

# Development of a Virtual Reality Environment for Rehabilitation of Tetraplegics

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**Abstract:** Treatments based on Virtual Reality have been successfully used in motor rehabilitation of issues such as Spinal Cord Injury and Stroke. Highly immersive Virtual environments combined with biofeedback can be utilized to train functional activities on patients with these motor disabilities. This work details the development of a portable Virtual Reality environment to train upper limbs activities on Spinal Cord Injury subjects. The Virtual Reality environment depicts a personalized physiotherapy room where the user trains elbow and shoulder by reaching 5 spots on table. Also the user have a biofeedback of both hands' position. Finally this system will be integrated a pilot biomechanical analysis using The Motion Monitor system to compare a group of patients before and after a 6 week intervention with Virtual Reality.

## 1 INTRODUCTION

Spinal Cord Injury (SCI) afflicts from 50 to 1218 cases per million worldwide according to Spinal Cord Injury Evidence (Devivo and Chen, 2011) and most of these cases are caused by vehicles accidents. SCI is classified by the neurological level of the injury so that motor and sensory functions below the injury are disabled. Because of that, SCI impacts social life and it limits the capacity to execute Activities of Daily Life (ADLs). Most of tetraplegic's ADLs use reach and grasp movements (Varoto and Cliquet, 2015) which involve complex biomechanical analysis of upper limbs in order to develop new techniques of rehabilitation of these subjects. Therefore, tetraplegic patients have a increasingly demand for innovative and creative solutions that integrate technology with physiotherapy to improve rehabilitation.

One of the main goals of motor rehabilitation is to induce neuroplasticity on the patients. Neuroplasticity or neural adaptation is the foundation of learning (Montgomery and Connolly, 2003) and it's the brain ability to reorganize itself as a response to external stimuli and consequently recover partially or com-

pletely motor and sensory functions. Some examples of stimuli are Functional Electrical Stimulation (FES) (Bergmann et al., 2019) and Motor Imagery. Mental practice of a muscular activity as well of the visualization of a muscular movement activates the corresponding area of the brain that would be activated in the actual movement (Edmund Jacobson, 1932). An application of motor imagery is on training of athletes by imaging the movement that would be executed during a real competition. Mizuguchi (Mizuguchi et al., 2012) made a study which stated that around 70 to 90 percent of a group of elite athletes agreed that motor imagery alongside real training improved their performance in real competition. Also his study concluded that motor imagery treatment could be used in motor rehabilitation.

An important example of motor imagery is Virtual Reality (VR). VR can be defined as an advance interface system that represents a 3D environment in real time. It encompasses both non-immersive systems such as video games or pc and immersive like Oculus Rift and HTC Vive. Villiger (Villiger et al., 2015) performed a study with incomplete SCI subjects using VR to train lower limbs by flexing ankle and knee in the VR environment. The results were a boost in motivation and in motor performance as well as increase of brain capacities.

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Other VR based systems helped to enhance motor rehabilitation. Park (An and Park, 2018) used a semi-immersive VR system to evaluate standing position in SCI subjects. Other example was a VR environment alongside an instrumented glove (Dimbwadyo-Terrer et al., 2016) used to train reach movements also on SCI subjects.

This paper describes the development of a VR environment to train upper limbs' exercises in SCI subjects. The hardware chosen was Oculus Quest (Facebook Technologies, Irvine, California, EUA) and the VR environment was made with Unity 3D (Unity Technologies, Copenhagen, Denmark). Oculus Quest is a portable device thus it can be easily used in hospitals and small places. This project is part of a collaborative work of Laboratory of Biocybernetics and Rehabilitation Engineering from University of São Paulo and Laboratory of Biomechanics and Rehabilitation of the Locomotor System of University of Campinas that contributed by developing the VR system and for the treatment of SCI patients. This paper's final part is the description of the biomechanical analysis that will be used to validate the VR Environment.

## 2 METHODOLOGY

### 2.1 Characterizing SCI Population and ADL Protocol

The criteria for selection SCI population for this study were the following: Tetraplegics, neurological level of lesion from C4 to C8 according to American Impairment Scale (AIS) from American Spinal Injury Association (ASIA), no autonomic dysreflexia and more than one year of lesion.

