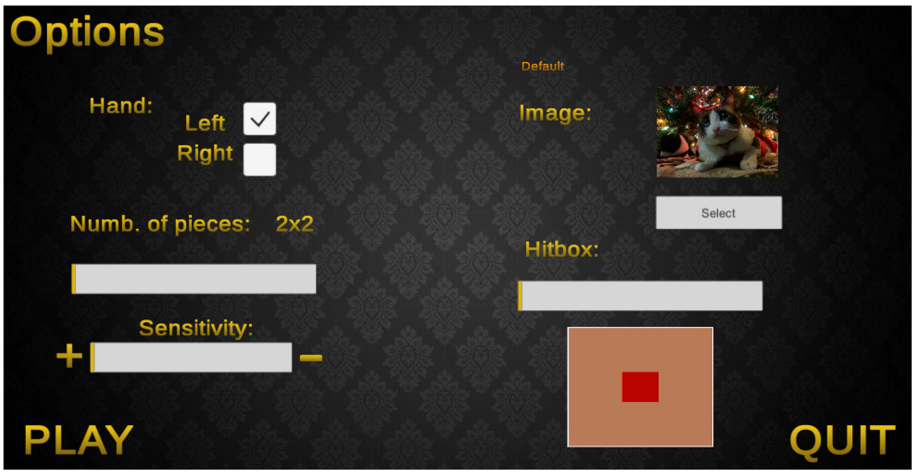


Fig. 3. Puzzle setting screen

The parameter level of sensitivity represents how the real motion will be translated into the VR environment. It is a number that can be set by the therapist between 200 to 2000. If the sensitivity is set in 200, this means that a small motion in the real-world will be translated as a larger one in the puzzle. On the other hand, this effect is less amplified when higher values for sensitivity are set. The therapist also sets the number of pieces that the patient will assemble to complete the full image. Now the value is limited to cut the image from 2×2 to 4×4 pieces, but it can be expanded based on the type of treatment.

The software works with one patient arm being used in the VR environment to control every interaction with the puzzle. Thus, the therapist must set whether the patient will move the puzzle pieces using the left or right hand. The precision reached by the user when catching and placing the pieces is another relevant feature that needs to be approached. Based on this demand, a hitbox sliding bar was implemented on the menu. The hitbox tells us how near to the centre of the piece the user must be closed enough to pick the piece up as well as to place it in the right position.

For instance, the orange square in Fig. 3 represents one piece, and the red square (hitbox) is where the user needs to go to pick the piece up. Once the user is holding the piece, she/he needs to put it in the right position. This position has the same hitbox as the piece; in other words, the user needs to get inside the area of the hitbox to put the piece in place. Figure 4 illustrates the hitbox when the user is catching and placing the piece.

The hitbox is not visible for the user, but the hitbox sliding bar in Fig. 3 gives the therapists the ability to control the size of the hitbox to fit the patient's necessities. Thus, the therapist can adjust the hitbox, becoming more or less challenging to pick up or to position the pieces as illustrated in Fig. 5.

The patient's motivation is an essential part of the rehabilitation process. Because of this, the puzzle was developed to accept different images, including personal ones from the patient.

4.2 Puzzle's Gameplay

After the therapist settings, the software initializes the protocol for device calibration. The calibration will evaluate and remove possible errors lead by noises when the device is not moving. If the sensor is not moving (spatial displacement), its output should be zero, but the sensor may present some noise. Moreover, the calibration protocol compiles all the noises and removes them. The VR's headset can be placed in the patient while the calibration is happening. Figure 6 shows the calibration processes screen.

After the calibration, the therapist can start the Jigsaw puzzle by pressing the red button on the device. At this point, the device will consider the real world's position as the centre of the virtual environment. The patient will need to have some space in the real environment to move the arm for all directions (up, down, left and right).