The main goal of this work is to improve ADLs of SCI tetraplegics by training functional activities with VR. C8 patients may still have hands movement whereas C4 patients barely can move arms. For this reason, the protocol chosen to be trained in the VR environment is a movement that utilizes shoulder and elbow to hands to reach 5 spots in a table. Starting with the left hand in the bottom left spot, the patient tries to reach every other spot in the table. Similarly, the same protocol is made with the right hand.

All the patient will be divided in two groups: a control group and a group that will make an intervention with VR. Subsequently, both groups will make an initial biomechanical analysis of upper limbs. Lastly, the intervention group will be subjected to a 6 week training with VR and, afterwards, another biomechanical analysis.

### 2.2 Head Mounted Display and Oculus Quest

Head Mounted Display (HMD) is a headset used to display VR. Each HMD has two lens and each one of them represents a image slightly displaced between them resulting in a 3D perception of the image. This effect is called stereoscopy and is one of the basis of VR since it turns a 2D non-immersive experience into a 3D immersive experience.

Another aspect of HMD that improves the immersive experience is the head tracking. Gyroscope and Accelerometers from HMD are responsible for tracking rotation and position respectively. Both sensors combined with stereoscopic vision results in 3D visual environment where the user can see objects as if they where real objects. In addition to the visual experience of VR some HMDs have input devices to capture commands of the user and turn them into actions in the virtual environment.

Oculus Quest is a portable HMD with two controllers with motion sensors that are used to track hand position (figure 1). In order to use the controllers with tetraplegics, each controller is attached to the wrist with a ribbon. Even though the protocol trains shoulder and elbow movement, Oculus Quest's controllers only need to collect hand's position and rotation data so the program can check if the user made the correct movement.



Figure 1: Oculus Quest HMD and Controllers.

### 2.3 VR Development and Setup

The VR environment was made using Unity 3D which is one of the most popular game engine worldwide. Oculus have a library with prefabricated assets

that get data from the Oculus Quest HMD and controllers and convert them into variables in Unity 3D. Unity 3D assets are capable of inherit classes from other library. As an example, the initial position in the VR scene is inherited from HMD real position. The figure 2 shows the main prefabs and scripts used in the project.

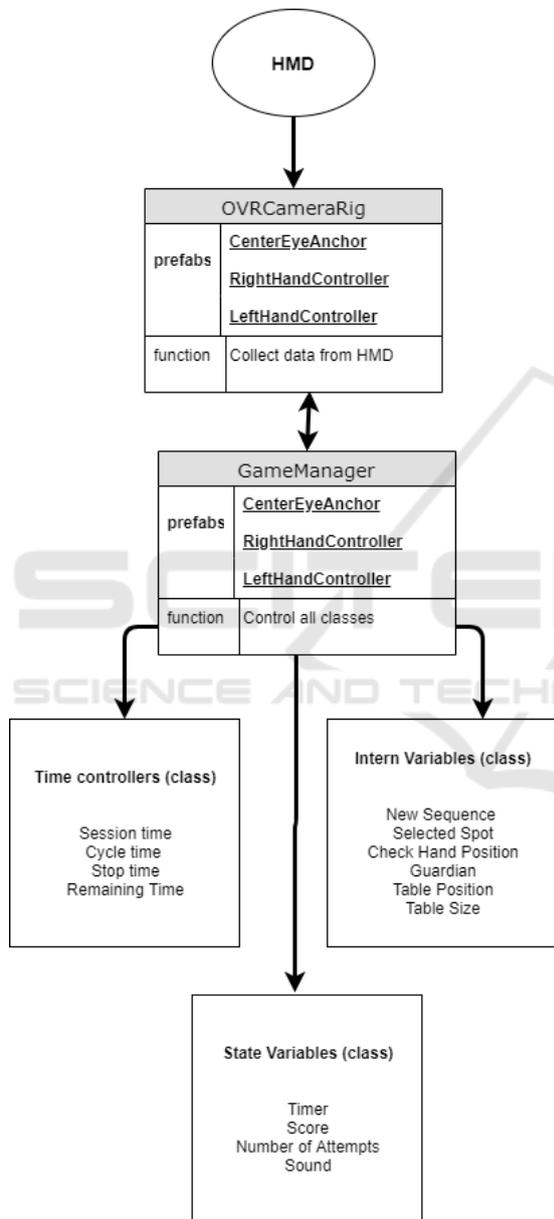


Figure 2: Main prefabs, classes and variables used to control the vr project.

One of the most important prefabs is the OVR-CameraRig which is the prefab that inherits data from the HMD. It contains a player controller scripts that

allows the user to control the main camera and a 3D vector that have the same direction that the user is looking. This vector is named CenterEyeAnchor. Alongside the center anchor there are two other children prefabs of the OVRCameraRig that are receiving data from the controllers. They are named LeftHandAnchor and RightHandAnchor and their position and rotation are referenced by the cylinder used as the proprioceptive feedback.

Another significant aspect of the VR environment is the main scene setup process. Before a VR session the objects size and positioning must be defined related to the real position of the user. This is made by an introductory scene where the user looks to a grid to select where the table will be created. Each point of the grid corresponds to a potential initial position and the user stares at the desired spot for a few seconds and it is selected. Tetraplegics could accomplish this procedure since it uses basically head movements in order to select the spawn spot for the table. Afterwards, he chooses the size of the table and the blue spots are positioned automatically. In the next step, the patient defines the size of the guardian. The guardian of Oculus Quest is the region where the user can move safely without hitting any objects in the real room. If the patients somehow trespasses the guardian, Oculus Quest will show the real room and the guardian's grid.

Finally, all the prefabs are organized by the GameManager which is a singleton class that holds all other classes of the project. Unity 3D allows the creation of classes in form of scripts and each script contains variables and functions used to control the game. As shown in figure 2, the classes were separated in 3 types in order to help to identify any incidental error and correct it. Time controllers define when each session and each cycle starts and ends as well they let the user stop the game at any moment. Intern variables generate random sequences at the beginning of each cycle and stores every action of the user. Finally, state variables record time remaining, score and cycles done. This last category is used as a feedback of the user's performance during the VR session.

## 2.4 User's Interface (UI)

So far this paper has focused on movement based interaction. However, some of the basic interaction such as selecting an option or a scene should be adapted for tetraplegics. The following section will discuss how an adapted User's Interface (UI) was created in a way that only head movements are used to trigger events in the VR environment.

Virtual Reality has a feature called Gaze Input

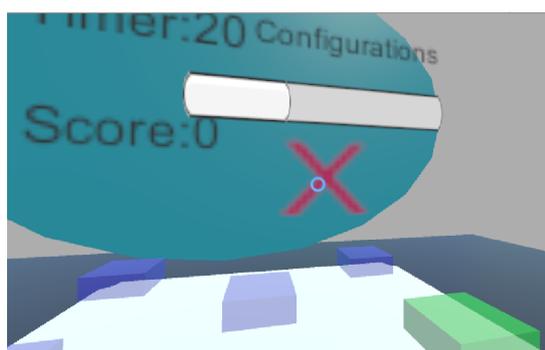


Figure 3: Gaze Input Controller and Slider example.

Controller (GIC) that is a pointer symbolized by a small blue circle, as shown in the figure 3.

GIC uses a raycaster that inherits the direction of the CenterEyeAnchor. Raycaster is a 3D vector used to interact with Unity native UI. In other words, GIC is a 3D vector that points to the direction where the user is looking and it is used to trigger events in the VR environment.

The UI is organized in several canvas and each one of them has buttons that have a component called event trigger which function is to switch in between scenes. When the user looks at a canvas, GIC collides with the canvas and a slider bar starts to charge. When the slider is fully charged, the next scene in sequence is displayed. The figure 4 shows all the scenes in the VR environment and how they are related.

## 2.5 The Motion Monitor and Biomechanical Analysis

This VR project will be used in a Biomechanical analysis to validate if the VR intervention improved the functional activities on tetraplegics. The Motion Monitor system that will be used in this analysis integrates 12 Vicon (Vicon Motion Systems Ltd, Oxford, United Kingdom) cameras with a data analysis software as well it uses clusters instead of markers to capture motion data. Hence, it reduces the number of markers that are normally used with Vicon (over 20 markers) to a set of 9 cluster for a full body motion capture.

For this study, only 5 clusters are used to capture motion data from upper limbs: left and right arms and forearms and thorax. For analysing motion data, the Motion Monitor software reconstructs a 3D model representing real time data of the upper limbs. The figure 5 shows an example of upper limbs' 3D model.