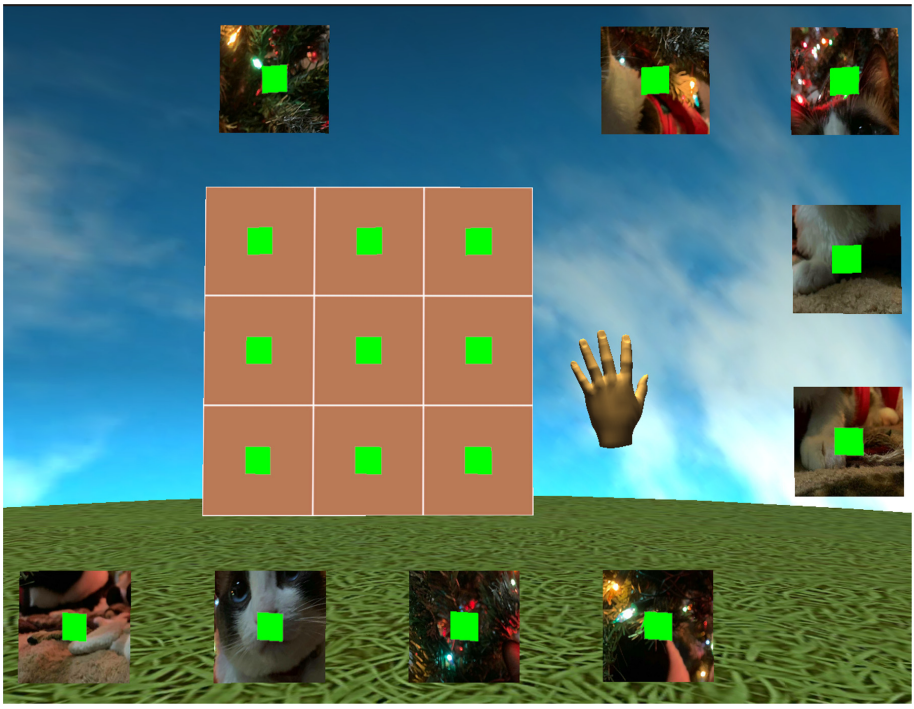
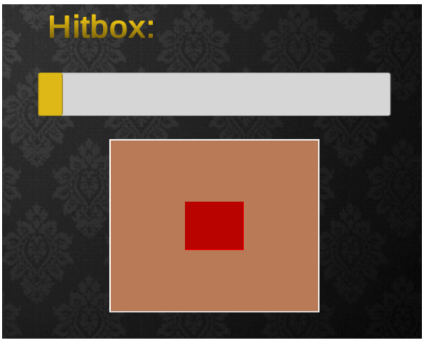


Fig. 4. Hitbox



(a) High precision - small hitbox



(b) Low precision - large hitbox

Fig. 5. Hitbox settings

Once the game started, the user only has to complete the virtual puzzle. When the user gets the piece, the software helps him to find the right position of the piece showing a red square in the respective area (Fig. 7). A full picture will be also shown in the upper right corner to help the patient finding the image.