To verify if the clusters could be used on a wheelchair, a healthy subject sat on a chair simulating a SCI subject. Afterwards, 5 clusters were positioned

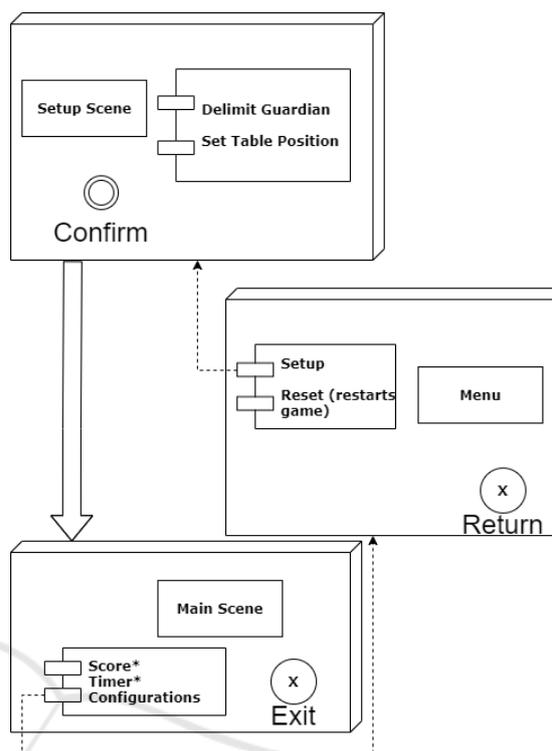


Figure 4: Diagram of main interfaces. Names with "\*" are non-intractable.

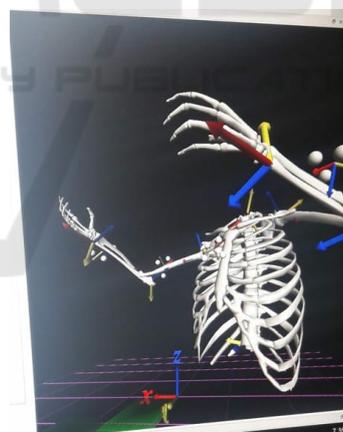


Figure 5: Example of a 3D model created with Motion Monitor.

on arms, forearms and thorax.

The kinematic data analyzed are angles and velocities from shoulders and elbows in 3 axes. During a collect session, the patient have to move each arm in 5 spots disposed in a table in the same place that the ones in the VR environment. This protocol is done 3 times for each hand to minimize eventual errors in measure. The main goal is to evaluate maximum values for elbow flexion, shoulder abduction and veloci-

ties during the protocol before and after the VR treatment and see if they were improved. Also a control group will be submitted to the same analysis to compare their performance with the intervention group.

### 3 RESULTS

#### 3.1 VR Environment

The main scene of the VR Environment depicts a table with 5 spots positioned in the center and in each corner of the table (figure 6). In each cycle the user have to move his hand to 5 different spots in 2 minutes. The sequence is generated randomly for each cycle to prevent the patient to memorize the same sequence and to simulate movements more similar to ADLs of reach.

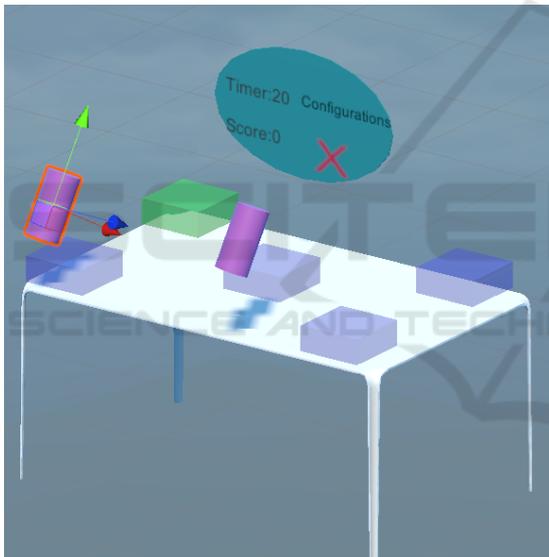


Figure 6: Main Scene of the VR Environment.