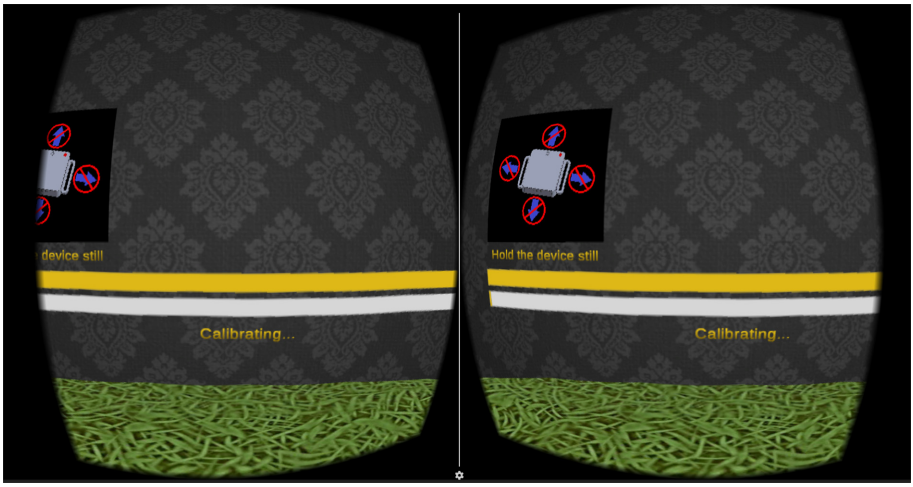


Fig. 6. Calibration screen

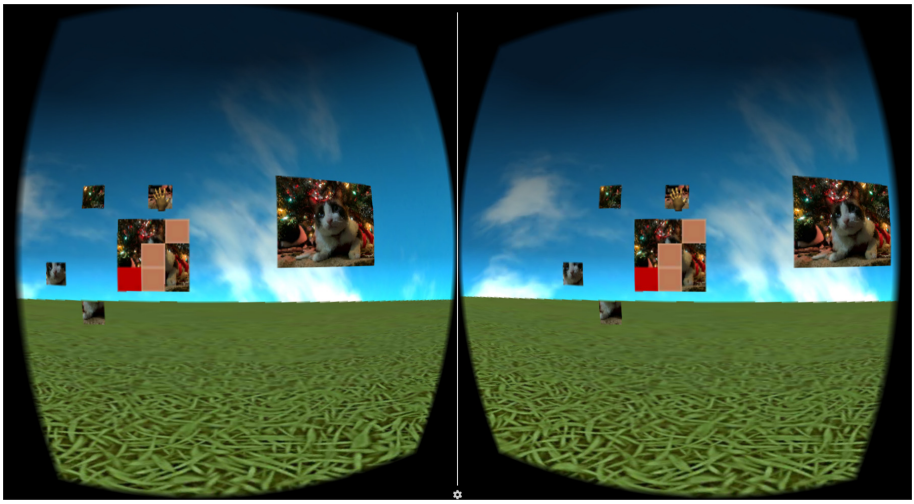


Fig. 7. Jigsaw Puzzle

4.3 Puzzle Data

The relevant data processed by the software is stored during the patient gameplay to evaluate his/her rehabilitation process. The data stored is the time that the patient needs to complete the puzzle, all the hand position the patient moved in the environment and all the settings the therapist put to start the VR environment. These data allows quantifying the movements performed by the patient during the execution of the puzzle.

5 Experimental Evaluation

The experimental evaluation was conducted with healthy volunteers at this stage of the project, and it was separated into two parts. First, the device is evaluated by itself before being used by the volunteers. Next, the volunteers will handle the device, play the game and report their remarks by answering a questionnaire.

5.1 Device's Evaluation

The device was submitted to a few tests before experimental procedures with volunteers. These tests evaluated the device's precision and the device's robustness.

Precision: To measure the accuracy, the device was left still for 3 min, and the data collected was evaluated. All the relevant data gathered is shown in Table 1. As expected, there is a minimum and acceptable deviation near zero degrees in the position setting.

Table 1. Device stability within a non-movement situation

Results	Max. deviation	Min. deviation	Standard deviation
Roll	0.038°	−0.351°	0.024°
Pitch	0.788°	−0.641°	0.253°
Yaw	0.027°	−0.022°	0.009°

The standard deviation must be around zero; otherwise, the user will start to notice hand movement over time. Thus, the maximum and minimum values in Table 1 need to be close to zero to achieve excellent accuracy without a spike in the movement.

Robustness: The device robustness is the reliability of the hardware, such as the precision of the movements after a long period using it. The device was in a non-movement stage for 1 h, after this time, the errors were evaluated as it can be seen in Table 2:

Table 2. Device's reliability in a long run

Results	Max. deviation	Min. deviation	Standard deviation
Roll	0.037°	−0.338°	0.028°
Pitch	0.672°	−0.596°	0.249°
Yaw	0.024°	−0.024°	0.011°

Comparing Table 1 and Table 2, we conclude that the device presented the same precision over time, without drifting in any angle for the long run. Next, the device was put in a zero position and moved 90° in roll, 90° in pitch and 90° in yaw, and returned to the point zero. After repeating this procedure five times, the device stayed still for 10 s, and the difference to the initial position was evaluated, as shown in Table 3:

Table 3. Device's precision in repetitive tasks

Results	Averages differences
Roll	0.186°
Pitch	−1.272°
Yaw	0.088°

The differences on average must be as close to zero as possible to get a better tracking device. There was a discrepancy in the average difference when comparing the pitch against row and yaw. This average difference is explained by how the DMP calculates the error. However, the pitch angle (rotation in Y-axis) is not used and relevant in the experiment, since such angle stands for the supination and pronation of the arm.

5.2 Evaluation with Volunteers

Volunteers evaluated the device taking into account the device delay, the VR motion sickness effects, level of sensitivity when solving the puzzle, and the overall evaluation of their experience. The volunteers were healthy adults with an undergraduate degree, and ranging from 28 to 50 years old.

Delay: The device's delay is the difference in time between moving the device and its respective arm motion simulation within the VR environment. For the delay evaluation, the volunteers were a total of 16 healthy subjects and five therapists. They answered some questions about how the delay affected their puzzle experience. In the 16 healthy subject group, the device's delay harmed the movements of the puzzle pieces for eight healthy subjects, there was delay but without compromising the movements for six subjects, and the delay was not observed by two subjects. On the other hand, all five therapists answered that there was a noticed delay for a healthy person, but it is not noticeable for a patient with post-stroke movement disability. Based on these reports, the delay problem must be better evaluated through a real situation with post-stroke patients. After such evaluation, we can decide whether it is or not a real problem when using the device.

Motion Sickness: The motion sickness occurs when there is a conflict between what the body is feeling, and the eyes see. For instance, the body is moving, but the eyes are seeing a still image, which can produce a motion sickness in a person [12,25]. In virtual reality devices, the motion sickness can happen when there is delay from the Virtual reality screen to the head movement, a drop in the number of screen frames per second happens, or some sensors data conflict resulting in a false screen image [13].

The 16 healthy volunteers helped us to evaluate this motion sickness based on two criteria: discomfort using the VR (headache, stomach awareness or nausea) and disorientation or instability. In this group, a total of 14 subjects evaluates that the VR experience did not lead to any discomfort; the other two said that they could not assess this point. Regarding disorientation, all subjects agree that there was no such sensation.

Level of Sensitivity: The 16 volunteers were submitted to a test in sensitivity variation. In other words, eight volunteers tested the 3×3 puzzle with minimal sensitivity (wide arm movement); the other eight volunteers tested the same 3×3 puzzle, but with maximum sensitivity, (restricted arm movement). The average time to complete the task is shown in Table 4.

Table 4. Average time to complete the puzzle

	Averages time(sec.)	Standard deviation(sec.)
Minimum sensitivity	133.162	28.668
Maximum sensitivity	107.535	13.344

The average time got higher in minimum sensitivity because of the wider range of motion needed to reach the pieces. In the other hand, the high standard deviation shows that there was a discrepancy the time between the users. One of the possible evaluation is the initial adaptation of some users when using the device. In the minimum sensitivity, there are volunteers that needed more few minutes to get used to the device and the virtual reality environment.

Overall Evaluation: The 16 subjects answered a questionnaire with a few questions about the software. Each volunteer solves the jigsaw puzzle once from 3×3 setup. The question and answers can be seen in Table 5.

Table 5. Volunteers evaluation of the Virtual reality puzzle

	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
It's a easy game	11	5	0	0	0
It's a intuitive game	10	6	0	0	0
It's a fun game	5	7	4	0	0
It's a immersive game	10	4	2	0	0

The results show that for a healthy person, the game can be considered secure, intuitive and immersive. On the other hand, the game was not considered a fun game for most of the subjects. This impression can mean that for a healthy subject, the game is too easy or monotonous in a certain way. Based on this feedback, a future work to improve the variations of arm exercise will be considered to make the interactive surrounds more fun. All these questions will be reevaluated with patients in the next phase of this project.

6 Conclusion and Future Works

The present paper introduced a low-cost virtual reality (VR) device to help patients and therapists during the motor rehabilitation process, where some preliminary results are reported. The current device costs around $11.00 and it can run on quad-core smartphones with only 2 GB of RAM.

The device presented few issues such as the delay noticed by the volunteers. However, the therapists evaluated that such level of delay will not be a problem for patients. As next step of this project, the device will be evaluated with patients during their motor rehabilitation procedures.

The device showed a very accurate precision for the application. Regarding the test of robustness, the device presented a consistent result for all aspects under evaluation. It means that the DMP used in the IMU was consistent and correct all possible errors in the long run.

The volunteers well evaluated the software as a whole, but it needs to be tested in a real situation with post-stroke patients. This will allow us to find more specific issues in the software.

As future works, the software and the device's hardware will be optimized to improve performance and include some changes in its functioning, such as a vibration sensor for user's feedback from the virtual world. One of the possibles complements is to use a second device between the shoulder (P0) and elbow (P1) to get depth as a new degree of freedom within the virtual environment. This new degree of freedom can improve the interaction with the virtual world. For instance, it can allow to achieve some object far away, stimulating the elbow extension of the patient.

Another possible software improvement is to make the environment more realistic, changing the surroundings for more daily ones such as chicken, parks or bedrooms environments. This can make the patients experience more immersive as well as improve their motivation.

Acknowledgments. This research was partially supported by Capes (from Portuguese, *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*) and FAPESP (Sao Paulo Research Foundation, Brazil). FAPESP process: 2015/03695-5 (grant related to author: A.F.B). The development of the proposed device is the result of a research collaboration between the Center for Research in Mathematics Science Applied to Industry - CeMEAI (from Portuguese, *Centro de Pesquisa em Ciências Matemáticas Aplicadas à Industria* (http://cepid.fapesp.br/en/centro/15/) - FAPESP

Process: 2013/07375-0) and the Brazilian Research Institute of Neuroscience and Neurotechnology - BRAINN (http://cepid.fapesp.br/en/centro/11/) (FAPESP Process: 2013/07559-3), both are Research, Innovation and Dissemination Centres (RIDC) funded by FAPESP.

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