The blue blocks indicate all the possible spots and the next spot of the sequence is the green one. If the patient successfully reaches the correct spot it returns a sound and the next spot of the sequence becomes green. In the other hand if he reaches the wrong spot all blocks blinks a red colour and the sequence restarts. Tetraplegics don't have sensory functions below the neurological level. Because of this, biofeedbacks such as colour changes and sound effects are important to indicate to the patient if an action taken in the scene is correct or not. Similarly, SCI subjects need a proprioceptive feedback from the VR system to know the real position of their hands. The VR environment have a proprioceptive feedback in form of

two small purple cylinder that have both rotation and position of the real hands depicted in real time. The green arrow and the blue arrow of each cylinder indicate parallel and orthogonal vectors related to each palm respectively.

Each cylinder and each spot have an invisible collider box to verify if the user correctly reached a selected spot. When the cylinder's collider enters in a spot, the program checks if the spot is correct and, when it leaves the spot, the next game action is taken. Besides that, there is a small menu above the table that displays time remaining, score, settings and exit button.

#### 3.2 Preliminary Tests

The VR environment is part of a pilot study where the main goal is to test viability. Consequently, the VR system was tested on healthy subjects to guarantee that it would be safe to use it with SCI subjects. The preliminary tests showed that the VR could check correctly if the user reached the selected spot only verifying hand's data. Other positive result was that the GIC interface that could be used to navigate throughout scenes alongside with the controllers. However, the setup scene had problems such as the floor level of the environment that was wrong in some cases. This may occur due to the default configurations of Oculus Quest. Also the Setup Scene will need to considerate additional information like height to calculate the user's baseline. Even though the protocol worked fine, baseline would increase redundancy and reduce errors of positioning.

First issue was holding controls using a ribbon. Although it hold still the controllers, a support would be more appropriated to use with SCI subjects. Nonetheless, both controller could capture data precisely while attached to the wrists.

#### 3.3 Biomechanical Analysis Pilot

A Biomechanical analysis pilot was made with a healthy subject sat on a wheelchair. While the arms and forearms had no issues, some changes had to be made before positioning the thorax cluster. Normally, the thorax cluster is positioned on the back, however that's not possible with the wheelchair. The second one was to calibrate the baseline with the subject seated because it's normally done with the subject standing. The solution found to resolve the first was to change the axis of the 3D model in order to change the cluster position to the chest. The second one couldn't be directly resolved but it didn't interfere drastically in the analysis. The protocol data can

be segmented and normalized using elbow flexion and shoulder flexion as reference to identify each part of the protocol.

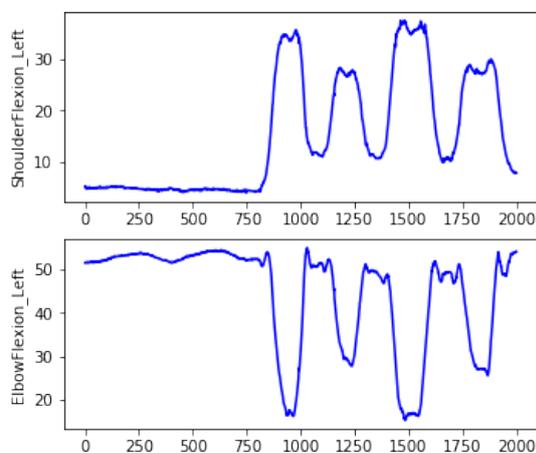


Figure 7: Graphics of Left Shoulder Flexion and Left Elbow Flexion.

The figure 7 shows raw data from shoulder and elbow of a test subject. Both graphs shows clearly that the protocol starts around the 750th time sample (sample rate of 100Hz) because both shoulder and elbow angles have a significant variance starting in this timestamp. This pattern is repeated for each spot, indicating that is possible to identify when the patient is reaching each spot. Hence, it's possible to calculate maximum and minimum values for flexion angles.

## 4 CONCLUSIONS

In conclusion, the preliminary study has brought some evidences that could lead on a innovative treatment for tetraplegics. A few improvements such as setup and an appropriate support for the controller should be made before the VR environment is used with SCI subjects. However, the main mechanics of the VR environment worked which may suggest that it could work with SCI. The next steps are: a) Create a baseline calibration for VR environment; b) Polish the 3D models to create a better immersive experience; c) Ethics committee approval for VR experiments on SCI subjects; d) Validate the VR Environment with a SCI population.

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